# 47th Annual DPS Meeting
**National Harbor, MD – November, 2015**
**Meeting Abstracts**

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## 100 – New Horizons Plenary Session

### 100.01 – The Pluto System: Initial Results from the Exploration by New Horizons

The Pluto system was recently explored by NASA's New Horizons spacecraft, which made closest approach on 14 July 2015. Pluto's surface is found to be remarkably diverse in landforms, terrain ages, and albedo, color, and composition gradients. Strong evidence is found for a water-ice crust, geologically young surface units, ice convection, wind streaks, and glacial flow. Pluto's atmosphere is found to be very extended, and contains newly discovered trace hydrocarbons, has an extensive global haze layer, and a surprisingly low surface pressure of ~10 microbars. Pluto's wide range of surface expressions and long term activity raises fundamental questions about how small planets can have active processes billions of years after their formation. The geology of Pluto's large moon Charon's is also surprisingly diverse, displaying tectonics and evidence for a heterogeneous crustal composition; the north pole displays puzzling dark terrain. No evidence for a Charon atmosphere is found. Pluto's small satellites Hydra and Nix are small, elongated objects with higher albedos than expected. Surprisingly, despite much improved diameter limits, no new satellites are found. We will present an overview of the New Horizons flyby, payload, and results. This work was supported by the NASA New Horizons project.

**Author(s): S.A. Stern4**, Harold Weaver[1], Leslie Young4, Catherine Olkin4, Kimberly Ennico3, Jeff Moore3, Will Grundy[2], Randall Gladstone5, Fran Bagenal[6]
**Institution(s):** *1. Johns Hopkins Applied Physics Laboratory, 2. Lowell Observatory, 3. NASA Ames Research Center, 4. SwRI, 5. SwRI, 6. University of Colorado*

### 100.02 – New Horizons Investigations of Charon and Pluto's Small Moons

During the flyby of the Pluto system in July 2014, the instruments on the New Horizons spacecraft (Weaver et al. 2008, Space Sci. Rev. 140, 75) acquired spatially resolved measurements of Charon and Pluto's small moons (Styx, Nix, Kerberos, and Hydra). The sunlit hemisphere of Charon was mapped in panchromatic light with resolutions as high as 0.15 km/pix using LORRI, and in four different color bands (400–550 nm, 540-700 nm, 780–975 nm, 860-910 nm; the latter is centered on a weak CH4 band) with resolutions as high as 1.4 km/pix using MVIC. Composition maps of Charon were obtained with the LEISA infrared spectral imager in the wavelength range 1.25-2.50 microns, with a spectral resolving power of ~250 and with spatial resolutions up to 4.9 km/pix. Solar occultation observations with the Alice ultraviolet spectrograph, and radio occultation measurements with REX, were used to search for an atmosphere around Charon. Nix was observed by LORRI in panchromatic light at 0.30 km/pix, by MVIC in color at 2.0 km/pix, and by LEISA at 3.6 km/pix (the latter to be downlinked later). Hydra was observed by LORRI in panchromatic light at 1.1 km/pix, in color at 4.6 km/pix, and by LEISA at 14.9 km/pix (the latter to be downlinked later). Limited resolved measurements of Kerberos (2.0 km/pix panchromatic; 8.0 km/pix color) and Styx (3.2 km/pix panchromatic; 8.0 km/pix color) were also obtained but have not yet been downlinked. An extensive series of unresolved, photometric measurements of Pluto's small moons were obtained with LORRI during several months preceeding closest approach in mid-July, which place tight constraints on their shapes and rotational states.
The New Horizons data have revealed that Charon has surprisingly diverse terrain, with evidence of tectonics and a heterogeneous crustal composition. Nix and Hydra are highly elongated bodies with high average albedos (suggesting water-ice dominated surfaces) and significant albedo and color variations over their surfaces. We will present estimates for the densities, spin periods, and physical properties of all the small satellites. This work was supported by NASA's New Horizons project.

**Author(s): Harold A. Weaver[2]**, S. A. Stern5, L. A. Young5, C. B. Olkin5, K. Ennico4, J. M. Moore4, W. B. McKinnon7, J. R. Spencer5, W. M. Grundy3, D. P. Cruikshank4, G. P. Gladstone5, M. E. Summers[1], F. Bagenal[6]
**Institution(s):** *1. George Mason University, 2. Johns Hopkins, APL, 3. Lowell Observatory, 4. NASA Ames Research Center, 5. Southwest Research Institute, 6. University of Colorado, 7. Washington University*

### 100.03 – Geology of Pluto and Charon Overview

Pluto's surface was found to be remarkably diverse in terms of its range of landforms, terrain ages, and inferred geological processes. There is a latitudinal zonation of albedo. The conspicuous bright albedo heart-shaped feature informally named Tombaugh Regio is comprised of several terrain types. Most striking is Texas-sized Sputnik Planum, which is apparently level, has no observable craters, and is divided by polygons and ovoids bounded by shallow troughs. Small smooth hills are seen in some of the polygon-bounding troughs. These hills could either be extruded or exposed by erosion. Sputnik Planum polygon/ovoid formation hypotheses range from convection to contraction, but convection is currently favored. There is evidence of flow of plains material around obstacles. Mountains, especially those seen south of Sputnik Planum, exhibit too much relief to be made of $CH_4$, CO, or $N_2$, and thus are probably composed of $H_2O$-ice basement material. The north contact of Sputnik Planum abuts a scarp, above which is heavily modified cratered terrain. Pluto's large moon Charon is generally heavily to moderately cratered. There is a mysterious structure in the arctic. Charon's surface is crossed by an extensive system of rift faults and graben. Some regions are smoother and less cratered, reminiscent of lunar maria. On such a plain are large isolated block mountains surrounded by moats. At this conference we will present highlights of the latest observations and analysis. This work was supported by NASA's New Horizons project.

**Author(s): Jeffrey M. Moore[2]**, S. A. Stern3, H. A. Weaver[1], Leslie A. Young3, Kimberly Ennico[2], Cathy B. Olkin3
**Institution(s):** *1. Johns Hopkins University Applied Physics Laboratory, 2. NASA Ames Research Center, 3. Southwest Research Institute*

### 100.04 – Pluto System Surface Composition Results

This talk will present an overview of surface composition discoveries from New Horizons' exploration of the Pluto system. The emphasis will be on results that could only have been obtained thanks to the uniquely high spatial resolution provided by a spacecraft visit. The Ralph instrument is New Horizons' primary tool for investigating surface compositions in the Pluto system. Ralph consists of a near-infrared spectral imager sharing a 75 mm aperture telescope assembly with a color CCD camera system. The Linear Etalon Imaging Spectral Array (LEISA) component of Ralph provides spectral coverage from 1.25 – 2.5 μm, at a resolving power ($\lambda/\Delta\lambda$) of 240. Ices such as $CH_4$, $N_2$, CO, $CO_2$, $C_2H_6$, $NH_3$, and $H_2O$ have uniquely diagnostic absorption bands in this wavelength region. The Multi-spectral Visible Imaging Camera (MVIC) has 7 CCD arrays of which 4 have interference filters affixed directly on the focal plane. The filters pass wavelengths ranging from 400 through 975 nm, sensitive to coloration by tholin-type materials as well as a weak CH4 ice absorption band at 890 nm. Both Ralph components are usually operated in a scanning mode, rotating the spacecraft about its Z axis to sweep Ralph's field of view across the scene such that each point in the scene is eventually imaged at each wavelength. The width of the scanned region is 0.9 degrees divided into 256 spatial pixels for LEISA and 5.7 degrees spanned by 5000 pixels for MVIC. Over the course of the summer 2015 flyby, numerous Ralph observations targeted the various bodies in the Pluto system. As of late 2015, transmission of the data to Earth continues, but already a number of spectacular data sets are available for analysis, including LEISA scans of Pluto at 6 to 7 km/pixel and of Charon at 3 km/pixel, as well as MVIC scans of Pluto at 700 m/pixel and of Charon at 5 km/pixel. This work was supported by the NASA New Horizons Project.

**Author(s): William M. Grundy[2]**, R P Binzel3, J C Cook7, D P Cruikshank4, C M Dalle Ore4, A M Earle3, K Ennico4, D E Jennings5, C J.A. Howett7, I R Linscott[6], A W Lunsford5, C B Olkin7, A H Parker7, J Wm Parker7, S Protopapa[8], D C Reuter5, K N Singer7, J R Spencer7, S A Stern7, C C.C. Tsang7, A J Verbiscer9, H A Weaver[1], L A Young7
**Institution(s):** *1. Johns Hopkins University Applied Physics Laboratory, 2. Lowell Obs., 3. MIT, 4. NASA Ames Research Center, 5. NASA Goddard Space Flight Center, 6. Stanford University, 7. SwRI, 8. University of Maryland, 9. University of Virginia*

### 100.05 – New Horizons Observations of the Atmospheres of Pluto and Charon

Major goals of the New Horizons (NH) mission are to explore and characterize the structure and composition of Pluto's atmosphere, and to establish whether Charon has a measurable atmosphere of its own. The primary instruments onboard NH which contribute to these goals are the REX instrument, through uplink X-band radio occultations, the Alice instrument, through extreme- and far-ultraviolet solar occultations, and the LORRI panchromatic imager, through high-phase-angle imaging. The associated datasets were obtained following closest approach of NH to Pluto. Pressure and temperature profiles of the lower atmosphere are derived from the REX data, the composition and structure of the extended atmosphere are derived from the Alice data (supported by approach observations of reflected ultraviolet sunlight), and the distribution and properties of Pluto's hazes are derived from the LORRI data. In this talk an overview of the early atmosphere science results will be presented.
This work was supported by NASA's New Horizons project.

**Author(s): G. R. Gladstone[6]**, S. A. Stern[6], H. A. Weaver[8], L. A. Young[6], K. A. Ennico3, C. B. Olkin[6], A. F. Cheng[8], T. K. Greathouse[6], D. P. Hinson5, J. A. Kammer[6], I. R. Linscott5, A. H. Parker[6], J. Wm. Parker[6], K. D. Retherford[6], E. Schindhelm[6], K. N. Singer[6], A. J. Steffl[6], D. F. Strobel7, M. E. Summers[1], C. C. C. Tsang[6], G. L. Tyler5, M. H. Versteeg[6], W. W. Woods5, N. Cunningham4, W. Curdt[2]
**Institution(s):** *1. George Mason University, 2. Max Planck Institute for Solar System Research, 3. NASA Ames Research Center, 4. Nebraska Wesleyan University, 5. SETI Institute, 6. Southwest Research Inst., 7. The Johns Hopkins University, 8. The Johns Hopkins University Applied Physics Laboratory*

### 100.06 – Solar wind interaction with Pluto's escaping atmosphere

NASA's New Horizons spacecraft carries two instruments, SWAP and PEPSSI, that measure low and high energy particles respectively. These particle instruments have been measuring the conditions in the solar wind for most of the trajectory from Earth to Pluto. The Venetia Burney Student Dust Counter measured impacts from micron-sixed dust particles. These particle instruments also made observations during the flyby of Pluto on July 14, 2015. We report on New Horizons measurements of the interaction of the solar wind interaction with Pluto's extended atmosphere and discuss comparisons with theoretical expectations.

**Author(s): Fran Bagenal[6]**, S A Stern3, H A Weaver[1], L A Young3, K Ennico[2], C Olkin3, D J McComas4, R L McNutt[1], M Horanyi[6], H A Elliott4, M E Hill[1], E Zernstein4, P Kollman[1], S M Krimigis[1], C M Lisse[1], D F Strobel5, J SzalAy[6], M Piquette[6]
**Institution(s):** *1. JHU-APL, 2. NASA Ames Research Center, 3. Southwest Research Institute, 4. Southwest Research Institute, 5. The Johns Hopkins University, 6. Univ. of Colorado*

## 101 – Pluto System I--New Horizons Headliner

### 101.01 – Color Variations on Pluto, Charon & Among Pluto's Small Satellites

This summer's flyby of NASA's New Horizons spacecraft past Pluto provided the first high spatial resolution imaging of the system. Using the Ralph instrument (Reuter et al. 2008, Space Sci. Rev. 140, 129), color images were obtained in 3 broadband filters and one narrow band filter: blue (400 – 550 nm), red (540-700 nm), NIR (780 – 975 nm) and methane (860 – 910 nm). These data revealed details about Pluto's variegated surface including distinct color boundaries in two halves of the region informally named, Tombaugh Regio, and intriguing color variations in Pluto's north pole. This talk will discuss the color variations on Pluto, Charon, Nix and Hydra. Color observations of Kerberos and Styx were taken, but will not be downlinked in time for inclusion in this talk. This work was supported by NASA's New Horizons project.

**Author(s): Catherine B. Olkin7**, D. C. Reuter5, S. A. Stern7, C. J. A. Howett7, A. H. Parker7, K. Ennico4, K. N. Singer7, W. M. Grundy[2], H. A. Weaver[1], L. A. Young7, R. P. Binzel3, M. W. Buie7, J. C. Cook7, D. P. Cruikshank4, C. M. Dalle Ore4, A. M. Earle3, D. E. Jennings5, I. R. Linscott[6], A. W. Lunsford5, J. Wm. Parker7, S. Protopapa[8], J. R. Spencer7, C.C.C. Tsang7, A. J. Verbiscer9
**Institution(s):** *1. Johns Hopkins University Applied Physics Laboratory, 2. Lowell Observatory, 3. MIT, 4. NASA Ames Research Center, 5. NASA Goddard Space Flight Center, 6. Stanford University, 7. SWRI, 8. University of Maryland, 9. University of Virginia*

### 101.02 – Pluto: Distribution of ices and coloring agents from New Horizons LEISA observations

Pluto was observed at high spatial resolution (maximum ~3 km/px) by the New Horizons LEISA imaging spectrometer. LEISA is a component of the Ralph instrument (Reuter, D.C., Stern, S.A., Scherrer, J., et al. 2008, Space Sci. Rev. 140, 129) and affords a spectral resolving power of 240 in the wavelength range 1.25-2.5 µm, and 560 in the range 2.1-2.25 µm. Spatially resolved spectra with LEISA are used to map the distributions of the known ices on Pluto ($N_2$, $CH_4$, CO) and to search for other surface components. The spatial distribution of volatile ices is compared with the distribution of the coloring agent(s) on Pluto's surface. The correlation of ice abundance and the degree of color (ranging from yellow to orange to dark red) is consistent with the presence of tholins, which are refractory organic solids of complex structure and high molecular weight, with colors consistent with those observed on Pluto. Tholins are readily synthesized in the laboratory by energetic processing of mixtures of the ices ($N_2$, $CH_4$, CO) known on Pluto's surface. We present results returned from the spacecraft to date obtained from the analysis of the high spatial resolution dataset obtained near the time of closest approach to the planet. Supported by NASA's New Horizons project.

**Author(s): Dale P. Cruikshank4**, William M. Grundy[2], S. Alan Stern[8], Catherine B. Olkin[8], Jason C. Cook[8], Cristina M. Dalle Ore[6], Richard P. Binzel3, Alissa M. Earle3, Kimberly Ennico4, Donald E. Jennings5, Carly J.A. Howett[8], Ivan R. Linscott7, Allen W. Lunsford5, Alex H. Parker[8], Joel W. Parker[8], Silvia Protopapa9, Dennis C. Reuter5, Kelsi N. Singer[8], John R. Spencer[8], Constantine C. C. Tsang[8], Anne J. Verbiscer[10], Harold A. Weaver[1], Leslie A. Young[8]
**Institution(s):** *1. Applied Phys. Lab., 2. Lowell Observatory, 3. MIT, 4. NASA Ames Research Center, 5. NASA Goddard Space Flight Center, 6. SETI Institute, 7. Stanford Univ., 8. SWRI, 9. Univ. Maryland, 10. Univ. Virginia*

### 101.03 – First Results from The New Horizons Radio Science Experiment: Measurements of Pluto's Atmospheric Structure, Surface Pressure, and Microwave Brightness Temperature

The Radio Science Experiment (REX), on board the New Horizons spacecraft, measured key characteristics of Pluto and Charon during the July 14, 2015, flyby. The REX flight instrument is integrated into the NH X-band radio transceiver and provides high precision, narrow band recording of powerful uplink transmissions from Earth stations, as well as a record of broadband radiometric power. This presentation reviews the performance and initial results of the radio occultation of Pluto, the radiometric temperature profiles, and gravity measurements during the encounter. REX received two pair of 20-kW uplink signals, one pair per polarization, transmitted from the DSN at 4.2- cm wavelength during a diametric radio occultation of Pluto. The REX recording of the uplinks affords a precise measurement of the surface pressure, the temperature structure of the lower atmosphere, and the surface radius of Pluto. The ingress portion of one polarization was played back from the spacecraft in July, while the egress portion of the same polarization was played back in August. Both ingress and egress segments of the occultation have been processed to obtain the pressure and temperature structure of Pluto's atmosphere. In addition, REX measured the thermal emission from Pluto at 4.2- cm wavelength during two linear scans across the disk at close range when both the dayside and the night side were visible. Both scans extend from limb to limb with a resolution of one-tenth Pluto's disk and temperature resolution of 0.1 K. A third radiometric scan was obtained during the dark side transit of the occultation. This work was supported by NASA's New Horizons project.

**Author(s): Ivan Linscott[3]**, Alan Stern[4], Hal Weaver[1], Leslie Young[4], Cathy Olkin[4], Kim Ennico[2]
**Institution(s):** *1. JHUAPL, 2. NASA AMES , 3. Stanford University, 4. SWRI*

### 101.04 – Volatile Transport Implications from the New Horizons Flyby of Pluto

The New Horizons flyby of Pluto has revealed a striking range of terrains, from the very bright region informally named Sputnik Planum, to very dark regions such as the informally named Cthulhu Regio. Such a variety was beyond the scope of recent models of Pluto's seasonal volatile cycle (Young 2013, ApJL 766, L22; Hansen, Paige and Young 2015, Icarus 246, 183), which assumed globally uniform substrate albedos. The "Exchange with Pressure Plateau (EPP)" class of models in Young (2013) and the favored runs from Hansen et al (2015) had long periods of exchange of volatiles between northern and southern hemispheres. In these models, the equators were largely devoid of volatiles; even though the equatorial latitudes received less insolation than the poles over a Pluto year, they were never the coldest place on the icy world. New models that include a variety of substrate albedos can investigate questions such as whether Sputnik Planum has an albedo that is high enough to act as a local cold trap for much of Pluto's year. We will present the implications of this and other assumption-busting revelations from the New Horizons flyby. This work was supported by NASA's New Horizons project.

**Author(s): Leslie Young[6]**, William M Grundy[3], RIchard P Binzel[4], Alissa M Earle[4], Ivan R Linscott[7], David P Hinson[7], Amanda M Zangari[6], William B McKinnon[8], S. Alan Stern[6], Harold A Weaver[2], Catherine B Olkin[6], Kimberly Ennico[5], G Randall Gladstone[6], Michael E Summers[1], Jeffrey M Moore[5], John R Spencer[6]
**Institution(s):** *1. George Mason University, 2. Johns Hopkins University Applied Physics Laboratory, 3. Lowell Observatory, 4. MIT, 5. NASA Ames Research Center, 6. Southwest Research Inst., 7. Stanford University, 8. Washington Univ in St. Louis*

### 101.05 – Small Satellites and Dust in the Pluto System: Upper Limits and Implications

To help ensure safe passage of the New Horizons (NH) spacecraft as it flew through the Pluto system, we took a series of deep images with the Long Range Reconnaissance Imager (LORRI) to search for previously undetected satellites or rings. We obtained a total of 1100 10-second exposures, spread over 20 epochs between May 11 and July 1 2015. HST observations had previously set an upper limit to the brightness of undetected moons of about half Styx's brightness (i.e., a diameter of ~5 km for an a Charon-like albedo of 0.38). The final NH observations in early July could have detected objects down to ~1.5 km in diameter in the Charon - Hydra region, and ~2 km between Charon's orbit and ~5000 km above Pluto's surface. Despite the sensitivity of the searches, no additional moons were found. The lower limit on the brightness ratio between Styx and any undiscovered fainter satellites, ~20, is comparable to the brightness ratio between Nix and Kerberos (~16), and a power-law satellite size distribution, analogous to that seen in the Saturn system, cannot be ruled out. Implications of the satellite size distribution for the origin of the satellite system will be discussed. The data also place an upper limit of ~1 x $10^{-7}$ on the I/F of any dust rings in the vicinity of the known small satellites, a factor of several improvement over previous HST limits. This work was supported by NASA's New Horizons project.

**Author(s): John R. Spencer[7]**, Mark R. Showalter[6], S. Alan Stern[7], Marina Brozovic[2], Marc W. Buie[7], Douglas P. Hamilton[8], Robert A. Jacobson[2], David E. Kaufmann[7], Tod R. Lauer[4], Alex H. Parker[7], Simon B. Porter[7], Henry B. Throop[5], Anne J. Verbiscer[9], Harold A. Weaver[1], Leslie A. Young[7], Kimberly Ennico[3], Catherine B. Olkin[7]
**Institution(s):** *1. Applied Physics Laboratory, 2. Jet Propulsion Laboratory, 3. NASA Ames Research Center, 4. National Optical Astronomy Observatory, 5. Planetary Science Institute, 6. SETI Institute, 7. Southwest Research Institute, 8. University of Maryland, 9. University of Virginia*

### 101.06 – What We Know Now: Synthesis for Understanding the Origin of the Pluto System

The July 2015 *New Horizons* flyby has removed a long-standing obstacle to understanding the cosmogony of the Pluto-Charon system: the uncertain radius of Pluto. Combined with precise astrometric fits to the barycenter of the Pluto-Charon binary from HST observations of the more distant, small satellites (Brozovic *et al.*, *Icarus* **246**, 317–329, 2015), the densities of both Pluto and Charon are now known. At the 10% level, these densities are rather similar, as opposed to the more divergent density estimates of years past in which Charon was thought to be substantially icier. In the context of a "giant impact" origin, a rock-rich Charon implies that the precursor impacting bodies were at most only partially differentiated — possessing relatively thin ice shells (Canup, *Astron. J.* **141**, 35, 2011). This suggests some combination of relatively slow and/or late accretion in the ancestral Kuiper belt. *New Horizons* has also shown that Nix and Hydra possess high albedos, consistent with ice-dominated compositions. Such compositions are consistent with a giant impact origin in which one or both precursor impacting bodies were partially differentiated, so that the small satellites ultimately formed from material ejected from ice-dominated surface layers (Peale and Canup, *Treatise on Geophysics*, 2nd Ed., chapter 10.17, 2015). We examine whether Pluto and Charon could actually possess the same bulk rock/ice ratio and whether this would allow for an alternate, non-giant-impact origin for the Pluto system.
This work was supported by NASA's *New Horizons* project.

**Author(s): William B. McKinnon[6]**, S. A. Stern[4], H. A. Weaver[1], J. R. Spencer[4], F. Nimmo[5], C. M. Lisse[1], O. M. Umurhan[3], J. M. Moore[2], M. W. Buie[4], S. B. Porter[4], C. B. Olkin[4], L. A. Young[4], K. Ennico[2]
**Institution(s):** *1. APL, 2. NASA Ames, 3. SETI, 4. SwRI, 5. UCSC, 6. Washington Univ.*

## 102 – Pluto System II--Pluto Surface and Satellites

### 102.01D – Vigorous Convection Underlies Pluto's Surface Activity

Against many expectations, *New Horizons'* images of the surface of Pluto and Charon show seemingly young surfaces. On Pluto, images of an equatorial region south of the Tombaugh Regio reveal a mountain range with peaks jutting as high as 3,500 meters. The low concentration of craters for these mountains suggests an age of 100 million years, indicating that Pluto is geologically active. Other evidence for geologic activity includes a fault cross-cutting ridges, smooth lightly cratered plains with flow fronts, and a pair of apparent stratovolcanoes. Charon similarly possesses very few craters and a spectacular system of troughs. Both observations suggest the possible presence of active cryogeysers and cryovolcanoes. The underlying cause of modern tectonic and volcanic activity on any object is likely a vigorous mantle

convection regime. We are thus led to consider what determines planetary vigor. While Pluto and Charon seem to be quite active, Ceres and the much larger Callisto seem to lack modern endogenic activity, even though all of these bodies are likely to possess water ice mantles.
We coupled a parameterized convection model with a temperature dependent rheology for pure water ice, deducing a barely critical Rayleigh number of ~1600 for Pluto's mantle and <1000 for Charon, suggesting that a water ice mantle alone may be insufficient to support vigorous convection in these bodies. However, in the outer solar system, other volatiles may have condensed. Ammonium hydrate has been reported on the surface of Charon. At temperatures above the eutectic (176 K), Durham et al. (1993) showed that $NH_3$ lowers the viscosity of water ice by 4 orders of magnitude. Our model indicates that, with $NH_3$, the mean temperature of the mantle of Pluto is at the eutectic and its Ra ~ 10^4. The presence of $NH_3$ dramatically increases the vigor of convection for the two bodies and suggests that ammonia-water slurries are the basis for Pluto's volcanism. We propose that the presence or absence of active mantle convection may offer a universal criterion for endogenic planetary vigor.

**Author(s): Alexander J. Trowbridge[1]**, Henry Jay Melosh[1], Andy M. Freed[1]
**Institution(s):** *1. Purdue University*

### 102.02 – Craters on Pluto and Charon: Characteristics and Impactor Population

Although both Pluto and Charon have a surprising number of young-looking surfaces, there are still plenty of craters for impact-phenomenon enthusiasts. We will present size, morphology, ejecta, and albedo pattern statistics, in addition to correlations with color/composition where possible. We use images and topography from the Long Range Reconnaissance Imager (LORRI; Cheng et al., 2008, *SSR* 140, 189-215) and data from the Ralph (Reuter et al., 2008, *SSR* 140, 129-154) color/composition instruments. Impactor sizes will be estimated from relevant scaling laws for cold water ice (see details in Singer and Stern, 2015, *ApJL* **808**, L50). For Pluto, an image strip at 125 m $px^{-1}$ includes some cratered terrains, and much of the encounter hemisphere (the anti-Charon hemisphere) will be covered at ~400 m $px^{-1}$. The ~smallest craters observable at these pixel scales (using a 5 pixel limit) would be ~0.63 km, and ~2 km in diameter, respectively, with impactor diameters estimated at ~50 m, and ~200 m. However, it is likely that degradation processes may obscure small craters, thus this lower observation limit will depend on terrain type. Additionally, lighting and observation geometries vary across the disk, which may make crater detection difficult in some areas. All of the illuminated portions of Pluto (during its 6.4 day rotation period) were imaged at ~20 km $px^{-1}$ or better during the encounter. The highest resolution images of Pluto (at ~80 m $px^{-1}$) occur in a narrow strip and are not scheduled for downlink before the DPS. The highest resolution Charon coverage (a strip at ~160 m $px^{-1}$), a broader swath at 400 m $px^{-1}$, and the entire encounter hemisphere (the sub-Pluto hemisphere) at ~890 m $px^{-1}$ may yield craters as small as 0.8, 2, and 4.5 km in diameter, respectively. The inferred impactor sizes for these craters would be ~50 m, 160 m, and 440 m. Although the dataset is limited, we will discuss what constraints can be put on the impactor population. This work was supported by the NASA New Horizons project.

**Author(s): Kelsi N. Singer[6]**, Paul M Schenk[2], Stuart J Robbins[6], Veronica J Bray[3], William B McKinnon[7], Jeffrey M Moore[4], John R Spencer[6], S A Stern[6], W M Grundy[1], Carly J.A. Howett[6], Cristina M Dalle Ore[5], Ross Beyer[5], Alex H Parker[6], Simon B Porter[6], Amanda M Zangari[6], Leslie A Young[6], Cathy B Olkin[6], Kimberly Ennico[4]
**Institution(s):** *1. Lowell Observatory, 2. Lunar and Planetary Institute, 3. Lunar and Planetary Laboratory, University of Arizona, 4. NASA Ames Research Institute, 5. SETI Institute, 6. Southwest Research Institute, 7. Washington University in St. Louis*

### 102.03 – Processes Modifying Cratered Terrains on Pluto

The July encounter with Pluto by the New Horizons spacecraft permitted imaging of its cratered terrains with scales as high as ~100 m/pixel, and in stereo. In the initial download of images, acquired at 2.2 km/pixel, widely distributed impact craters up to 260 km diameter are seen in the near-encounter hemisphere. Many of the craters appear to be significantly degraded or infilled. Some craters appear partially destroyed, perhaps by erosion such as associated with the retreat of scarps. Bright ice-rich deposits highlight some crater rims and/or floors. While the cratered terrains identified in the initial downloaded images are generally seen on high-to-intermediate albedo surfaces, the dark equatorial terrain informally known as Cthulhu Regio is also densely cratered. We will explore the range of possible processes that might have operated (or still be operating) to modify the landscape from that of an ancient pristinely cratered state to the present terrains revealed in New Horizons images. The sequence, intensity, and type of processes that have modified ancient landscapes are, among other things, *the* record of climate and volatile evolution throughout much of the Pluto's existence. The deciphering of this record will be discussed. This work was supported by NASA's New Horizons project.

**Author(s): Jeffrey M. Moore3**, Alan D. Howard5, Oliver L. White3, Orkan M. Umurhan3, Paul M. Schenk[2], Ross A. Beyer3, William B. McKinnon[6], Kelsi N Singer4, John Spencer4, S. A. Stern4, H. A. Weaver[1], Leslie A. Young4, Kimberly Ennico3, Cathy B. Olkin4
**Institution(s):** *1. Johns Hopkins University Applied Physics Laboratory, 2. Lunar and Planetary Institute, 3. NASA Ames Research Center, 4. Southwest Research Institute , 5. University of Virginia , 6. Washington University*

### 102.04 – In Charon's Shadow: Analysis of the UV Solar Occultation from *New Horizons*

Observations of Charon, Pluto's largest moon, have so far yielded no evidence for a substantial atmosphere. However, during the flyby of *New Horizons* through the Pluto-Charon system, the Alice ultraviolet spectrograph successfully acquired the most sensitive measurements to date during an occultation of the sun as *New Horizons* passed through Charon's shadow. These observations include wavelength coverage in the extreme- and far-ultraviolet (EUV and FUV) from 52 nm to 187 nm. We will present these results from Alice, and discuss their implications for an atmosphere on Charon.
This work was supported by NASA's *New Horizons* project.

**Author(s): Joshua A. Kammer5**, S. A. Stern5, H. A. Weaver[2], L. A. Young5, K. A. Ennico4, C. B. Olkin5, G. R. Gladstone[6], M. E. Summers[1], T. K. Greathouse[6], K. D. Retherford[6], M. H. Versteeg[6], J. W. Parker5, A. J. Steffl5, E. Schindhelm5, D. F. Strobel3, I. R. Linscott7, D. P. Hinson7, G. L. Tyler7, W. W. Woods7
**Institution(s):** *1. George Mason University, 2. JHU Applied Physics Laboratory, 3. Johns Hopkins University, 4. NASA Ames Research Center, 5. Southwest Research Institute, 6. Southwest Research Institute, 7. Stanford University*

### 102.05 – Charon's Color: A view from New Horizon Ralph/Multispectral Visible Imaging Camer

The Multispectral Visible Imaging Camera (MVIC; Reuter et al., 2008) is part of Ralph, an instrument on NASA's New Horizons spacecraft. MVIC is the color 'eyes' of New Horizons, observing objects using four bands from blue to infrared wavelengths. MVIC's images of Charon show it to be an intriguing place, a far cry from the grey heavily cratered world once postulated. Rather Charon is observed to have large surface areas free of craters, and a northern polar region that is much redder than its surroundings. This talk will describe these initial results in more detail, for example is Charon's redder pole caused by molecules that have escaped Pluto's atmosphere only to be captured and frozen onto the surface of Charon's cold polar region, where they have undergone photolysis? Charon's global geological color variations will also be discussed, to put these results into their wider context. This work was supported by NASA's New Horizons project.

**Author(s): Carly Jacqueline Amy Howett[6]**, Cathy B Olkin[6], William M Grundy[2], Alex H Parker[6], Kimberly Ennico4, Sol Alan Stern[6], Richard P Binzel3, Jason C Cook[6], Dale P Cruikshank4, Cristina M Dalle Ore4, Alissa Earle3, Don E Jennings5, Ivan Linscott7, Allen W Lunsford5, Joel Wm Parker[6], Silvia Protopapa[8], Dennis C Reuter5, Kelsi N Singer[6], John R Spencer[6], Con C.C. Tsang[6], Anne J Verbiscer9, Hal A Weaver[1], Leslie A Young[6]
**Institution(s):** *1. Applied Physics Laboratory, 2. Lowell Observatory, 3. Massachusetts Institute of Technology, 4. NASA Ames, 5. NASA Goddard Space Flight Center, 6. Southwest Research Institute, 7. Stanford University, 8. University of Maryland, 9. University of Virigina*

### 102.06 – The Chasmata and Montes of Charon

The New Horizons spacecraft made the first-ever high-resolution observations of Pluto's largest moon, Charon, on 14 July 2015. Those observations returned views of complicated topography on this icy world in the outer solar system. Charon posseses a series of chasmata and fossae that appear to form an organized tectonic belt that spans across the disk of the Pluto-facing hemisphere and may extend beyond. In addition, there are enigmatic, isolated mountains visible that are surrounded by depressions. These, in turn, are surrounded by a relatively smooth plain, broken by occaisional rilles, that stretches from these montes northward up to the chasmata region. We will discuss these features and more. This work was supported by NASA's New Horizons project.

**Author(s): Ross A. Beyer4**, Olivier Barnouin[1], Kimberly Ennico3, Jeff Moore3, Francis Nimmo[6], Cathy B Olkin5, Paul Schenk[2], John Spencer5, S Alan Stern5, Hal A Weaver[1], Leslie A Young5
**Institution(s):** *1. Applied Physics Laboratory, Johns Hopkins University, 2. Lunar and Planetary Institute, 3. NASA Ames Research Center, 4. SETI Institute, 5. Southwest Research Institute, 6. University of California Santa Cruz*

### 102.07 – Investigating Surface Features on Nix and Hydra

The LORRI (Cheng et al. 2008,Space Sci. Rev. 140, 189) and MVIC (Reuter et al. 2008,Space Sci. Rev. 140, 129) imagers on the New Horizons (NH) spacecraft obtained spatially resolved measurements of Nix and Hydra, two of Pluto's four small moons. Nix was observed by LORRI in panchromatic light (350-850 nm) at resolutions up to 0.30 km/pix, and by MVIC in color (400–550 nm, 540-700 nm, 780–975 nm, 860-910 nm; the latter is centered on a weak $CH_4$ band) at resolutions up to 2.0 km/pix. Hydra was observed by LORRI in panchromatic light at 1.1 km/pix, and by MVIC in color at 4.6 km/pix. The lossless versions of the images, which we will employ in our analysis, are scheduled for downlink in September and October 2015. After image deconvolutions, which typically double the spatial resolution, the NH images provide hundreds to thousands of pixels across the surfaces of Nix and Hydra. We will present results on our searches for craters, lineaments, and other features on the surfaces of Nix and Hydra. We will also present results on any correlations between morphological features and color and albedo variations on the surface. This work was supported by NASA's New Horizons project.

**Author(s): Harold A. Weaver[1]**, O. S. Barnouin[1], A. F. Cheng[1], C. M. Ernst[1], T. R. Lauer3, S. A. Stern4, C. B. Olkin4, K. Ennico[2], L. A. Young4
**Institution(s):** *1. Johns Hopkins, APL, 2. NASA Ames Research Center, 3. National Optical Astronomy Observatories, 4. Southwest Research Institute*

### 102.08 – The Orbits and Masses of Pluto's Satellites after New Horizons

Brozović et al. (2015 *Icarus* **246**, 317) reported on Pluto's mass and the masses and numerically integrated orbits of Pluto's satellites, Charon, Nix, Hydra, Kerberos, and Styx. These were determined via a fit to an extensive set of astrometric, mutual event, and stellar occultation observations over the time interval April 1965 to July 2012. The data set contained the Hubble Space Telescope (HST) observations of Charon relative to Pluto that were corrected for the Pluto center-of-figure center-of-light offset due to the Pluto albedo variations (Buie et al. 2012 *AJ* **144**, 15). Also included were all of the available HST observations of Nix, Hydra, Kerberos, and Styx. For the New Horizons encounter with the Pluto system, the initial satellite ephemerides (PLU043) and the initial planet and satellite masses were taken from the Brozović et al. analysis. During the New Horizons approach, the ephemerides and masses were periodically updated along with the spacecraft trajectory by the New Horizons navigation team using imaging of the planet and satellites against the stellar background. In this work, we report on our post-flyby analysis of the masses and satellite orbits derived from a combination of the original PLU043 data set, the New Horizons imaging data, and HST observations acquired after 2012.

**Author(s): Robert A. Jacobson[2]**, Marina Brozovic[2], Marc Buie5, Simon Porter5, Mark Showalter4, John Spencer5, S. Alan Stern5, Harold Weaver[1], Leslie Young5, Kimberly Ennico3, Cathy Olkin5
**Institution(s):** *1. Johns Hopkins, APL, 2. JPL, 3. NASA Ames Research Center, 4. SETI Institute, 5. Southwest Research Institute*

### 102.09 – Orbital and Rotational Dynamics of Pluto's Small Moons

Four small moons, Styx, Nix, Kerberos and Hydra, orbit the central binary planet comprising Pluto and Charon. Showalter and Hamilton (Nature 522, 45-49, 2015) analyzed Hubble Space Telescope (HST) data from 2010-2012 to explore some of the dynamical consequences of orbiting a binary planet. They noted evidence for a chaotic rotation of Nix and Hydra, and identified a possible three-body resonance between Styx, Nix and Hydra. We revisit the dynamics of the outer moons based on the latest data from the New Horizons flyby. As the spacecraft approached Pluto, the LORRI camera regularly imaged the moons over a period of ~100 days. This data set will make it possible to derive light curves and rotation rates unambiguously, something that has not been possible from the sparsely sampled HST data. It also extends the time baseline of the orbit determinations by several years, providing a more precise test of the proposed orbital resonances. We will discuss the latest measurements and their dynamical implications for the evolution of the Pluto system. This work was supported by NASA's New Horizons project.

**Author(s): Mark R. Showalter4**, John R. Spencer5, Simon B. Porter5, Douglas P. Hamilton[6], Richard P. Binzel[2], S. Alan Stern5, Harold A. Weaver[1], Cathy B. Olkin5, Leslie A. Young5, Kimberly Ennico3
**Institution(s):** *1. Applied Physics Lab, 2. MIT, 3. NASA Ames Research Center, 4. SETI Institute, 5. Southwest Research Institute, 6. University of Maryland*

### 102.10 – Shapes and Poles of the Small Satellites of Pluto

Pluto-Charon is a binary dwarf planet surrounded by four much smaller satellites: Styx, Nix, Kerberos, and Hydra (in order of increasing distance from the barycenter). These satellites were discovered with the Hubble Space Telescope, which also showed that their orbits are nearly circular around the system barycenter and coplanar to the central binary. NASA's New Horizons spacecraft flew through the Pluto system on July 14, 2015, and obtained the first resolved images of all four small satellites. We will present initial models for the shapes and densities of the small satellites determined from both those resolved images and earlier unresolved images, as well as measurements of the rotational poles of small satellites at the time of the Pluto encounter. This work was supported by the NASA New Horizons Project.

**Author(s): Simon B Porter5**, Mark R Showalter4, John R Spencer5, H A Weaver[1], Richard P Binzel[2], Douglas P Hamilton[6], S A Stern5, Catherine B Olkin5, Leslie A Young5, Kimberly Ennico3
**Institution(s):** *1. Johns Hopkins University Applied Physics Laboratory , 2. Massachusetts Institute of Technology, 3. NASA Ames Research Center, 4. SETI Institute, 5. Southwest Research Institute, 6. University of Maryland*

### 102.11D – Stability of coorbital objects around the Pluto-Charon binary

The Pluto-Charon binary system is dynamical interesting with its unusual retinue of four small moons. The system is relatively full with few remaining stable locations for additional moons on uninclined, circular orbits; most of these are Trojan (Tadpole/Horseshoe) orbits (Pires et al. 2011; Porter and Stern 2015).
In this work, we study the coorbital region of each moon with long time integrations taking into account the gravitational effects of the satellites Charon, Styx, Nix, Kerberos and Hydra. We numerically simulate a sample of 10,000 test particles initially located randomly around each moon's orbit. All test particles start on nearly circular and uninclined orbits and are followed for 5,000 years. The results of our numerical simulations show stable coorbital objects – both Tadpoles and Horseshoes – for each of the small moons. Horseshoe orbits are most common at all moons, although Hydra also has a sizeable population of Tadpole orbits. We also find interesting cases where the orbits switch from $L_4$ Tadpoles to Horseshoes and even to $L_5$ Tadpoles. These transitioning orbits comprise less than 1% of coorbital objects at all moons, and are most common at Styx. We have also tested two different models for the system: i) Pluto and Charon as independent bodies. ii) A single central body with the combined mass of Pluto-Charon and an effective $J_2$ coefficient. Preliminary results show only minor differences between the two models indicating that the binary does not have a strong effect on coorbital motion. We have also investigated eccentric and inclined orbits and will report on our findings.

**Author(s): Andre Amarante Luiz[1]**, Douglas P Hamilton[1]
**Institution(s):** *1. University of Maryland*

## 103 – Ceres Jubilee and Vested Interests

### 103.01 – Interior Evolution of Ceres Revealed by Dawn

Dawn's exploration of Ceres has revealed its geophysical characteristics, informing the processes that have shaped it. Dawn has determined the average diameter of Ceres to be 940 km, smaller than the previously estimated 975 km [1]. This implies a density of 2160 kg/m3, indicating that Ceres is less differentiated than predicted [2]. The low-degree gravity field is consistent with the body being in hydrostatic equilibrium and the magnitude of $J_2$ implies some central condensation. Ceres' entire surface is cratered, implying the lack of a thick (10's of km) water ice layer at the surface. Variability in Ceres' crater morphology indicates that the near-surface layer has variable strength and rheology, likely due to heterogeneity in the near-surface mixture of rock, ice and salt. The lack of a number of expected large impact basins on Ceres can be interpreted to be the result of viscous relaxation, resurfacing or a combination of both. These data provide insights into Ceres' thermal evolution and mechanical properties, which appear to be unique to this warm, icy body.
[1] Thomas, P. C., et al., Differentiation of the asteroid Ceres as revealed by its shape, *Nature*, 437, 224–226, 2005; [2] McCord et al., Ceres: Its Origin, Evolution and Structure and *Dawn*'s Potential Contribution, Space Sci RevDOI 10.1007/s11214-010-9729-9, 2011.

**Author(s): Carol A Raymond4**, Ryan S Park4, Alex S Konopliv4, Michael T. Bland7, Simone Marchi[6], Julie C Castillo-Rogez4, Thomas B McCord[1], Ralf Jaumann[2], Christopher T Russell3, Thomas H Prettyman5
**Institution(s):** *1. Bear Fight Institute, 2. DLR, 3. IGPP/UCLA, 4. Jet Propulsion Laboratory, California Institute of Technology, 5. Planetary Science Institute, 6. SwRI, 7. USGS Astrogeology Science Center*

### 103.02 – Dawn at Ceres reveals an ammoniated surface

The Visible and Infrared Mapping Spectrometer (VIR) on board the Dawn spacecraft has observed Ceres' surface and acquired spectra (0.5 to 5 µm) since January 2015. Here we report the average Ceres spectrum, including the important spectral range (2.6-2.9 µm) previously precluded from (telescopic) measurements due to telluric atmospheric absorptions. The VIR data confirm that the surface is very dark with an average albedo of 0.090 ±0.006 at 0.55 µm, consistent with Hubble Space Telescope data (Li et al., Icarus, 2006) and contains no prominent absorption features in the visible and near-Infrared at wavelengths less than 2.5 µm. Ceres' average spectrum, however, is characterized by a prominent diagnostic absorption band at 2.7 µm along with weaker absorption bands observed between 3.05-3.1, 3.3-3.4 and 3.9-4 µm. We modeled the new VIR spectra of Ceres with various ices, meteorites, silicates, carbonates, and hydrates using Hapke theory. Results of the spectral modeling indicate that extensive water ice is not present in spectra representing the typical surface acquired to date at relatively low spatial resolution (<11 km/pixel). The best fit is obtained with a mixture of ammoniated phyllosilicates mixed with other clays, Mg-carbonates, serpentine, and a strongly absorbing material, such as magnetite (De Sanctis et al., Nature, 2015, in review). The presence of ammonia-bearing materials in the crust across much of the surface has implications for the origin of Ceres and its internal structure and evolution. At the time of this presentation the Dawn spacecraft will have also completed its high altitude mapping orbit to look for anticipated small-scale mineralogy variations across this remarkable dwarf planet.
Acknowledgements: VIR is funded by the Italian Space Agency–ASI and was developed under the leadership of INAF, Rome-Italy. The instrument was built by Selex-Galileo, Florence-Italy. The analyses are supported by ASI, NASA, and the German Space Agency. Enabling contributions from the Dawn Instrument, Operations, and Science Teams are gratefully acknowledged.

**Author(s): Carle M. Pieters[2]**, Maria Cristina De Sanctis4, Eleonora Ammannito 4, Andrea Raponi4, Jean-Philippe Combe[1], Thomas B. McCord[1], Harry McSween[10], Lucy A. McFadden[6], Simone Marchi4, Fabrizio Capaccioni4, Maria Teresa Capria4, Giacomo Carrozzo4, Mauro Ciarniello4, Andrea Longobardo4, Sergio Fonte4, Michelangelo Formisano4, Alessandro Frigeri4, Marco Giardino4, Gianfranco Magni4, Enersto Palomba4, Federico Tosi4, Diego Turrini4, Francesca Zambon4, Ralf Jaumann3, William Feldman[8], Thomas Prettyman[8], Michael Toplis7, Carol A. Raymond5, Christopher T. Russell9
**Institution(s):** *1. Bear Fight Institute, 2. Brown Univ., 3. DLR, 4. IAPS, INAF, 5. JPL/CalTech, 6. NASA Goddard, 7. Observatoire Midi Pyrénées , 8. PSI, 9. UCLA, 10. Univ. Tenn.*

### 103.03 – The Origin of Dwarf Planet Ceres Constrained by Dawn

The Dawn spacecraft has acquired important clues regarding the origin of dwarf planet Ceres. The surface composition is characterized by a prominent absorption band at 2.7 micron that is best explained by the presence of ammoniated phyllosilicates (De Sanctis et al. 2015), while the average density indicates a bulk water content of 30-40%. The occurrence of widespread smooth terrains, marked by a flat topography and few superposed craters, associated with a large 290-km crater is best explained by the present of low viscosity material mobilized by the impact energy (Marchi 2015). Such low viscosity material is compatible with an ice-rich outer shell whose melting temperature is reduced by the presence of salts and/or ammonia hydrates. Such inferred internal structure could also explain the lack of impact structures larger than about 400 km,

which may have relaxed leaving no obvious signatures in imaging data.
The presence of ammoniated phyllosilicates points toward the presence of ammonia available in Ceres' makeup. Ammonia is relatively rare among meteorites due to its high volatility at typical main belt temperatures, thus indicating a potential contribution of material from the colder outer solar system.
Two main scenarios emerge. Either Ceres formed in the trans-neptunian disk and subsequently was captured in the main belt, or it formed close to its current position with a late addition of material drifting from the outer solar system. The two scenarios imply rather different collisional evolution, therefore Ceres' cratering record can potentially help to discriminate the more likely evolution. As craters are susceptible to degradation due to internal heat flow, terrain properties and superposed cratering, here we will evaluate the evidence for and against these formation scenarios by taking into account the latest digital terrain models and gravity data acquired by Dawn.
De Sanctis et al, submitted, July 2015.
Marchi S., IAU General Assembly, August 2015.

**Author(s): Simone Marchi6**, Cristina De Sanctis2, David O'Brien5, Eleonora Ammannito7, Julie Castillo-Rogez3, Ralf Jaumann1, Paul Schenk4, Carol Raymond3, Christopher Russell7, Ryan Park3
**Institution(s):** *1. DLR, 2. INAF, 3. JPL, 4. LPI, 5. PSI, 6. Southwest Research Institute, 7. UCLA*

## 103.04 – Photometric Properties of Ceres and the Occator Bright Spots

Dawn discovered several extremely bright spots on Ceres, the most prominent of which is located inside the Occator crater that is at least 4-5 times brighter than the average Ceres. Interestingly, these bright spots are located in relatively young craters that are at the longitudes corresponding to the maximum water vapor observed by the Herschel Space Observatory, suggesting possible correlation with water sublimation on Ceres. We used the multi-color imaging data collected by the Dawn Framing Camera to analyze the global photometric properties of Ceres and the bright spots, especially those located inside the Occator crater. Our objectives are to determine the albedo and other light scattering properties of the bright spots on Ceres in the visible wavelengths, in order to characterize their physical properties and find clues about their composition and possible formation mechanisms and the correlation with water sublimation. The overall geometric albedo of Ceres' global surface is 0.09-0.10, consistent with previous studies. The Hapke roughness parameter is about 20°, close to many other asteroids, rather than 44° as reported earlier. Correspondingly, the phase function of Ceres is less backscattering than previously modeled. In contrast, the geometric albedo of the bright spots inside the Occator crater is 0.4-0.5, and the single scattering albedo is 0.7-0.8, brighter than Vesta's global albedo but much darker than many icy satellites in the outer solar system. The Hapke roughness of the bright spots is much higher than Ceres average, suggesting relatively loose deposit of materials rather than more coherent or tightly packed materials. The phase function of bright spots material is relatively more forward scattering than average Ceres, possibly correlated to stronger multiple scattering due to high albedo resulting from more transparent materials. The highest resolution images as of late-August 2015 show fine structures within the Occator bright spots. We will also report the results from the albedo distribution within the bright spots.

**Author(s): Jian-Yang Li7**, Lucille Le Corre7, Vishnu Reddy7, Mark V Sykes7, Andreas Nathues5, Carle M. Pieters1, Mauro Ciarniello3, Diego Turrini3, Lucy A McFadden6, Carol A. Raymond4, Christopher T. Russell2
**Institution(s):** *1. Brown University, 2. Institute of Geophysics and Planetary Physics, University of California at Los Angeles, 3. Instituto di Astrofisica e Planetologia Spaziali, INAF, 4. Jet Propulsion Laboratory, California Institute of Technology, 5. Max Planck Institute for Solar System Research, 6. NASA Goddard Space Flight Center, 7. Planetary Science Institute*

## 103.05 – Spectrophotometry of the Ceres surface

The Dawn spacecraft is in orbit around dwarf planet Ceres. The onboard Framing Camera (FC) is mapping the surface through a clear filter and 7 narrow-band filters at various observational geometries and image resolutions. Generally, Ceres' appearance in these images is affected by shadows and shading, effects which obscure the intrinsic reflective properties of the surface. By means of photometric modeling we remove these effects and reconstruct the surface reflectance for each of the FC filters, creating albedo and color maps in the process. Considering these maps in unison provides clues to the physical nature and composition of the surface and the dominant geologic processes that shape the surface. We assess the nature of color variations in the visible wavelength range for Ceres globally. We identify which terrains express the dominant colors and investigate why some areas are exceptions to the rule. By correlating the color over the surface with geologic units we find an relatively strong enhancement of the reflectance towards the blue end of the visible spectrum for recent impacts and their ejecta.

**Author(s): Stefan Schröder1**, Stefano Mottola1, Uri Carsenty1, Ralf Jaumann1, Uwe Keller5, Katrin Krohn1, Jian-Yang Li4, Klaus-Dieter Matz1, Lucy McFadden2, Katharina Otto1, Frank Preusker1, Thomas Roatsch1, Frank Scholten1, Katrin Stephan1, Roland Wagner1, Carol Raymond3, Chris Russell6
**Institution(s):** *1. DLR, 2. Goddard Space Flight Center, 3. JPL, 4. PSI, 5. Technische Universität Braunschweig, 6. UCLA*

## 103.06 – First Spectral Coverage of two regions on Ceres in the far-UV

We present the first spectral observations of Ceres in the far-ultraviolet, along with new measurements in the near-UV and visible, as measured by HST/STIS as part of Cycle 22, in August-September, 2015. The observations are motivated by early broad-band UV observations [1][2][3] suggesting a UV absorption centered near 260 nm along with a very strong increase in UV reflectance into the far-UV (~160 nm). We have observed two central longitudes of Ceres – near 0°W and 120°W (this latter area one of the regions in which Herschel detected water vapor) – using the G140L (~120-172 nm), G230L (~170-310 nm) and G430L (~300-570 nm) detectors. We use the data to test a prediction of graphitized carbon on the surface, and we look for signatures of water ice and/or water vapor.
[1] Parker, J. W., S. A. Stern, P. C. Thomas, M. C. Festou, W. J. Merline, E. F. Young, R. P Binzel, L. A. Lebofsky (2002). *Astron J.* 123, 549
[2] Li et al. (2006). Icarus 182: 143-160.
[3] Rivkin, A. S., J.-Y. Li, R. E. Milliken, L. F. Lim, A. J. Lovell, B. E. Schmidt, L. A. McFadden, B. A. Cohen (2011). *Space Sci Rev* 163, 95.

**Author(s): Amanda R. Hendrix1**, Faith Vilas1, Jian-Yang Li1
**Institution(s):** *1. Planetary Science Institute*

## 103.07 – Ceres' impact craters: probes of near-surface internal structure and composition

Dawn Framing Camera images of Ceres have revealed the existence of a heavily cratered surface. Shape models derived from these images indicate that most (though not all) large craters are quite deep: up to 6 km for craters larger than 100 km in diameter. The retention of deep craters is not consistent with a simple differentiated internal structure consisting of an outer layer composed solely of pure water ice (covered with a rocky lag) overlying a rocky core. Here we use finite element simulations to show that, for Ceres' relatively warm surface temperatures, the timescale required to completely flatten a crater 60-km in diameter (or greater) is less than 100 Myr, assuming a relatively pure outer ice layer (for ice grain sizes ≤ 1 cm). Preserving substantial topography requires that the viscosity of Ceres' outer-most layer (25-50 km thick) is substantially greater than that of pure water ice. A factor of ten increase in viscosity can be achieved by assuming the layer is a 50/50 ice-rock mixture by volume; however, our simulations show that such an increase is insufficient to prevent substantial relaxation over timescales of 1 Gyr. Only particulate volume fractions greater than 50% provide an increase in viscosity sufficient to prevent large-scale, rapid relaxation. Such volume fractions suggest an outer layer composed of frozen soil/regolith (i.e., more rock than ice by volume), a very salt-rich layer, or both. Notably, while most basins appear quite deep, a few relatively shallow basins have been observed (e.g., Coniraya), suggesting that relaxation may be occurring over very long timescales (e.g., 4 Ga), that Ceres' interior is compositionally and spatial heterogeneous, and/or that temporal evolution of the interior structure and composition has occurred. If these shallow basins are in fact the result of relaxation, it places an upper limit on the viscosity of Ceres' outer-most interior layer, implying at least some low-viscosity material is present and likely eliminating the possibility of a purely rocky (homogeneous, low density, high porosity) interior.

**Author(s): Michael T. Bland[7]**, Carol Raymond[4], Ryan Park[4], Paul Schenk[3], Tom McCord[1], Vishnu Reddy[5], Scott King[2], Mark Sykes[5], Chris Russell[6]
**Institution(s):** *1. Bear Fight Institute, 2. Department of Geoscience, Virginia Tech, 3. Lunar and Planetary Institute, 4. NASA JPL, 5. Planetary Science Institute, 6. University of California Los Angeles, IGPP/EPSS, 7. USGS Astrogeology*

### 103.08 – Geomorphological evidence for pervasive ground ice on Ceres from Dawn data

Five decades of observations of Ceres have explored the likelihood that the innermost dwarf planet boasts an ice rich bulk composition. We report geomorphological evidence from Dawn Framing Camera data suggesting that its surface has likely been shaped by surface and/or shallow subsurface ice, including possible evaporative and flow processes within silicate-ice mixtures. Here we highlight three classes of features that possess strong evidence for ground ice. First, ubiquitous craters with scallop-shaped rims, in some cases "breached," are characterized by mass wasting processes and by the recession of crater walls in asymmetric patterns; these could be influenced by processes analogous to those in sublimating ice-rich terrain on Mars and those formed by mass wasting in terrestrial glaciated regions. The degradation of crater walls appears to be responsible for the nearly complete removal of some craters, particularly at low latitudes. Second, several high latitude, high elevation craters feature lobed flows that emanate from cirque-shaped head walls and bear strikingly similar morphology to flows on other ice-rich planetary surfaces. Possible similarities to terrestrial rock glaciers include lobate toes and indications of furrows and ridges consistent with flow of ice-cored or ice-cemented material. Other lobed flows persist at the base of crater walls and mass wasting features. Many flow features evidently terminate at ramparts. Third, there are frequent irregular domes, peaks and mounds within crater floors that depart from traditional crater central peaks or peak complexes. In some cases the irregular domes show evidence for high albedo or activity. One possible formation scenario could include extrusion and refreezing of subsurface water, forming domes in similar processes to ice lens formation in pingos. The distribution of these classes of features, including latitudinal variation in their abundance and/or appearance, suggests that ground ice is a key controller of geology on Ceres, and that ice content within the surface and subsurface is spatially varied and/or activated by energetic events.

**Author(s): Britney E Schmidt[3]**, Jennifer Scully[6], Heather T Chilton[3], Kynan Hughson[11], Hanna Sizemore[9], Michael Bland[14], Paul Schenk[7], Andreas Nathues[8], Thomas Platz[8], David P O'Brien[9], Shane Byrne[12], Norbert Schorghofer[4], Eleonora Ammanito[11], Christopher T Russell[11], Carol A Raymond[6], Maria Cristina DeSanctis[5], Simone Marchi[10], Jian-Yang Li[9], Lucille LeCorre[9], Vishnu Reddy[9], Harald Hiesinger[13], Ralf Jaumann[2], Mark Sykes[9], Thomas McCord[1]
**Institution(s):** *1. Bear Fight Institute, 2. DLR, 3. Georgia Institute of Technology, 4. IFA, University of Hawaii, 5. INAF, 6. JPL, 7. LPI, 8. MPS, 9. PSI, 10. SWRI, 11. UCLA, 12. University of Arizona, 13. University of Muenster, 14. USGS*

### 103.09 – Thermal Stability of Ice on Ceres with Rough Topography

The dwarf planet Ceres may have an ice-rich crust, and subsurface ice exposed by impacts or endogenic activity would be subject to sublimation. The "bright spots" recently discovered by the Dawn mission on the illuminated surface of Ceres have prompted speculation regarding their possible icy composition and the youthful age this might imply. Furthermore, sublimation of ice at the surface or in the interior of Ceres could explain water vapor observed on more than one occasion in the exosphere. We investigated the possible distribution and lifetimes of water ice and other volatiles on Ceres using detailed thermal models, including realistic thermophysical properties and surface roughness. Topographic shadowing creates polar cold traps where a small, but non-negligible fraction (~0.4%) of Ceres' surface is perennially below the ~110 K criterion for 1 Gyr of $H_2O$ ice stability. These areas are found above 60° latitude. Other molecules ($CH_3OH$, $NH_3$, $SO_2$, $CO_2$) may be cold-trapped in smaller abundances. A model for the transport, gravitational escape and photoionization of $H_2O$ molecules suggests net accumulation in the cold traps. At latitudes 0° - 30°, ice is stable under solar illumination only briefly (~10-100 yr), unless it has high albedo and thermal inertia, in which case lifetimes of > $10^4$ yr are possible.
Buried ice is stable within a meter for > 1 Gyr at latitudes higher than ~50°. An illuminated polar cap of water ice would be stable within a few degrees of the poles only if it maintained a high albedo (> 0.5) at present obliquity. If the obliquity exceeded 5° in the geologically recent past, then a putative polar cap would have been erased. Finally, a small hemispheric asymmetry exists due to the timing of Ceres' perihelion passage, which would lead to a detectable enhancement of ice in the northern hemisphere if the orbital elements vary slowly relative to the ice accumulation rate. Our model results are potentially testable during the Dawn science mission.

**Author(s): Paul O. Hayne[1]**, Oded Aharonson[2]
**Institution(s):** *1. Jet Propulsion Laboratory, 2. Weizmann Institute of Science*

### 103.10D – Geophysics and geochemistry intertwined: Modeling the internal evolution of Ceres, Pluto, and Charon

Liquid water likely shaped dwarf planet evolution: observations [1,2] and models [3-5] suggest aqueous alteration of silicates or volatiles accreted by these worlds. Driven by thermo-physical settings, aqueous alteration also feeds back on dwarf planet evolution in unconstrained ways. Can rocky dwarf planet cores crack, increasing the water-rock interface? Might radionuclides be leached into fluids, changing the distribution of this chief heat source? What is the fate of antifreezes, on which may hinge long-term liquid persistence? Is volcanism favored or impeded? What are predicted cryomagma compositions?
We have modeled silicate core fracturing [6], geochemical equilibria between chondritic rock and aqueous fluids [7], and prerequisites for cryovolcanism [8]. These models, coupled to an evolution code [3], allow us to study geophysics/chemistry feedbacks inside dwarf planets.
Ice-rock differentiation, even partial [9,10], yields a rocky, brittle core cracked by thermal stresses; liquid circulation through core cracks transports heat into the ice mantle, yielding runaway melting that quickly ceases once convection cools the mantle to its freezing point [6]. Hot fluids can leach radionuclides at high water:rock ratios (W:R); $NH_3$ antifreeze can turn into $NH_4$-minerals at low W:R [7]. Volatile (chiefly CO) exsolution enables explosive cryovolcanism [8]; this may explain Pluto's young, CO-rich Tombaugh Regio.
Applied to Ceres, such models are consistent with pre-Dawn and Dawn data [11] provided Ceres partially differentiated into a rocky core and muddy mantle [10]. They suggest Ceres' hydrated surface [2] was emplaced during a $^{26}$Al-fueled active phase, and predict its bright spots result from cryovolcanic fluids squeezed by mantle refreezing and effusing through pre-existing subsurface cracks [11].
[1] Cook et al. 2007 ApJ 663:1406
[2] Milliken & Rivkin 2009 Nat Geosc 2:258
[3] Desch et al. 2009 Icarus 202:694

[4] Castillo-Rogez et al. 2010 Icarus 205:443
[5] Robuchon & Nimmo 2011 Icarus 216:426
[6] Neveu et al. 2015 JGR 120:123
[7] Neveu et al., in prep.
[8] Neveu et al. 2015 Icarus 246:48
[9] Rubin et al. 2014 Icarus 236:122
[10] Travis et al. 2015 46th LPSC abstr. 2360
[11] Neveu & Desch, in review

**Author(s): Marc Neveu[1]**, Steven J Desch[1], Julie C Castillo-Rogez[2]
**Institution(s):** *1. Arizona State University, 2. Jet Propulsion Laboratory*

### 103.11D – The geological evolution of asteroid Vesta from Dawn orbital observations and meteorite analogs

Asteroid Vesta is a survivor protoplanet and the knowledge it yields is essential to understand the early stages of planet formation. To support mineralogical characterization of its surface, mineralogical and near-IR (0.7-2.5 µm) analyses of 24 howardite-eucrite-diogenite meteorites were performed (Ruesch et al., 2015). The range of observation geometries within which the compositional variations can be distinguished from geometry effects were determined, and empirical calibrations relating the position of absorption bands to average pyroxene compositions were established. Next, the empirical calibrations were applied to reflectance spectra of Vesta from the Dawn's near-IR spectrometer (VIR) revealing that Vesta´s iron-poor terrains have a $Fs_{30}Wo_5$ pyroxene, whereas iron-rich terrains have an average $Fs_{47}Wo_{14}$ (Ruesch et al. 2015). This confirms that, despite a homogeneous regolith, different terrains are preserved, and formed during an early magmatic period. To further characterize Vesta's igneous processes, a search for olivine's near-IR signature was performed. Concentrations of olivine-enriched areas were found in the northern hemisphere (Ruesch et al. 2014a), corroborating other studies. As such location was unexpected, the geology of the northern was characterized with the Dawn Framing Camera observations (Ruesch et al., 2014b). The hemisphere is composed of an ancient (pre-Veneneian epoch), densely cratered terrain, partly disrupted by a subdued tectonic system (Veneneian epoch). Olivine-enriched materials are exposed recently (Marcian epoch) by impacts and mass wasting, but most of their parent lithologies are probably the result of shallow magmatic activity during the pre-Veneneian. The presence of olivine-enriched material in this context and not as exposure of an olivine-rich mantle, partly contradicts many pre-Dawn concepts of Vestan differentiation. As an alternative to the HED parent body model, few scenarios exist for Vesta's early evolution, and none provide consistent explanation for the entire range of observations reported in this comprehensive mineralogical and geological study. This reveals that protoplanets experienced a complex differentiation process, which is only partly understood.

**Author(s): Ottaviano Ruesch[1]**
**Institution(s):** *1. NASA Goddard Space Flight Center/ORAU*

## 104 – Planetary Rings

### 104.01 – Constraints on Chariklo's rings from HST and VLT observations

In June 2013, a stellar occultation revealed for the first time ever the presence of two dense and narrow rings around a small object of the solar system, the Centaur (10199) Chariklo (Braga-Ribas et al., Nature 508, 72, 2014). This body follows an eccentric orbit between Saturn and Uranus, with perihelion and aphelion distances of 13.1 and 18.5 AU. Due to Uranus perturbations, its orbit is unstable on the very short time scale of ~10 Myr (Horner at al. MNRAS 354, 798, 2004). The two rings (C1R and C2R, respectively) have orbital radii $a_{C1R}$= 390.6±3.3 km and $a_{C2R}$= 404.8±3.3 km, and typical widths $W_{C1R}$ ~6.5 km and $W_{C2R}$ ~2 km, optical depths $\tau_{C1R}$ ~ 0.4 and $\tau_{C1R}$ ~ 0.06, with a gap of ~9 km between the two. Chariklo's radius, $R_C$~ 120 km (Duffard et al. AA 568, A79, 2014 Fornasier et al. AA 518, L11, 2014), implies that the ring system lies at 3.3-3.4 $R_C$, farther away than the classical Roche limit of 2.4 $R_C$ that would be obtained for spherical ring particles with the same density as Chariklo.
To better understand Chariklo's surroundings, and thus the origin of the rings, direct imaging of Chariklo has been performed using HST and VLT, with respectively 3 visits and 2 runs performed between April and August 2015. The HST images were obtained with the WFC3/UVIS camera with filters F300X (250-350 nm), F475X (400-650 nm) and F350LP (300-1000 nm), and typical PSF size of 30 milli-arcsec (mas), corresponding to about 300~km at Chariklo. Conversely, the SPHERE high contrast instrument at ESO VLT provided images in the near IR (Y, J and H bands), with typical expected PSF sizes of 30-40 mas (300-400~km at Chariklo). The main goals of those observations were: (1) obtain direct images of the rings, confirming their geometry and their orientation, (2) derive multi-wavelength photometry, thus constraining their composition (concerning in particular the presence of water ice), (3) perform a deep search of small satellites (down to a few km in diameter), (4) faint dusty rings around Chariklo (down to about $\tau$ ~$10^{-5}$-$10^{-6}$), and (5) search possible cometary jets or coma, akin to what is observed around another Centaur, Chiron (Ortiz et al. AA 576, A8, 2015). Premiminary results obtained from those observations will be presented.

**Author(s): Bruno Sicardy[3]**, Marc W Buie[5], Gustavo Benedetti-Rossi[4], Felipe Braga-Ribas[1], Julio I Bueno de Camargo[4], Rene Duffard[2], Jose Luis Ortiz[2], Damien Gratadour[3], Christophe Dumas[6]
**Institution(s):** *1. Federal University of Technology (UTFPR/DAFIS) - Paraná, 2. Instituto de Astrofísica de Andalucía CSIC, 3. Observatoire de Paris/LESIA and Univ. Paris 6, 4. Observatorio Nacional, 5. SWRI, 6. Thirty-Meter-Telescope International Observatory*

### 104.02 – Chariklo's size, shape and orientation from stellar occultations

Chariklo is the largest Centaur object known to date, and it is surrounded by dense and narrow rings (Braga-Ribas et al. Nature 508, 72, 2014). The size, shape and orientation of the central body are important parameters to better understand the dynamics of the rings.
In that context, we have analyzed three stellar occultations by Chariklo and its main ring observed on June 3, 2013, April 29, 2014 and June 28, 2014. Elliptical limb fitting to Chariklo's main body occultation chords has been performed, where we denote $a$ (resp. $b$) the semi-major (resp. semi-minor) axis of the limb. Preliminary results indicate that Chariklo's limb is elliptical with axes ratio $b/a$~0.89. We obtain $a$~133 km and $b$~119 km, providing an equivalent radius of $R_{equiv}=\sqrt{(ab)}$~126 km. The rms dispersion of the fit, about 4 km, is compatible with local topographic features on a small icy body. For comparison, an equivalent radius of $R_{equiv}$= 119±5 km, based on thermal data, is given by Fornasier et al, AA 518, L11, 2014, while Duffard et al. AA 568, A79, 2014 estimate $a$= 122 km and $b$= 117 km.
Our results are obtained under the simplifying assumption that the main ring is circular and that its center coincides with that of Chariklo. Caveats and error bars will be discussed, and dynamical implications will be presented. In particular, rough estimations of the ring apsidal precession rates will be given, as well as constraints on Chariklo's density.

**Author(s): Diane Bérard[6]**, Bruno Sicardy[6], Marcelo Assafin[8], Felipe Braga-Ribas[2], Julio Camargo[9], Roberto Vieira Martins[9], Rene Duffard[4], Jose Luis Ortiz[4], Colin Snodgrass[12], Emmanuel Jehin[3], Joe Pollock[10], François Colas[7], Jean Luc Dauvergne[1], Jean Lecacheux[6], Lucie Maquet[7], Amanda A. Sickafoose[11], Karl Ludwig Bath[5], Wolfgang Beisker[5], Rodrigo Leiva[6]
**Institution(s):** *1. Ciel & Espace, 2. Federal University of Technology (UTFPR/DAFIS) - Paraná, 3. Institut d'Astrophysique de l'Université de Liège, 4. Instituto de Astrofísica de Andalucía - CSIC, 5. International Occultation Timing Association, 6. Observatoire de Paris - LESIA & UPMC, 7. Observatoire de Paris, IMCCE, UPMC, CNRS, 8. Observatório do Valongo - UFRJ, 9. Observatorio Nacional, 10. Physics and Astronomy Department, Appalachian State University, 11. South African Astronomical Observatory & MIT, 12. The Open University*

### 104.03D – Particle Sizes in Saturn's Rings from Diffraction Signals in Cassini UVIS Occultation Data

Since its arrival at Saturn in 2004, the Cassini spacecraft has illuminated many aspects of the planet's extensive ring system, including its vast range of particle sizes. Constraints on the particle size distribution are critical for understanding the evolution of the ring system. Our investigation focuses on modeling diffraction signals in occultation data from the Cassini Ultraviolet Imaging Spectrograph (UVIS) to measure the population of the smallest particles in Saturn's rings.
Occultation data from Cassini's Radio Science Subsystem and the Visual and Infrared Mapping Spectrometer also provide measurements of the size distribution. The amount of light diffracted by the occulting particles is a reflection of the ratio of the wavelength of light and the radius of the particles. We can utilize the diffraction signals at different wavelengths measured by different instruments to describe the particle size distribution of Saturn's rings.
The UVIS wavelength bandpass, 51.2-180 nm, is the shortest of these instruments, making it most sensitive to the smallest particles. We model the diffraction signals detected in stellar occultation data at ring edges and find that Saturn's outer A ring lacks any significant population of sub-mm particles, but the average size of the smallest particles decreases from ~1.5 cm at the Encke Gap to ~4 mm at the outer edge of the A ring. Diffraction spikes have also been identified at the edge of the B ring and at sharp edges of ringlets in the C ring and Cassini Division, suggestive of mm-sized particles throughout the rings. We analyze solar occultations by the F ring and sporadically detect diffracted light, indicating the population of sub-mm particles responsible for the diffraction is transient or spatially variable. Comparisons with images from the Cassini Imaging Science Subsystem suggest that these diffraction signals coincide with nearby collisional events in the F ring core. This may indicate that such events release dust particles, producing a diffraction signature in the UVIS data.
We will present an overview of the concerted efforts to measure the particle size distribution of Saturn's rings and the recent results from our investigation of UVIS occultation data.

**Author(s): Tracy M Becker3**, Joshua E Colwell3, Larry W Esposito[1], Nicholas O Attree[2], Carl D Murray[2]
**Institution(s):** *1. LASP, University of Colorado, Boulder, 2. Queen Mary University of London, 3. University of Central Florida*

### 104.04 – A traveling feature in Janus spiral density waves

Every 4.0 years on 21 January, the Saturnian co-orbital satellites Janus and Epimetheus move radially and switch relative positions. This swap also alters the locations of the resonances within the rings corresponding to these moons. In stellar occultations by the A and B rings observed by the Cassini Ultraviolet Imaging Spectrograph's High Speed Photometer between 2005 and 2015, we report the detection of many density-wave interference structures as a result of these orbital swaps.
Most prominent in the Janus 2:1, 4:3, 5:4, and 6:5 resonance regions is a soliton-like traveling wave which propagates through the rings. This wave moves at approximately twice the group velocity of the A-ring spiral density waves and at a similar velocity to that of the Janus 2:1 density wave in the B ring. The optical depth of the B ring near the Janus 3:2 spiral density wave is too great for it to be visible and no similar traveling features were detected within three Mimas and Prometheus density waves.

**Author(s): Morgan Rehnberg[1]**, Larry W Esposito[1], Zarah L Brown[1], Miodrag Sremčević[1], Nicole Albers[1]
**Institution(s):** *1. CU/LASP*

### 104.05 – An analysis of the A ring's outer edge probes Saturn's interior

We present a study of the behavior of the outer edge of Saturn's A ring, using images and occultation data obtained by the Cassini spacecraft over a period of 8 years from 2006 to 2014. More than 5000 images and 150 occultations of the A ring outer edge are analyzed. Our fits confirm the expected response to the Janus 7:6 Inner Lindblad resonance (ILR) between 2006 and 2010, when Janus was on the inner leg of its regular orbit swap with Epimetheus. During this period, the edge exhibits a regular 7-lobed pattern with an amplitude of 12.8 km and one minimum aligned with the orbital longitude of Janus, as has been found by previous investigators. However, between 2010 and 2014, the Janus/Epimetheus orbit swap moves the Janus 7:6 LR away from the A ring's outer edge, and the 7-lobed pattern disappears.
In addition to the perturbation forced by Janus, we have identified a variety of normal modes at the edge of the A ring, with values of "m" ranging from 3 to 18 and appropriate pattern speeds. These modes may represent waves trapped in resonant cavities at the edge (Spitale and Porco 2010, Nicholson et al 2014).
We further identified some other signatures consistent with tesseral resonances that might be associated with inhomogeneities in Saturn's interior. This result is consistent with previous studies (Hedman et al 2009, 2014). These signatures may provide information about differential rotation in Saturn's interior.

**Author(s): Maryame El Moutamid[1]**, Philip Nicholson[1], Peter Gierasch[1], Richard French5, Joseph Burns[1], Matthew Tiscareno3, Matthew Hedman4, Carl Murray[2]
**Institution(s):** *1. Cornell University, 2. Queen Mary University of London, 3. SETI Institue, 4. University of Idaho, 5. Wellesley College*

### 104.06 – Analysis and Dynamics of a Saturnian Satellite at the A Ring Edge

An object found (Murray et al. 2014) at the edge of Saturn's A ring presents a unique opportunity to investigate Charnoz et al. (2010)'s suggestion that moonlets form in the rings as well as to conduct dynamical studies near the ring edge. We track this object in Cassini images to learn its connection, if any, to Janus' co-rotation and Lindblad resonances before and after the 2014 orbital shift of Janus and Epimetheus. We find that it may have undergone an abrupt eight-kilometer shift in semi-major axis in 2013, which is unexplained by resonant effects but may be due to a collision with something in or outside of the rings. Furthermore, we propose the potential existence of another object near the ring edge, which would obviate any change in the semi-major axis of Murray's object. Such an object may have been captured in co-rotation resonance with Janus between 2010 and 2014.

**Author(s): Christie J. Trimble[1]**, Maryame El Moutamid[2], Philip D. Nicholson[2], Joseph A. Burns[2], Carl D. Murray3, Nicholas J. Cooper3
**Institution(s):** *1. Arizona State University, 2. Cornell University, 3. Queen Mary University of London*

### 104.07 – Wisps in the outer edge of the Keeler Gap

Superposed upon the relatively smooth outer edge of the Keeler Gap are a system of "wisps," which appear to be ring material protruding inward into the gap, usually with a sharp trailing edge and a smooth gradation back to the background edge location on the leading side (Porco et al. 2005, Science). The radial amplitude of wisps is usually 0.5 to 1 km, and their azimuthal extent is approximately a degree of longitude (~2400 km). Wisps are likely

caused by an interplay between Daphnis (and perhaps other moons) and embedded moonlets within the ring, though the details remain unclear.
Aside from the wisps, the Keeler Gap outer edge is the only one of the five sharp edges in the outer part of Saturn's A ring that is reasonably smooth in appearance (Tiscareno et al. 2005, DPS), with occultations indicating residuals less than 1 km upon a possibly non-zero eccentricity (R.G. French, personal communication, 2014). The other four (the inner and outer edges of the Encke Gap, the inner edge of the Keeler Gap, and the outer edge of the A ring itself) are characterized by wavy structure at moderate to high spatial frequencies, with amplitudes ranging from 2 to 30 km (Tiscareno et al. 2005, DPS).
We will present a catalogue of wisp detections in Cassini images. We carry out repeated gaussian fits of the radial edge location in order to characterize edge structure and visually scan those fitted edges in order to detect wisps. With extensive coverage in longitude and in time, we will report on how wisps evolve and move, both within an orbit period and on longer timescales. We will also report on the frequency and interpretation of wisps that deviate from the standard morphology. We will discuss the implications of our results for the origin and nature of wisps, and for the larger picture of how masses interact within Saturn's rings.

**Author(s): Matthew S. Tiscareno[2]**, Ethan G. Arnault[1]
**Institution(s):** *1. Cornell University, 2. SETI Institute*

### 104.08 – Strong orbital expansion of Saturn’s inner ice-rich moons through ring torques and mutual resonances during their accretion from a massive ring

Saturn has a diversity of moons with possibly diverse origins. Titan likely formed in Saturn’s sub-nebula (e.g., Canup & Ward 2006). The small moons interior to Mimas are likely recent aggregates of ring’s material spreading through the Roche limit (Charnoz et al. 2010). The origin of the mid-size moons, Mimas through Rhea, is debated. Charnoz et al. (2011) considered a massive ice-rock ring and strong tidal dissipation in Saturn (Q ~ 103), and found that moons out to Rhea could be spawned from such a ring. However such a small value for Q for Saturn is debated. In addition, capture into mutual Mean Motion Resonances (MMR) and resulting eccentricity growth (not included in the Charnoz et al. (2011) model) could lead to orbital destabilization as the moons tidally expand over such large distances (Peale & Canup 2015).
Here we consider weak planetary tides (Q ≥ 104) and investigate whether Mimas, Enceladus and Tethys could have been spawned from a massive ice ring (Canup 2010). In this scenario, the rock in these moons would be delivered by material from outside the rings, e.g. by heliocentric impactors during the LHB (Canup 2013). We have expanded a numerical model developed to study the Moon’s accretion (Salmon and Canup 2012, 2014), which couples an analytic Roche-interior disk model to the N-body code SyMBA (Duncan et al. 1998) for satellites, so that we can directly track their accretion and mutual interactions (including MMRs), as well as their tidal interaction with the planet. We consider an initially large Saturn (Fortney et al. 2007) and its progressive contraction, which impacts the strength of tides and the location of the corotation resonance. We perform simulations with and without Dione and Rhea, and study the influence of tidal dissipation into the moons. We find that recoil of the moons due to ring torques, together with capture of moons into MMRs, can produce a distribution similar to that observed. If tidal dissipation in the moons was weak, we show that even if the final moons have low eccentricity and inclination, they experience a phase of high values that is subsequently damped by mutual collisions. The latter seem to typically preserve the overall stability of the system.

**Author(s): Julien Salmon[1]**, Robin M Canup[1]
**Institution(s):** *1. Southwest Research Institute*

### 104.09 – Non-Linear Dynamics of Saturn’s Rings

Non-linear processes can explain why Saturn’s rings are so active and dynamic. Ring systems differ from simple linear systems in two significant ways: 1. They are systems of granular material: where particle-to-particle collisions dominate; thus a *kinetic,* not a *fluid* description needed. We find that stresses are strikingly inhomogeneous and fluctuations are large compared to equilibrium. 2. They are strongly forced by resonances: which drive a non-linear response, pushing the system across thresholds that lead to persistent states.
Some of this non-linearity is captured in a simple Predator-Prey Model: Periodic forcing from the moon causes streamline crowding; This damps the relative velocity, and allows aggregates to grow. About a quarter phase later, the aggregates stir the system to higher relative velocity and the limit cycle repeats each orbit.
Summary of Halo Results: A predator-prey model for ring dynamics produces transient structures like ‘straw’ that can explain the halo structure and spectroscopy: This requires energetic collisions (v ≈ 10m/sec, with throw distances about 200km, implying objects of scale R ≈ 20km).
Transform to Duffing Eqn : With the coordinate transformation, z = $M^{2/3}$, the Predator-Prey equations can be combined to form a single second-order differential equation with harmonic resonance forcing.
Ring dynamics and history implications: Moon-triggered clumping at perturbed regions in Saturn’s rings creates both high velocity dispersion and large aggregates at these distances, explaining both small and large particles observed there. We calculate the stationary size distribution using a cell-to-cell mapping procedure that converts the phase-plane trajectories to a Markov chain. Approximating the Markov chain as an asymmetric random walk with reflecting boundaries allows us to determine the power law index from results of numerical simulations in the tidal environment surrounding Saturn. Aggregates can explain many dynamic aspects of the rings and can renew rings by shielding and recycling the material within them, depending on how long the mass is sequestered. We can ask: Are Saturn’s rings a *chaotic* non-linear driven system?

**Author(s): Larry W. Esposito[1]**
**Institution(s):** *1. Univ. of Colorado*

### 104.10 – NanoRocks: Experimental Study of Collisional Damping and Aggregation at Low Velocities

The NanoRocks experiment on the International Space Station consists of 8 separate sample trays of particles from ~0.1 mm – 2.0 mm in diameter that undergo collisional evolution. The microgravity environment of the ISS allows collision speeds of less than 1 mm/s to be studied. At these speeds the experiment reproduces the velocity dispersion found in unperturbed regions of Saturn’s rings. Observations of the rings from Cassini instruments hint at aggregation and fragmentation of clumps depending on the local surface mass density, particle size distribution and velocity dispersion.
The eight NanoRocks samples include plastic beads, copper, glass, and JSC-1 lunar regolith simulant. The samples are shaken at 1 minute intervals to provide initial collision velocities of a few cm/s, and video is recorded of the collisional evolution of the particle samples. We derive mean coefficients of restitution for the different samples based on the damping of the mean velocity dispersion as well as tracking of individual particle trajectories. The evolution of the velocity distribution is consistent with a uniform random distribution of the coefficient of restitution, independent of collision velocity. This is consistent with results of Heißelmann et al. (Icarus Vol. 206, pp. 424-430, 2010) using larger icy particles. We also find the onset of cluster formation at speeds of a few mm/s. We will present our results and discuss applications to models of the collisional evolution of Saturn’s rings.

**Author(s): Joshua E. Colwell[1]**, Julie Brisset[1], Adrienne R Dove[1], Jessica Metzger[1], Allison Rascon[1]
**Institution(s):** *1. University of Central Florida*

### 104.11 – Impact of Saturn Main Ring Mass on interpretation of Pioneer 11 and Cassini SOI Radiation Measurements Across the Rings

The Pioneer 11 (1979) and Cassini Orbiter (2004) missions measured the energetic particle and gamma ray flux environments across the A, B, and outer C rings of Saturn. This radiation originates as secondary proton, neutron, electron, and gamma ray emissions from the interaction of high-energy (> 20 GeV) galactic cosmic ray protons and other ions with bulk ice material in the rings and is sensitive to the surface mass density of the rings. The Pioneer 11 analysis from the University of Chicago High Energy Telescope, published in 1985, was consistent with a average surface density of about 50 g/cm$^2$, assuming pure water ice, and a total ring mass of 2.7x10$^{-8}$ Saturn masses ($M_S$). This independently-derived value confirmed the post-Voyager result of 3x10$^{-8}$ $M_S$ from radio and stellar occultations, and from observed damping of density waves in the rings. Although some later ring models in the Cassini mission era (2004 - present) allow for a greater mass by an order of magnitude, the latest density wave analysis from Cassini indicates that the Pioneer-Voyager value may be correct. GEANT radiation transport simulations have been performed to update the ring radiation model and enable ongoing assessments of the Pioneer 11 HET and Cassini MIMI/LEMMS responses to this radiation. The $O_2$ gas production by radiation chemistry within the ring material is also estimated as a function of ring mass for comparison to Cassini and earlier measurements of the ring atmosphere and ionosphere. More massive rings would produce more $O_2$.

**Author(s): John F. Cooper**[3], Steven J. Sturner[3], Edward C. Sittler, Jr.[3], Peter Kollmann[1], Elias Roussos[2], Robert E. Johnson[4]
**Institution(s):** *1. Applied Physics Laboratory Johns Hopkins University, 2. Max Planck Institute for Solar System Research, 3. NASA Goddard Space Flight Center, 4. University of Virginia*

## 105 – Pluto System III--Pluto's Atmosphere

### 105.01 – Radio Occultation Measurements of Pluto's Atmosphere with New Horizons

The reconnaissance of the Pluto System by New Horizons included radio occultations at both Pluto and Charon. This talk will present the latest results from the Pluto occultation. The REX instrument onboard New Horizons received and recorded uplink signals from two 70-m antennas and two 34-m antennas of the NASA Deep Space Network - each transmitting 20 kW at 4.2-cm wavelength - during a diametric occultation by Pluto. At the time this was written only a short segment of data at occultation entry (193°E, 17°S) was available for analysis. The REX measurements extend unequivocally to the surface, providing the first direct measure of the surface pressure and the temperature structure in Pluto's lower atmosphere. Data from occultation exit (16°E, 15°N) are scheduled to arrive on the ground in late August 2015. Those observations will yield an improved estimate of the surface pressure, a second temperature profile, and a measure of the diameter of Pluto with a precision of a few hundred meters. This work is supported by the NASA New Horizons Mission.

**Author(s): David P. Hinson**[5], Ivan Linscott[7], Len Tyler[7], Mike Bird[9], Martin Paetzold[10], Darrell Strobel[3], Mike Summers[2], Will Woods[7], Alan Stern[6], Hal Weaver[1], Cathy Olkin[6], Leslie Young[6], Kimberly Ennico[4], Randy Gladstone[8], Tommy Greathouse[8], Josh Kammer[6], Alex Parker[6], Joel Parker[6], Kurt Retherford[8], Eric Schindhelm[6], Kelsi Singer[6], Andrew Steffl[6], Con Tsang[6], Maarten Versteeg[8]
**Institution(s):** *1. Applied Physics Laboratory, 2. George Mason University, 3. Johns Hopkins University, 4. NASA Ames Research Center, 5. SETI Institute, 6. Southwest Research Institute, 7. Stanford University, 8. SwRI, 9. University of Bonn, 10. University of Cologne*

### 105.02 – Discovery of Hazes in Pluto's Atmosphere

The New Horizons spacecraft made the first reconnaissance of the Pluto-Charon system on Jul 14, 2015. The Long Range Reconnaissance Imager (LORRI) on New Horizons obtained images of Pluto and Charon on approach, near closest approach, and on departure. The departure images, obtained at high solar phase angles , unexpectedly revealed that Pluto's atmosphere is hazy. The haze in Pluto's atmosphere was detected in each of five images obtained in two separate observations on Jul 14 and on Jul 26, at solar phase angles of 167° and 165° respectively. The haze extends to altitudes of at least 150 km above Pluto's surface, with evidence for layering and/or gravity waves. We will present the haze observations and discuss derived physical properties and implications for the atmosphere and its interactions with the surface, including estimates for the rate of deposition of haze particles on the surface of Pluto.This work was supported by NASA's New Horizons Project.

**Author(s): Andrew F. Cheng**[2], Randy Gladstone[3], Michael Summers[1], Alex Parker[3], John Spencer[3], Leslie Young[3], Hal Weaver[2], Kim Ennico[3], Cathy Olkin[3], Alan Stern[3]
**Institution(s):** *1. George Mason, 2. Johns Hopkins, APL, 3. Southwest Research*

### 105.03 – Haze in Pluto's atmosphere: Results from SOFIA and ground-based observations of the 2015 June 29 Pluto occultation

We observed the 29 June 2015 occultation by Pluto from SOFIA and several ground-based sites in New Zealand. Pre-event astrometry (described in Zuluaga et al., this conference) allowed us to navigate SOFIA into Pluto's central flash (Person et al., this conference). Fortuitously, the central flash also fell over the Mt. John University Observatory (Pasachoff et al., this conference). We combine all of our airborne and ground-based data to produce a geometric solution for the occultation and to investigate the state of Pluto's atmosphere just two weeks before the New Horizons spacecraft's close encounter with Pluto. We find that the atmosphere parameters at half-light are unchanged from our observations in 2011 (Person et al. 2013) and 2013 (Bosh et al. 2015). By combining our light-curve inversion with recent radius measurements from New Horizons, we find strong evidence for an extended haze layer in Pluto's atmosphere. See also Sickafoose et al. (this conference) for an evaluation of the particle sizes and properties.
SOFIA is jointly operated by the Universities Space Research Association, Inc. (USRA), under NASA contract NAS2-97001, and the Deutsches SOFIA Institut (DSI) under DLR contract 50 OK 0901 to the University of Stuttgart. Support for this work was provided by NASA SSO grants NNX15AJ82G (Lowell Observatory), NNX10AB27G (MIT), and NNX12AJ29G (Williams College), and by the National Research Foundation of South Africa.

**Author(s): A. S. Bosh**[6], M. J. Person[6], C. A. Zuluaga[6], A. A. Sickafoose[10], S. E. Levine[5], J. M. Pasachoff[21], B. A. Babcock[21], E. W. Dunham[5], I. McLean[15], J. Wolf[17], F. Abe[8], E. Becklin[20], T. A. Bida[5], L. P. Bright[5], T. Brothers[6], G. Christie[2], P. L. Collins[5], R. F. Durst[21], A. C. Gilmore[18], R. Hamilton[20], H. C. Harris[14], C. Johnson[15], P. M. Kilmartin[18], M. R. Kosiarek[6], K. Leppik[20], S. E. Logsdon[15], R. Lucas[13], S. Mathers[11], C. J. K. Morley[9], P. Nelson[1], H. Ngan[2], E. Pfüller[17], T. Natusch[2], H.-P. Röser[17], S. Sallum[12], M. Savage[20], C. H. Seeger[21], H. Siu[6], C. Stockdale[4], D. Suzuki[19], T. Thanathibodee[6], T. Tilleman[14], P. J. Tristram[7], J. Van Cleve[20], C. Varughese[3], L. W. Weisenbach[6], E. Widen[16], M. Wiedemann[17]
**Institution(s):** *1. AAVSO, 2. Auckland Observatory, 3. Earth & Sky Limited, 4. Hazelwood Observatory, 5. Lowell Observatory, 6. MIT, 7. Mt. John University Observatory, 8. Nagoya University, 9. Sandy Ridge Observatory, 10. South African Astronomical Observatory, 11. Southern Cross Observatory, 12. Steward Observatory, 13. Sydney University, 14. U.S. Naval Observatory, 15. UCLA, 16. United States Antarctic Program, 17. Universität Stuttgart, 18. University of Canterbury, 19. University of Notre Dame, 20. USRA, 21. Williams College*

### 105.04 – Investigation of particle sizes in Pluto's atmosphere from the 29 June 2015 occultation

The 29 June 2015 observations of a stellar occultation by Pluto, from SOFIA and ground-based sites in New Zealand, indicate that haze was present in the lower atmosphere (Bosh et al., this conference). Previously, slope changes in the occultation light curve profile of Pluto's lower atmosphere have been attributed to haze, a steep thermal gradient, and/or a combination of the two. The most useful diagnostic for differentiating between these effects has been observing occultations over a range of wavelengths: haze scattering and absorption are functions of particle size and are wavelength dependent, whereas effects due to a temperature gradient should be largely independent of observational wavelength. The SOFIA and Mt. John data from this event exhibit obvious central flashes, from multiple telescopes observing over a range of wavelengths at each site (Person et al. and Pasachoff et al., this conference). SOFIA data include Red and Blue observations from the High-speed Imaging Photometer for Occultations (HIPO, at ~ 500 and 850 nm), First Light Infrared Test Camera (FLITECAM, at ~1800 nm), and the Focal Plan Imager (FPI+, at ~ 600 nm). Mt. John data include open filter, g', r', i', and near infrared. Here, we analyze the flux at the bottom of the light curves versus observed wavelength. We find that there is a distinct trend in flux versus wavelength, and we discuss applicable Mie scattering models for different particle size distributions and compositions (as were used to characterize haze in Pluto's lower atmosphere in Gulbis et al. 2015).

SOFIA is jointly operated by the Universities Space Research Association, Inc. (USRA), under NASA contract NAS2-97001, and the Deutsches SOFIA Institut (DSI) under DLR contract 50 OK 0901 to the University of Stuttgart. Support for this work was provided by the National Research Foundation of South Africa, NASA SSO grants NNX15AJ82G (Lowell Observatory), PA NNX10AB27G (MIT), and PA NNX12AJ29G (Williams College), and the NASA SOFIA Cycle 3 grant NAS2-97001 issued by USRA.

**Author(s): Amanda A. Sickafoose[10]**, A. S. Bosh[6], M. J. Person[6], C. A. Zuluaga[6], S. E. Levine[5], J. M. Pasachoff[21], B. A. Babcock[21], E. W. Dunham[5], I. McLean[15], J. Wolf[17], F. Abe[8], T. A. Bida[5], L. P. Bright[5], T. Brothers[6], G. Christie[2], P. L. Collins[5], R. F. Durst[21], A. C. Gilmore[18], R. Hamilton[20], H. C. Harris[14], C. Johnson[15], P. M. Kilmartin[18], M. R. Kosiarek[6], K. Leppik[20], S. Logsdon[15], R. Lucas[13], S. Mathers[11], C. J. K. Morley[9], T. Natusch[2], P. Nelson[1], H. Ngan[2], E. Pfüller[17], H.-P. roeser@irs.uni-stuttgart.de[17], S. Sallum[12], M. Savage[20], C. H. Seeger[21], H. Siu[6], C. Stockdale[4], D. Suzuki[19], T. Thanathibodee[6], T. Tilleman[14], P. J. Tristam[7], J. Van Cleve[20], C. Varughese[3], L. W. Weisenbach[6], E. Widen[16], M. Wiedemann[17]
**Institution(s):** *1. Astronomical Society of Victoria, 2. Auckland Observatory, 3. Earth & Sky Limited, 4. Hazelwood Observatory, 5. Lowell Observatory, 6. MIT, 7. Mt. John University Observatory, 8. Nagoya University, 9. Sandy Ridge Observatory, 10. South African Astronomical Observatory, 11. Southern Cross Observatory, 12. Steward Obs., 13. Sydney University, 14. U.S. Naval Observatory, 15. UCLA, 16. United States Antarctic Program, 17. Universität Stuttgart, 18. University of Canterbury, 19. University of Notre Dame, 20. USRA, 21. Williams College*

### 105.05 – Central Flash Analysis of the 29 June 2015 Occultation

After an extensive prediction effort, the 29 June 2015 occultation by Pluto was observed from both airborne (Stratospheric Observatory for Infrared Astronomy - SOFIA) and numerous ground-based telescopes (Bosh et al. - this meeting). Real-time prediction updates allowed placement of the SOFIA telescope with its four detectors deep within the central-flash region of the atmospheric occultation. Fortuitously, the Mount John University Observatory (Lake Tekapo, New Zealand) was also within the central-flash region (Pasachoff et al. – this meeting). This happenstance resulted in multiple central-flash detections in several colors from each facility allowing direct comparison of different areas of the central-flash evolute.

Here we examine and discuss the central-flash signatures from the highest signal-to-noise light curves from each facility. The relative orientations and asymmetries in the central flashes allow us to use them to tightly constrain the lower atmospheric ellipticity and orientation of likely winds with respect to Pluto's figure. The ratio of the two separate central flashes is also a strong constraint on the geometric solution for the full occultation data set, and the absolute height of the central flashes with respect to those expected for a clear isothermal atmosphere places constraints on haze densities and thermal gradients in Pluto's lower atmosphere. We can also compare the central-flash signatures in several colors (similar to Sickafoose et. al – this meeting) to establish bounds on haze-particle sizes in the lower atmosphere.

SOFIA is jointly operated by the Universities Space Research Association, Inc. (USRA), under NASA contract NAS2-97001, and the Deutsches SOFIA Institut (DSI) under DLR contract 50 OK 0901 to the University of Stuttgart. Support for this work was provided, in part, by NASA grants SSO NNX15AJ82G (Lowell Observatory), PA NNX10AB27G (MIT), and PA NNX12AJ29G (Williams College), as well as the National Research Foundation of South Africa, and the NASA SOFIA Cycle 3 grant NAS2-97001 issued by USRA.

**Author(s): Michael J. Person[6]**, A S Bosh[6], A A Sickafoose[6], C A Zuluaga[6], S E Levine[6], J M Pasachoff[20], B A Babcock[20], E W Dunham[5], I McLean[13], J Wolf[15], F Abe[8], E Becklin[13], T A Bida[5], L P Bright[5], T C Brothers[6], G Christie[2], P L Collins[5], R F Durst[20], A C Gilmore[16], R Hamilton[19], H C Harris[18], C Johnson[13], P M Kilmartin[16], M R Kosiarek[6], K Leppik[19], S E Logsdon[13], R Lucas[12], S Mathers[10], C J K Morley[9], T Natusch[2], P Nelson[1], H Ngan[2], E Pfueller[15], H-P Roeser[15], S Sallum[11], M Savage[19], C H Seeger[20], H Siu[6], C Stockdale[4], D Suzuki[17], T Thanathibodee[6], T Tilleman[18], P J Tristram[7], J Van Cleeve[19], C Varughese[3], L W Weisenbach[6], E Widen[14], M Wiedemann[15]
**Institution(s):** *1. AAVSO, 2. Auckland Observatory, 3. Earth & Sky Limited, 4. Hazelwood Observatory, 5. Lowell Observatory, 6. MIT, 7. Mt. John University Observatory, 8. Nagoya University, 9. Sandy Ridge Observatory, 10. Southern Cross Observatory, 11. Steward Observatory, 12. Sydney University, 13. UCLA, 14. United States Antarctic Program, 15. Universität Stuttgart, 16. University of Canterbury, 17. University of Notre Dame, 18. USNO, 19. USRA, 20. Williams College*

### 105.06 – Detection of Atmospheric CO on Pluto with ALMA

We observed Pluto and Charon using the Atacama Large Millimeter/submillimeter Array (ALMA) interferometer in Northern Chile on June 12.2 and June 13.15, 2015, just one month prior to the New Horizons flyby of the system. The configuration of ALMA at the time provided ~0.3" resolution, allowing separation of emission from Pluto and Charon. This project targeted multiple science goals, including a search for HCN in Pluto's atmosphere [1] and high precision measurements of the individual brightness temperatures of Pluto and Charon [2], also presented at this meeting. Here we report the high SNR detection of carbon monoxide in the atmosphere of Pluto. The CO(3-2) rotational line, at 345.796 GHz (867 μm), was observed with 117 kHz spectral resolution for 45 min (on-source) on each date, providing ~3.5mJy/channel RMS. CO emission was clearly detected on both days, with a contrast of ~65 mJy above the Pluto continuum, and ~1.8 MHz FWHM linewidth, with the combined integrated line SNR >50. The presence of CO in Pluto's atmosphere is expected due to it's presence as ice on the surface in vapor pressure equilibrium with the atmosphere (e.g. [3],[4]), and it was previously detected at modest SNR in the near-IR using the VLT [5]. A preliminary assessment based upon the CO line wings shows the fractional abundance of CO is 500-750 ppm, consistent with that found in [5]. Further, the shape of the line core emission (assuming a constant CO mixing ratio), suggests that the atmospheric temperature rises quickly from the surface to ~100-110 K in the altitude range 20-70 km but decreases above that, falling to about 70 K by 200 km altitude. A detailed line inversion analysis will be performed and results presented.

[1] Lellouch et al, this meeting. [2] Butler et al., this meeting. [3] Owen et al (1993), Science, 261, pp. 745–748. [4] Spencer et al (1993), In Pluto and Charon, pp. 435–473. Univ. of Arizona Press, Tucson. [5] Lellouch et al (2011), A&A, 530, L4.

**Author(s): Mark Gurwell[1]**, Emmanuel Lellouch[6], Bryan Butler5, Arielle Moullet4, Raphael Moreno[6], Dominique Bockelée-Morvan[6], Nicolas Biver[6], Thierry Fouchet[6], Darek Lis[6], Alan Stern7, Leslie Young7, Eliot Young7, Hal Weaver3, Jeremie Boissier [2], John Stansberry[8]
**Institution(s):** *1. Harvard-Smithsonian Center For Astrophysics, 2. Institut de Radio-Astronomie Millimétrique, 3. Johns Hopkins University Applied Physics Laboratory, 4. National Radio Astronomy Observatory - Charlottesville, 5. National Radio Astronomy Observatory - Socorro, 6. Observatoire de Paris, 7. Southwest Research Institute, 8. Space Telescope Science Institute*

### 105.07 – Detection of HCN in Pluto's atmosphere

We report on the first detection of hydrogen cyanide in Pluto's atmosphere, obtained with the ALMA interferometer. ALMA observations of the HCN(4-3) line at 354.505 GHz were conducted on June 12.2 and June 13.15, 2015 at ~0.3" spatial resolution, separating Pluto from Charon, with a 234 kHz spectral sampling. The HCN line was detected on both dates, with a ~100 mJy contrast and a ~0.75 MHz FWHM linewidth. The narrow linewidth and the absence of Lorentzian wings indicate that most of the HCN resides in Pluto's upper atmosphere. As on Titan, HCN is an expected photochemical product in a N2-CH4 atmosphere. Data interpretation in terms of the HCN abundance/vertical distribution and comparison with photochemical models will be presented.

**Author(s): Emmanuel Lellouch[6]**, Mark Gurwell[1], Bryan Butler5, Arielle Moullet4, Raphael Moreno[6], Dominique Bockelée-Morvan[6], Nicolas Biver[6], Thierry Fouchet[6], Darek Lis[6], Alan Stern7, Leslie Young7, Eliot Young7, Hal Weaver3, Jeremie Boissier[2], John Stansberry[8]
**Institution(s):** *1. Harvard-Smithsonian Center For Astrophysics, 2. Institut de Radio-Astronomie Millimétrique, 3. Johns Hopkins University Applied Physics Laboratory, 4. National Radio Astronomy Observatory - Charlottesville, 5. National Radio Astronomy Observatory - Socorro, 6. Observatoire de Paris, 7. Southwest Research Institute, 8. Space Telescope Science Institute*

### 105.08 – Pluto's Extended Atmosphere: New Horizons Alice Lyman-α Imaging

Pluto's upper atmosphere is expected to extend several planetary radii, proportionally more so than for any planet in our solar system. Atomic hydrogen is readily produced at lower altitudes due to photolysis of methane and transported upward to become an important constituent. The Interplanetary Medium (IPM) provides a natural light source with which to study Pluto's atomic hydrogen atmosphere. While direct solar Lyman-α emissions dominate the signal at 121.6 nm at classical solar system distances, the contribution of diffuse illumination by IPM Lyman-α sky-glow is roughly on par at Pluto (Gladstone et al., Icarus, 2015). Hydrogen atoms in Pluto's upper atmosphere scatter these bright Lyα emission lines, and detailed simulations of the radiative transfer for these photons indicate that Pluto would appear dark against the IPM Lyα background. The Pluto-Alice UV imaging spectrograph on New Horizons conducted several observations of Pluto during the encounter to search for airglow emissions, characterize its UV reflectance spectra, and to measure the radial distribution of IPM Lyα near the disk. Our early results suggest that these model predictions for the darkening of IPM Lyα with decreasing altitude being measureable by Pluto-Alice were correct. We'll report our progress toward extracting H and $CH_4$ density profiles in Pluto's upper atmosphere through comparisons of these data with detailed radiative transfer modeling. These New Horizons findings will have important implications for determining the extent of Pluto's atmosphere and related constraints to high-altitude vertical temperature structure and atmospheric escape.
This work was supported by NASA's New Horizons project.

**Author(s): Kurt D. Retherford7**, G. Randall Gladstone7, S. Alan Stern7, Harold A. Weaver3, Leslie A. Young7, Kimberly A. Ennico5, Cathy B. Olkin7, Andy F. Cheng3, Thomas K. Greathouse7, David P. Hinson[8], Joshua A. Kammer7, Ivan R. Linscott[8], Alex H. Parker7, Joel Wm. Parker7, Wayne R. Pryor[1], Eric Schindhelm7, Kelsi N. Singer7, Andrew J. Steffl7, Darrell F. Strobel9, Michael E. Summers[2], Constantine C. C. Tsang7, G. Len Tyler[8], Maarten H. Versteeg7, William W. Woods[8], Nathaniel J. Cunningham[6], Werner Curdt4
**Institution(s):** *1. Central Arizona College, 2. George Mason University, 3. JHU Applied Physics Laboratory, 4. Max Planck Institute for Solar System Research, 5. NASA Ames Research Center, 6. Nebraska Wesleyan University, 7. Southwest Research Inst., 8. Stanford University, 9. The Johns Hopkins University*

### 105.09 – Escape of Pluto's Atmosphere: In Situ Measurements from the Pluto Energetic Particle Spectrometer Science Investigation (PEPSSI) instrument on New Horizons and Remote Observations from the Chandra X-ray observatory

The escape rate of Pluto's atmosphere is of significant scientific interest. The Pluto Energetic Particle Spectrometer Science Investigation (PEPSSI) is a compact, energy by time-of-flight (TOF) instrument developed to help address this science goal. Pluto is known to have an atmosphere, and pre-encounter models have postulated a majority $N_2$ composition with free escape of up to ~$10^{28}$ molecules/sec. The expected major ionization product near Pluto is singly ionized $N_2$ molecules with pickup energies sufficient to be measured with PEPSSI. In the process of measuring the local energetic particle environment, such measurements can also provide constraints on the local density of Pluto's extended atmosphere, which, along with plasma measurements from the Solar Wind Around Pluto (SWAP) instrument, also on New Horizons, could allow the inference of the strengh and extent of mass-loading of the solar wind due to Pluto's atmosphere. Pluto's neutral atmosphere also provides a source population for charge exchange of highly ionized, minor ions in the solar wind, such as O, C, and N. This process allows these ions to capture one electron and be left in an excited state. That state, in turn decays with the emission of a low-energy (100 eV to 1 keV) X-ray. Observations of such solar wind charge exchange (SWCX) X-rays have been made in the past of the Earth's geocorona and Mars's extended atmosphere. The award of almost 40 hours of Director's Discretionary Time (DDT) for observing Pluto with the Chandra X-ray observatory near the period of closest approach of New Horizons to Pluto potentially enabled a remote determination of Pluto's global outgassing rate using the local solar wind flux as measured by the SWAP instrument. Preliminary anaysis of data returned from these observations reveal a definite interaction of Pluto with the solar wind, but at a lower strength than had been predicted. This work was supported by NASA's New Horizons project.

**Author(s): Ralph L. McNutt3**, Matthew E. Hill3, Carey M. Lisse3, Peter Kollmann3, Fran Bagenal4, Stamatios M. Krimigis3, David J. McComas[6], Heather A. Elliott[6], Scott J. Wolk[1], Darrell F. Strobel[2], Xun Zhu3, S. A. Stern7, H. A. Weaver3, L. A. Young7, K. Ennico5, C. B. Olkin7
**Institution(s):** *1. Harvard-Smithsonian Center for Astrophysics, 2. Johns Hopkins University, 3. Johns Hopkins University Applied Physics Laboratory, 4. Laboratory for Atmospheric and Space Physics, University of Colorado, 5. NASA Ames Research Center, 6. Southwest Research Institute, 7. Southwest Research Institute, Boulder*

### 105.10 – First Results on Pluto's Energetic Particle Environment from the PEPSSI Instrument

The New Horizons spacecraft flew by Pluto in July 2015 and passed through the wakes of Pluto and its largest moon Charon. Pluto interacts with the solar wind via the magnetic fields created by currents in its ionosphere and the pick-up of charge-exchange ions escaping from its atmosphere. The PEPSSI instrument (Pluto Energetic Particle Spectrometer Science Investigation) passed through this interaction region. Closest approach distance to Pluto was 11 Pluto radii, inside the orbit of Charon. PEPSSI measures intensities of keV to MeV ions and can distinguish ions in the solar wind from ions originating from Pluto. Pluto's energetic particle environment clearly stands out compared to the surrounding solar wind at these heliospheric distances. Electrons in the same energy range as the ions do not show a distinct signature throughout the flyby. There is no indication in the particle observations for an intrinsic magnetic field of Pluto. We will present an analysis of the data that is downlinked throughout August and set them into context with measurements taken by PEPSSI in Jupiter's magnetotail in 2007. This work was supported by NASA's New Horizons project.

**Author(s): Peter Kollmann[2]**, M. E. Hill[2], R. McNutt[2], H. T. Smith[2], J. Vandegriff[2], M. Kusterer[2], L. Brown[2], D. K. Haggerty[2], C. M. Lisse[2], H. A. Elliott[5], D. Strobel[1], F. Bagenal[6], E. Sidrow[6], D. J. McComas[5], M. Horanyi[6], E. Zirnstein[5], S. M. Krimigis[2], K. Ennico[3], L. A. Young[4], H. A. Weaver[2], C. B. Olkin[4], S. A. Stern[4]
**Institution(s):** *1. Johns Hopkins University, 2. Johns Hopkins University Applied Physics Laboratory, 3. NASA Ames, 4. Southwest Research Institute, 5. Southwest Research Institute, 6. University of Colorado Boulder*

### 105.11 – Photochemistry, Ion Chemistry, and Haze Formation in Pluto's Atmosphere

The detection of ethylene ($C_2H_4$) and acetylene ($C_2H_2$) in Pluto's atmosphere provides important ground-truth observations for validating photochemical models of Pluto's atmosphere. Their detection also confirms the production of precursor chemical compounds involved in the formation of tholins, which are thought to give Pluto's surface its reddish color. Photochemical models predict many other hydrocarbon and nitrile products, currently undetected, which may also be participants in tholin production on Pluto's surface or on atmospheric haze particles. The observed atmospheric haze layer extending to altitudes of ~140 km above Pluto's surface, suggests a global and very robust process of atmospheric particle nucleation, growth, and sedimentation onto Pluto's surface. The high altitude extent of the haze layer suggests that the nucleation process begins above the expected altitude range where hydrocarbons become supersaturated (below ~30 km altitude). This situation may be analogous to that in Titan's atmosphere, wherein nucleation and aerosol growth is directly related to large negative ion production. In the case of Pluto, this means that nucleation may occur at altitudes as high as 1200 km altitude where ionization in Pluto's atmosphere peaks. In this paper we discuss these processes and their implications for haze formation in Pluto's atmosphere and its deposition onto Pluto's surface. This work was supported by NASA's New Horizons project.

**Author(s): Michael E. Summers[2]**, S. A. Stern[4], G. Randal Gladstone[4], Leslie A. Young[4], C. B. Olkin[4], H. A. Weaver[1], A. F. Cheng[1], D. F. Strobel[6], K. A. Ennico[3], J. A. Kammer[4], A. H. Parker[4], K. D. Retherford[4], E. Schindhelm[4], K. N. Singer[4], A. J. Steffl[4], C. C. Tsang[4], M. H. Versteeg[4], T. K. Greathouse[4], I. R. Linscott[5], L. G. Tyler[5], W. W. Woods[5], D. P. Hinson[7], J. W. Parker[4], J. P. Renaud[2], M. Ewell[2], Cary M. Lisse[1]
**Institution(s):** *1. Applied Physics Laboratory, 2. George Mason Univ., 3. NASA Ames Research Center, 4. Southwest Research Institute, 5. Stanford University, 6. The Johns Hopkins University, 7. The SETI Institute*

### 105.12 – A 3D Global climate model of the Pluto atmosphere to interpret New Horizons observations, including the $N_2$, $CH_4$ and CO cycles and the formation of organic hazes

To interpret New Horizons observations and simulate the Pluto climate system, we have developed a Global Climate Model (GCM) of Pluto's atmosphere. In addition to a 3D "dynamical core" which solves the equations of meteorology, the model takes into account the $N_2$ condensation and sublimation and its thermal and dynamical effects, the vertical turbulent mixing, the radiative transfer through methane and carbon monoxide, molecular thermal conduction, and a detailed surface thermal model with different thermal inertia for various timescales (diurnal, seasonal). The GCM also includes a detailed model of the $CH_4$ and CO cycles, taking into account their transport by the atmospheric circulation and turbulence, as well as their condensation and sublimation on the surface and in the atmosphere, possibly forming methane ice clouds. The GCM consistently predicts the 3D methane abundance in the atmosphere, which is used as an input for our radiative transfer calculation.
Because of the radiative timescales, the surface thermal inertia and the slow evolution of the methane cycle, the model takes more than 20 years to become insensitive to the assumed atmospheric initial states. We typically start our simulations in 1975 to simulate 2015, but remain sensitive to the assumed initial ices distribution and seasonal thermal inertia map. The simulated thermal structure and waves can be compared to the New Horizons occultations measurements. As observed, the longitudinal variability is very limited, for fundamental reasons.
In addition, we have developed a 3D model of the formation of organic hazes within the GCM. It includes the different steps of aerosols formation as understood on Titan: photolysis of $CH_4$ in the upper atmosphere by the Lyman-alpha radiation, production of various gaseous precursor species, conversion into solid particles through chemistry and aggregation processes, and gravitational sedimentation. Significant amount of haze particles are found to be present at all latitudes up to 100 km. However, if $N_2$ ice is already condensing in the polar night, most of the haze tend to accumulate in the winter/fall hemisphere because of the transport of the haze precursors and aerosols by the condensation flow.

**Author(s): Francois Forget[1]**, Tanguy Bertrand[1], Melanie Vangvichith[1], Jeremy Leconte[1]
**Institution(s):** *1. LMD, IPSL, CNRS, Université P. et M. Curie*

## 106 – The Asteroid Composition Channel: From Soft Rock to Heavy Metal

### 106.01 – NIR spectral and mineralogic studies of nine Vp-type asteroids: 7 likely Vestoids and 2 likely new outer belt basaltic asteroid candidates

Nine additional Vp-type asteroids as candidate basaltic asteroids were observed at the NASA Infrared Telescope Facility (IRTF) from January 15-19, 2015 UT, as part of a continuing NASA Planetary Astronomy Program grant to better characterize the abundance and distribution of basaltic asteroids in the main asteroid belt. The Vp-type asteroids, which are classified based on Sloan ugriz colors and the subsequent coarse visible-wavelength spectra that results, includes: (2168) Swope, (3715) Stohl, (3849) Incidentia, (5754) 1999 FR2, (10666) Feldberg, (19165) 1991 CD, (34698) 2001 OD22, and (36118) 1999 RE135. The first seven of these Vp-type asteroids either reside near (4) Vesta dynamical space or are located within the 3:1 mean-motion resonance. The latter two Vp-type asteroids are located beyond the 3:1 mean-motion resonance. NIR spectra were obtained using SpeX in prism mode (0.7 to 2.5 microns) at the parallactic angle using the 0.8 arsec slit. Seven of the Vp-type asteroids were observed on two nights while (2168) Swope was observed on three nights and (19165) 1991 CD was observed on a single night. Average near-infrared (NIR) reflectance spectra of the asteroids were analyzed using MATLAB-based (Reddy et al., 2011) and IDL-based SARA (Lindsay et al., 2013) routines to isolate absorption features and measure band centers, band areas, and band depths. Temperature corrections were applied to band centers to allow comparison with HED meteorite band parameters. Initial results indicate that all nine asteroids exhibit similar spectral band centers and Band Area Ratios (BAR) across different nights with little or no significant variation. The MATLAB and SARA analysis routines also produce similar results for all nine asteroids. All nine asteroids exhibit BAR values consistent with basaltic achondrites or exhibit larger values beyond the BAR zone as found in Gaffey et al. (1993). WISE-derived albedos for these asteroids range from 24-50%. Initial analysis indicates that the seven inner-belt Vp-type asteroids are likely Vestoids and are associated with (4) Vesta while (34698) and (36118) are new candidates for outer-belt basaltic asteroids.

**Author(s): Paul S. Hardersen[2]**, Vishnu Reddy[1], Matt Nowinski[2], Maggie Dievendorf[2]
**Institution(s):** *1. Planetary Science Institute, 2. Univ. of North Dakota*

### 106.02 – Are near-Earth Vestoids volatile-rich asteroids?

Asteroids that are linked to carbonaceous chondrite meteorites exhibit an absorption feature at ~3 µm, which is generally attributed to hydroxyl- and/or water-bearing materials. However, relatively weaker 3-µm features have been detected on some bodies that are not linked to carbonaceous chondrites. For these bodies, the 3-µm feature could be due to surficial OH implanted from solar wind or from emplacement of exogenically sourced carbonaceous (low albedo) material. Such emplacement has been seen on asteroid (4) Vesta, which was visited by NASA's Dawn spacecraft. Carbonaceous chondrite impactors have been suggested as the source of the exogenic low-albedo material on Vesta and the source of the event that created the older Veneneia basin on Vesta's south pole. If the low-albedo material delivered to Vesta during the Veneneia-forming event were mixed with howarditic material to form Vestoids, some of which were later transported to Earth-crossing orbits, we would expect to detect this carbonaceous material on these near-Earth Vestoids. HED meteorites also show carbonaceous chondrite clasts. To test this hypothesis, we have observed Vestoids in the 3-µm region using the long-wavelength cross-dispersed (LXD: 1.9–4.2-µm) mode of the SpeX spectrograph/imager at the NASA Infrared Telescope Facility (IRTF). Here we present high-quality 3-µm spectra of two Near-Earth Vestoids: (357439) 2004 $BL_{86}$, which was observed during close flyby of Earth January 2015, and (4055) Magellan, which was observed in August 2015. This work has implications for both the understanding of the origin of Vestoids and the characterization of the 3-µm region in spectra of near-Earth asteroids.
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**Author(s): Driss Takir[2]**, Vishnu Reddy[1], Juan A. Sanchez[1], Lucille Le Corre[1], Paul S. Hardersen3
**Institution(s):** *1. Planetary Science Institute, 2. U.S. Geological Survey, 3. University of North Dakota*

### 106.03 – Early Evolution of the Main Belt Informed by the Compositional Diversity of Basaltic Asteroids

We present near-infrared (0.78-2.45 micron) reflectance spectra for eight outer main belt (a > 2.5 AU) asteroids that have been taxonomically classified as V-types based on visible wavelength data. Three of these objects are spectrally distinct from all classifications in the Bus-DeMeo spectral catalogue, and thus could represent either spectral end members of the V-type taxonomic class or a small population of a new spectral type. The remainder of the sample are classified as V- or R-type. All of these asteroids are dynamically distinct from the Vestoid family, implying that they originated from differentiated planetesimals which have since been destroyed or ejected from the solar system. The 1- and 2-µm band centers of all objects, determined using Modified Gaussian Model fits, were compared to those of 47 Vestoids and fifteen HED meteorites of known composition. Formulas relating Band 1 and Band 2 centers to the pyroxene mineralogies of these asteroids were derived from the sample of HED meteorites and used to determine the Fs numbers of all asteroids. The Fs numbers of the five outer belt V- and R-type asteroids are, on average, between five and ten molar percent lower than those of the Vestoids, implying that these objects formed in a more reducing environment than Vesta. Given the complex evolution of oxygen fugacity in the solar nebula, these compositional results suggest that these outer belt basaltic asteroids formed either interior to Vesta and were later scattered to the outer belt or formed at a later epoch than Vesta.

**Author(s): Thomas Leith[2]**, Nicholas Moskovitz[2], Rhiannon Mayne4, Francesca DeMeo3, Driss Takir[1]
**Institution(s):** *1. Astrogeology Science Center, United States Geological Survey, 2. Lowell Observatory, 3. Massachusetts Institute of Technology, 4. Monnig Meteorite Collection, Texas Christian University*

### 106.04 – Finding metal-rich asteroids – a NEOShield-2 Study

The 1.2 km diameter Barringer Crater in Arizona was produced by an impact of a metallic asteroid, whereas the impact of a similar sized stony asteroid in 1908 over Tunguska, Russia, resulted in a large airburst but no crater.
Studies of the metal content of asteroids are relevant not only to estimations of their potential to wreak devastation on impacting the Earth, but also for theories of their origins and nature, and possibly in the future for endeavors in the field of planetary resources.
However the reflection spectra of metallic asteroids are largely featureless, which makes it difficult to identify them and relatively few are therefore known. With reference to radar albedos and taxonomic classifications, we showed (Harris and Drube, 2014) that data from the WISE/NEOWISE thermal-infrared survey (Wright et al. 2010; Mainzer et al. 2011a) fitted with a simple thermal model (NEATM; Harris 1998), can reveal asteroids likely to be metal rich, based on the NEATM fitting parameter, η, which carries information on thermal inertia.
To further explore the dependence of η and thermal inertia on taxonomic type, we are continuing analyses of WISE/NEOWISE data and expanding them to include IRAS data (Tedesco et al., 2002). We are calculating the angle between the spin vector and the solar direction, θ, for different sightings of asteroids having known spin vectors. The η values of objects with high thermal inertia and moderate to high spin rates should depend strongly on θ, whereas those with low thermal inertia and/or low spin rates should not. We will present the latest results of our work and provide a demonstration of its potential.
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**Author(s): Line Drube[1]**, Alan W. Harris[1]
**Institution(s):** *1. German Aerospace Center*

### 106.05 – Near Earth Asteroid (4015) Wilson-Harrington: a Possible Source of Meteorites from the Polana or the Themis Family

Near-Earth asteroid (4015) Wilson-Harrington is particularly interesting for a number of reasons. It has displayed cometary activity, hence its designation as comet 107P, and since Wilson-Harrington likely originated in the main asteroid belt (Bottke at al. 2002a), it could also be called a Main-belt Comet. This object has been linked to fireballs capable of producing recoverable meteorites (Campins and Swindle 1998), and it is a potential target of spacecraft missions. We have carried out spectroscopic and dynamical studies of Wilson-Harrington and we narrow its likely origin to either the Polana or the Themis asteroid families. We present new visible and near-infrared spectra of Wilson-Harrington that show significant similarities with members of the Themis and Polana families. These spectral parallels are consistent with dynamical arguments that connect the current orbit of Wilson-Harrington with each of these two families. However, it is not clear at this time which of the families is the more likely origin for Wilson-Harrington. Our work also has implications on sources of primitive meteorites.

**Author(s): Humberto Campins4**, Javier Licandro[2], Julia de León[2], Noemí Pinilla-Alonso5, Vania Lorenzi[1], Victor Ali-Lagoa3, Alessandro Morbidelli3
**Institution(s):** *1. Fundación Galileo Galilei – INAF, 2. Instituto de Astrofísica de Canarias – IAC, 3. Laboratoire Lagrange, Observatoire de la Côte d'Azur, 4. Univ. of Central Florida, 5. University of Tennessee*

## 106.06 – 3-µm spectroscopy of Near-Earth Asteroids: Searching for OH/$H_2O$ on small planetary bodies

Near-Earth asteroids (NEAs) are not expected to have OH and/or $H_2O$ ice on their surfaces because; a) most accreted dry in the inner Solar System and therefore never contained hydrated materials, and b) their relatively high surface temperatures should quickly drive OH/$H_2O$ off their surface. However, OH/$H_2O$ has been detected on other anhydrous inner solar system objects, including the Moon and Vesta. Possible mechanisms to explain OH/$H_2O$ on surfaces in the inner Solar System include production via solar wind interactions, carbonaceous chondrite or cometary impact delivery, or native OH/$H_2O$ molecules bound to phyllosilicates. As these processes are active in near-Earth space, we hypothesize that detectable levels of OH/$H_2O$ are present on NEAs.
The OH/$H_2O$ feature can be comprised of an OH absorption feature centered near 2.7 µm and $H_2O$ features near 2.9 and 3.1 µm, or a blend of both, producing a relatively wide feature spanning 2.7 – 3.1 µm. Analysis of the shape of the 3-µm feature, coupled with the observed NEA orbital parameters and albedos, can help distinguish between the possible sources of OH/$H_2O$. Here we present results of an ongoing observational program to measure spectra of NEAs in the 3-µm region. We are using the SpeX instrument on NASA's IRTF to measure spectra from ~2 to 4.2 µm. So far, we have 12 observations of 8 NEAs. Of these objects, three exhibit a 3-µm feature: both of our observations of (443) Eros, three observations of (1036) Ganymed, and (3122) Florence exhibit. The NEAs (54789) 2001 MZ7, (96590) 1998 XB, (285944) 2001 RZ11, (214088) 2004 JN13, (357439) 2004 BL86 do not exhibit a feature. Rivkin et al. (2013; LPSC) has also reported detections of the 3-µm feature on Ganymed and Eros with data taken in the same year as ours (2012). Band shape, albedo, and orbital analysis of the NEAs exhibiting the 3-µm feature indicate that the primary production mechanism of OH/$H_2O$ on Eros and Ganymed is solar wind interactions. For Florence, on the other hand, it appears that in-fall of carbonaceous material might be the primary mechanism. We will discuss the implications of these results for potential sources of OH/$H_2O$ on the surfaces of NEAs in general, and prospects for future observations.

**Author(s): Nathanael Wigton3**, Joshua Emery3, Cristina Thomas[2], Andy Rivkin[1]
**Institution(s):** *1. JHU/APL, 2. Planetary Science Institute, 3. University of Tennessee*

## 106.07 – Euphrosyne As An NEO Source: Spectral Properties and Inferences from Meteorites

The Euphrosyne family is interpreted as ejecta from an impact into 31 Euphrosyne, a large C-class asteroid in the outer part of the main belt. Recent work by Masiero et al. suggests that Euphrosyne family members may preferentially find their way into the NEO population, and presumably from there into the meteorite collections of the world.
Interestingly, observations of Euphrosyne in the 3-µm spectral region by Takir et al. and Rivkin et al. show it to have a rounded band shape and a band center near 3.1 µm. Such a band shape has never been seen in any meteorite spectra collected to date, but these characteristics are reminiscent of 24 Themis and 65 Cybele, whose spectra have been interpreted as having bands due to ice frost and organic materials. The spectra of Euphrosyne family objects, and those NEOs thought to have originated in that family, therefore may show how icy objects evolve as they move from the asteroid belt to orbits near 1 AU and how they may (or may not) be represented in the meteorite record. Alternately, they may give rise to new interpretations of the absorptions that have not yet been considered.
We will discuss the combined implications of Euphrosyne's spectrum and family dynamics, and the opportunities for better understanding the nature of outer belt asteroids that observations of the Euphrosyne family provide.

**Author(s): Andrew S. Rivkin[1]**, Lucy F. Lim[2], Joshua P. Emery3
**Institution(s):** *1. JHU/APL, 2. NASA GSFC, 3. University of Tennessee*

## 106.08 – SOFIA observations of dark asteroids: Evidence for hydrated minerals on asteroidal surfaces?

We present results from recent SOFIA+FORCAST observations of three primitive asteroids and compare these to archived *Spitzer Space Telescope* (*Spitzer)* observations of similar objects. Three asteroids from a total of 12 have been observed with SOFIA+FORCAST in our Cycle-3 campaign. Currently, we have observed asteroids 38 Leda, 194 Prokne with both G111 and G227 grisms and asteroid 266 Aline with G227. Both wavelength regions (G111: 8.5-13.5-µm and G227: 17.6-27.7) have recently been shown to contain spectral features directly related degree of alteration of primitive meteorites, including unaltered CO and CV meteorites (McAdam, *et al.,* 2015a ,b). Spectral features in the 17.6-27.7-µm region can be indicative of olivine (19.5-µm), hydrated minerals (21-µm) and silica glass (22-µm). *Spitzer* observed eight large, primitive, main-belt asteroids using both low-resolution modes (short-low, SL and long-low, LL) of the *Infrared Spectrograph* (IRS) covering 8.5-38-µm. Additionally, *Spitzer* observed 22 dark primitive asteroids in the 8.5-13.5-µm region. Asteroids observed with *Spitzer* fall into three categories: asteroids with a 12-µm feature of 1-5% depth, interpreted as ~60-70% hydrated minerals (McAdam, *et al.,* 2015a); asteroids with a broader 12-13-µm feature with strengths ranging from 4-6% with potential features between 19-22-µm (where observed) and asteroids with a strong 13-µm feature (5-10%), 15-µm and potentially 19-22-µm features (where observed) interpreted as olivine-rich. However, the uncertain calibration at the edges of the LL spectral orders complicates feature identification. 194 Prokne has a feature ~12-13-µm feature and potentially a broad feature between 20-22-µm. This is consistent with primitive asteroids observed with *Spitzer* that are interpreted as hydrated mineral-bearing. 38 Leda is largely featureless at the noise limit of the spectrum with a potential feature at 25-µm, unlike asteroids observed by *Spitzer*. 266 Aline has a weak feature at 22.5-µm and is potentially similar to those asteroids observed with both modes that are hydrated-mineral bearing.
McAdam *et al.,* (2015a) *Icarus*, *245*, 320-332.
McAdam *et al.,* (2015b) *LPSC* abstract # 2540.

**Author(s): Margaret McAdam[1]**, Jessica M Sunshine[1], Michael S. P. T. Kelley[1]
**Institution(s):** *1. University of Maryland*

## 106.09 – PRIMitive Asteroids Spectroscopic Survey – PRIMASS: First Results

NASA OSIRIS-REx and JAXA Hayabusa 2 sample-return missions have targeted two near-Earth asteroids: (101955) Bennu and (162173) 1999 JU3, respectively. These are primitive asteroids that are believed to originate in the inner belt, where five distinct sources have been identified: four primitive collisional families (Polana, Erigone, Sulamitis, and Clarissa), and a population of low-albedo and low-inclination background asteroids. Identifying and characterizing the populations from which these two NEAs might originate will enchance the science return of the two missions.
With this main objective in mind, we initiated in 2010 a spectroscopic survey in the visible and the near-infrared to characterize the primitive collisional families in the inner belt and the low-albedo background population. This is the **PRIMitive Asteroids Spectroscopic Survey – PRIMASS**. So far we have obtained more than 200 spectra using telescopes located at different observatories. PRIMASS uses a variety of ground based facilities. Most of the spectra have been obtained using the 10.4m

Gran Telescopio Canarias (GTC), and the 3.6m Telescopio Nazionale Galileo (TNG), both located at the El Roque de los Muchachos Observatory (La Palma, Spain), and the 3.0m NASA Infrared Telescope Facility on Mauna Kea (Hawai, USA).
We present the first results from our on-going survey (de Leon et al. 2015; Pinilla-Alonso et al. 2015; Morate et al. 2015), focused on the Polana and the Erigone primitive families, with visible and near-infrared spectra of more than 200 objects, most of them with no previous spectroscopic data. Our survey is already the largest database of primitive asteroids spectra, and we keep obtaining data on the Sulamitis and the Clarissa families, as well as on the background low-albedo population.

**Author(s): Julia de Leon3**, Noemi Pinilla-Alonso6, Humberto Campins5, Vania Lorenzi1, Javier Licandro3, David Morate3, Paolo Tanga4, Alberto Cellino2, Marco Delbo4
**Institution(s):** *1. Fundacion Galileo Galilei - INAF, 2. INAF, Osservatorio Astrofisico di Torino, 3. Instituto de Astrofisica de Canarias, 4. Laboratoire Lagrange, Observatoire de la Côte d'Azur, 5. University of Central Florida, Physics Department, 6. University of Tennessee, Department of Earth and Planetary Sciences*

### 106.10 – 5 – 14 µm Spitzer spectra of primitive asteroid families

Compositional studies of primitive asteroid families provide constraints on the physical and chemical environment of the solar nebula and the evolution of the asteroid belt. Spectroscopic studies in the visible and near-infrared have shown spectral diversity between primitive families. Our goal is to better constrain the composition of two primitive families with very different ages: Themis (~2.5 Gyr) and Veritas (~8 Myr). We analyzed 5 – 14 µm Spitzer Space Telescope spectra of a total of 18 asteroids, nine from each family. We report the presence of a broad 10-µm emission feature, attributed to a layer of fine-grained silicates, in the spectra of all nine Themis asteroids and six of nine Veritas asteroids in our sample. Spectral contrast in statistically significant detections of the 10-µm feature ranges from 1% ± 0.1% to 8.5% ± 0.9%. Comparison with the spectra of primitive meteorites (McAdam et al. 2015, Icarus, 245, 320) suggests asteroids in both families are similar to meteorites with lower abundances of phyllosilicates. We used the Near-Earth Asteroid Thermal Model to derive diameters, beaming parameters and albedos for our sample. Asteroids in both families have beaming parameters near unity and geometric albedos in the range 0.06 ± 0.01 to 0.14 ± 0.02. We find that contrast of the silicate emission feature is not correlated with asteroid diameter; however, higher 10-µm contrast may be associated with flatter spectral slopes in the near-infrared. The spectra of both families suggest icy bodies with some amount of fine-grained silicates, but with coarser grains or denser surface structure than Trojan asteroids and comets.

**Author(s): Zoe A. Landsman3**, Javier Licandro1, Humberto Campins3, Julie Ziffer4, Mário de Prá2
**Institution(s):** *1. Instituto de Astrofísica de Canarias, 2. Observatório Nacional, 3. University of Central Florida, 4. University of Southern Maine*

### 106.11 – Compositional study of the Themis family

Themis is an outer main-belt family comprising more than 4,000 dynamically well-established members (Nesvorny 2012), mainly B- and C-type asteroids (Florczak et al. 1999; Mothé-Diniz et al. 2005; Ziffer et al. 2011). This family is rather unique for a number of reasons:
- It is believed to be the only main-belt family formed from the catastrophic disruption of a large (D>200 km) B-/C-type body (Brož et al. 2013). As such, it offers a unique view on the internal composition of a primitive asteroid.
- Elst-Pizarro, one of the family member, was one of the first main belt comets to be discovered (Hsieh & Jewitt 2006).
- 24 Themis is the first main belt asteroid for which water ice was detected at its surface (Campins et al. 2010; Rivkin & Emery 2010).
- The low density values recorded for two family members (<1.3 g/cm$^3$, Descamps et al. 2007; Marchis et al. 2008) likely imply high fractions of ice(s) in the interior of these bodies.
The last three features all point towards an ice-rich composition for the Themis parent body while showing little compatibility with a thermally metamorphosed body that has been heated throughout at temperatures exceeding 300 K. The latter interpretation was previously suggested on the basis of a similarity between the near-infrared spectral properties of heated CI/CM chondrites and those of the family members' surfaces (Clark et al. 2010; Ziffer et al. 2011). In brief, the Themis family members appear unsampled by our meteorite collections. Recently, Vernazza et al. (2015) instead proposed that Interplanetary Dust Particles (IDPs) may be more appropriate extraterrestrial analogs for these objects' surfaces.
In the light of Vernazza et al. (2015)'s recent work, we investigated the surface mineralogy of a sample of Themis family members using a combined dataset of spectra covering the visible (Bus & Binzel 2002; Lazzaro et al. 2004), near-infrared (this work), and mid-infrared (Licandro et al. 2012; Hargrove et al. 2015) spectral ranges.
Assuming particle sizes (typically sub- to micrometer sizes) and end-members composition similar to those found in chondritic porous IDPs, we modeled the spectral properties of the Themis family members. The results of this study will be presented in details.

**Author(s): Michael Marsset2**, Pierre Vernazza4, Mirel Birlan3, Francesca DeMeo5, Richard P Binzel5, Christophe Dumas2, Julien Milli2, Marcel Popescu1
**Institution(s):** *1. Astronomical Institute of the Romanian Academy, 2. European Southern Observatory, 3. Institut de Mécanique Céleste et de Calcul des Ephémérides, 4. Laboratoire d'Astrophysique de Marseille, 5. Massachusetts Institute of Technology*

### 106.12 – Interplanetary Dust Particles As Samples of Icy Asteroids

Meteorites have long been considered as reflections of the compositional diversity of main belt asteroids and consequently they have been used to decipher their origin, formation, and evolution. However, while some meteorites are known to sample the surfaces of metallic, rocky and hydrated asteroids (about one-third of the mass of the belt), the low-density icy asteroids (C-, P-, and D-types), representing the rest of the main belt, appear to be unsampled in our meteorite collections. Here we provide conclusive evidence that the surface compositions of these icy bodies are compatible with those of the most common extraterrestrial materials (by mass), namely anhydrous interplanetary dust particles (IDPs). Given that these particles are quite different from known meteorites, it follows that the composition of the asteroid belt consists largely of more friable material not well represented by the cohesive meteorites in our collections. In the light of our current understanding of the early dynamical evolution of the solar system, meteorites likely sample bodies formed in the inner region of the solar system (0.5–4 AU) whereas chondritic porous IDPs sample bodies that formed in the outer region (>5 AU).

**Author(s): Pierre Vernazza5**, Michael Marsset1, Pierre Beck4, Richard Binzel6, Mirel Birlan3, Rosario Brunetto2, Francesca DeMeo6, Zahia Djouadi2, Christophe Dumas1, Sihane Merouane8, Olivier Mousis5, Brigitte Zanda7
**Institution(s):** *1. ESO, 2. IAS, 3. IMCCE, 4. IPAG, 5. Laboratoire d'Astrophysique de Marseille, 6. MIT, 7. MNHN, 8. MPS*

## 107 – Mercury and the Moon

### 107.01 – Mercury's exosphere: New detections, discoveries, and insights

For over 16 Mercury years, the MESSENGER spacecraft orbited the planet Mercury and conducted a variety of observations of the exosphere. Part of the overall observing plan was a search for exospheric species that are less abundant and/or more weakly emitting than the more easily observed Na, Ca, and Mg. For most of the orbital phase, this search has resulted in nothing more than increasingly refined upper limits. However, in the last few Mercury years, three species that had eluded this programmatic search were observed. Emission from multiple lines of $Ca^+$ was detected, validating the observation of a single line of $Ca^+$ during the third MESSENGER Mercury flyby. Multiple lines of Al were also detected, providing definitive evidence for a species that has been suggested from ground-based observations. Finally, emission from Mn has been discovered, adding another member to the pantheon of exospheric species. All these detections were somewhat localized about the planet and during the Mercury year. Equally interesting as these observations is absence of detectable emission from other species, such as O. We will report on both the detections and non-detections, provide altitude profiles where possible, and discuss the insights gained from these species in the context of the overall exosphere. The NASA MESSENGER Participating Scientist Program supported this work.

**Author(s): Ronald J. Vervack, Jr.[2]**, William E. McClintock5, Rosemary M. Killen[1], Aimee W. Merkel5, Matthew H. Burger3, Menelaos Sarantos4, Timothy A. Cassidy5
**Institution(s):** *1. GSFC, 2. JHU/Applied Physics Laboratory, 3. Morgan State University/GESTAR, 4. UMBC, 5. University of Colorado*

### 107.02 – A seasonal feature in Mercury's exosphere caused by meteoroids from comet Encke

The planet Mercury is enveloped in a tenuous atmosphere, the result of a delicate balance between poorly understood sources and sinks (Killen et al, 2007). Meteoroid impacts are a contributing source process (eg Wurz et al, 2010), but their importance compared to other production mechanisms is uncertain.
Killen and Hahn (2015) found that seasonal variations in Mercury's calcium exosphere as observed by Mercury Atmospheric, and Surface Composition Spectrometer (MASCS) onboard the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft (Burger et al, 2014) may be attributed to impact vaporization of surface material by the infall of interplanetary dust. However, an additional dust source was required to explain a Ca excess at a True Anomaly Angle (TAA) of 25±5 deg. Killen and Hahn suggested that dust from comet 2P/Encke, crossing Mercury's orbital plane at TAA=45 deg, may be the culprit.
We have simulated numerically the stream of meteoroids ejected from Encke in order to identify those particles that impact Mercury at the present epoch and test the Killen and Hahn conjecture. We find that Encke particles evolving solely under the gravity of the major planets and the Sun encounter Mercury at TAA=50-60 deg, well after the peak of the Ca excess emission. This result is independent of the time of ejection. However, the addition of Poynting-Robertson (P-R) drag in our model couples the age and size of the meteoroids to the TAA at encounter, causing smaller, older particles to encounter Mercury progressively earlier in the Hermean year. In particular, mm-sized grains ejected between 10 and 20 kyr ago impact on the nightside hemisphere of Mercury at TAA = 350–30 deg, near the observed peak time of the exospheric feature.
During this presentation, we will describe our model results and discuss their implications for the physical mechanism that injects impact-liberated Ca into sunlight as well as the origin and evolution of the Encke stream of meteoroids.
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**Author(s): Apostolos Christou[1]**, Rosemary M Killen3, Matthew H Burger[2]
**Institution(s):** *1. Armagh Obs., 2. Goddard Earth Sciences, Technology, and Research, Morgan State University, 3. NASA Goddard Space Flight Center*

### 107.03 – Solar Wind Charge Exchange X-ray emission from Mercury's exosphere: Detectability with Bepi Colombo's MIXS spectrometer

We have conducted preliminary hybrid simulations to calculate the Solar Wind Charge Exchange (SWCX) X-ray emission in Mercury's exosphere. Our results imply that the OVII triplet emission intensity for standard slow solar wind conditions is of the same order as the one predicted by simulations for Mars and measured by Chandra in past observations of Mars. Using an oversimplified detector and observation geometry we explore the detectability of Mercury's SWCX emission by the MIXS spectrometer on board Bepi Colombo's planetary orbiter (MPO).

**Author(s): Dimitra Koutroumpa[1]**, Konrad Dennerl[2], François Leblanc[1], Ronan Modolo[1]
**Institution(s):** *1. LATMOS-CNRS, 2. MPE*

### 107.04 – Mercury's EUV Reflectance Spectrum From Mariner 10 Revisited

Carbon, as graphite, has emerged from recent analyses of MESSENGER spectrophotometry and theoretical modeling as a possible source for the darkening component in the Low Reflectance Material (LRM), pervasive across Mercury's surface. Murchie et al. (Icarus 254, 287, 2015) propose graphite, in amounts consistent with results from MESSENGER's elemental experiments for the presence of C, as the most likely darkening component in LRM. Vander Kaaden and McCubbin (JGR Planets 120, 195, 2015) report that graphite would be the only buoyant phase in an early magma ocean, and any primary flotation crust would have retained C in the form of graphite. Alternatively, Gillis-Davis et al. (Abstract P1 1A-07, AGU, 2013) suggest that nanophase and microphase iron, produced by impacts into Mercury's crust before and during the late heavy bombardment, could darken the LRM. Carbon in the forms of graphite and anthracite has distinctive far-UV spectral reflectance features. The MESSENGER MASCS UVVS spectrometer does not extend to wavelengths short enough to observe these features. The Mariner 10 EUV airglow spectrometer observed broad swaths of Mercury in 10 filters at wavelengths ranging from 304Å to 1657Å, each having 20Å passbands. We now re-analyze these data in a search for this distinctive UV signature of graphite across large areas of Mercury's surface, and will report on the results.

**Author(s): Faith Vilas[1]**, Amanda R. Hendrix[1], Elizabeth A. Jensen[1]
**Institution(s):** *1. Planetary Science Institute*

### 107.05 – Mercury's gravity field, tidal Love number *k2*, and spin axis orientation revealed with MESSENGER radio tracking data

We are conducting an independent analysis of two-way Doppler and two-way range radio tracking data from the MESSENGER spacecraft in orbit around Mercury from 2011 to 2015. Our goals are to estimate Mercury's gravity field and to obtain independent estimates of the tidal Love number $k2$ and spin axis orientation. Our gravity field solution reproduces existing values with high fidelity, and prospects for recovery of the other quantities are excellent.
The tidal Love number $k2$ provides powerful constraints on interior models of Mercury, including the mechanical properties of the mantle and the possibility of a solid FeS layer at the top of the core. Current gravity analyses cannot rule out a wide range of values ($k2$=43–0.50) and a variety of plausible interior models. We are seeking an independent estimate of tidal Love number $k2$ with improved errors to further constrain these models.
Existing gravity-based solutions for Mercury's spin axis orientation differ from those of Earth-based radar and topography-based solutions. This difference may indicate an error in one of the determinations, or a real difference between the orientations about which the gravity field and the crust rotate, which can exist in a variety of plausible configuration. Securing an independent estimate of the spin axis orientation is vital because this quantity has a profound impact on the determination of the moment of inertia and interior models.
We have derived a spherical harmonic solution of the gravity field to degree and order 40 as well as estimates of the tidal Love number $k2$ and spin axis orientation

**Author(s): Ashok Kumar Verma[1]**, Jean-Luc Margot[1]
**Institution(s):** *1. UCLA*

### 107.06 – Perpetual long libration of terrestrial planets in tidal resonances

On the example of Mercury, I show that firm planets of terrestrial composition, locked in the 3:2 or higher spin-orbit resonances, undergo long-period perpetual libration in longitude without any influence of third bodies. This non-damped libration at the natural frequency is driven by a secular tidal torque, which is increasing with frequency within a narrow interval around the resonance. The spectrum of regular forced, eccentricity-driven, libration defines the conditions for the perpetual long libration. The possibility of validating the tidal theory from the observable amplitude of perpetual libration is discussed.

**Author(s): Valeri Makarov[1]**
**Institution(s):** *1. US Naval Observatory*

### 107.07 – The Lunar Profile and Baily's Beads at Solar Eclipses

The lunar mapping from NASA's Lunar Reconaissance Orbiter and JAXA's Kaguya has provided information that allows calculation of the lunar limb profile whose low points at total solar eclipses provides the Baily's Beads. Preparations for the forthcoming August 21, 2017, total solar eclipse (lunar occultation) whose totality crosses the continental United States from northwest to southeast (http://eclipses.info for the International Astronomical Union Working Group on Solar Eclipses) has led to new calculations of the Baily's Beads and of comparisons of the totality duration between predictions and observations for historical events.

JMP's research on the annular and total solar eclipses of 2012 was supported in part by the Solar–Terrestrial Program of the Atmospheric and Geospace Sciences Division of the National Science Foundation through grant AGS–1047726. His observations of the 2013 and 2015 total solar eclipses were supported by grants 9327-13 and 9616-14, respectively, from the Committee for Research and Exploration of the National Geographic Society, with additional support from Williams College.

**Author(s): Jay M. Pasachoff[2]**, Ernest T. Wright[1]
**Institution(s):** *1. NASA's GSFC, 2. Williams College*

### 107.08 – Transitional lava flows as potential analogues for lunar impact melts

Lunar impact melt deposits are among the roughest surface materials on the Moon at the decimeter scale, even though they appear smooth at the meter scale. These characteristics distinguish them from well-studied terrestrial analogues, such as Hawaiian pāhoehoe and ʻaʻā lava flows. The morphology of impact melt deposits can be related to their emplacement conditions, so understanding the origin of these unique surface properties will inform us as to the circumstances under which they were formed. Although there is no perfect archetype for lunar impact melts on Earth, certain terrestrial environments lend themselves as functional analogues. Specifically, a variety of transitional lava flow types develop if the surface of a pāhoehoe-like flow is disrupted, producing 'slabby' or 'rubbly' flows that are extremely rough at the decimeter scale. We investigated the surface roughness of transitional lava flows at Craters of the Moon (COTM) National Monument, comparing radar imagery and high-resolution topographic profiles to similar data sets acquired by the Lunar Reconnaissance Orbiter for impact melt deposits on the Moon. Results suggest that the lava flows at COTM have similar radar properties to lunar impact melt deposits, but the terrestrial flows are considerably rougher at the meter scale. It may be that lunar impact melts represent a unique lava type not observed on Earth, whose surface texture is influenced by their high emplacement temperatures and/or cooling in a vacuum. Information about the surface properties of lunar impact melt deposits will be critical for future landed missions that wish to sample these materials.

**Author(s): Catherine Neish[7]**, Scott Hughes[1], Christopher Hamilton[6], Shannon Kobs Nawotniak[1], William Brent Garry[3], John Roma Skok[4], Richard Elphic[2], Lynn Carter[3], Joshua Bandfield[5], Gordon Osinski[7], Darlene Lim[2], Jennifer Heldmann[2]
**Institution(s):** *1. Idaho State University, 2. NASA Ames Research Center, 3. NASA GSFC, 4. SETI Institute, 5. Space Science Institute, 6. The University of Arizona, 7. The University of Western Ontario*

### 107.09 – The Effect of Pre-Impact Porosity and Vertical Density Gradients on the Gravity Signature of Lunar Craters

As a result of NASA's dual spacecraft Gravity Recovery And Interior Laboratory (GRAIL) mission [Zuber et al., 2013; doi:10.1126/science.1231507], we now know that the lunar crust is highly porous and that the porosity varies laterally [Wieczorek et al., 2013; doi:10.1126/science.1231530] and vertically [Besserer et al., 2014; doi:10.1002/2014GL060240]. Analysis of complex craters located within the lunar highlands reveals that: 1) craters larger than diameter D~210 have positive Bouguer Anomalies (BAs), 2) craters with D ≲ 100 km have both positive and negative BAs that vary about the (near 0) mean by approximately ± 25 mGal, and, 3) D and BA are anticorrelated for craters with D ≲ 100 km [Soderblom et al., 2015; doi:10.1002/2015GL065022]. Numerical modeling by Milbury et al. [2015, LPSC] shows that pre-impact porosity is the dominant influence on the gravity signature of complex craters with D ≲ 100 km, and mantle uplift dominates the gravity for those with D > 140 km. Phillips et al. [2015, LPSC] showed that complex craters located in the South Pole-Aitken (SPA) basin tend to have more-negative BAs than similar craters in the highlands. We use the iSALE hydrocode including pore space compaction [Wünnemann et al., 2006; doi:10.1016/j.icarus.2005.10.013] and dilatant bulking [Collins, 2014; doi:10.1002/2014JE004708] to understand how the gravity signature of impact craters develop. In this study we vary crustal porosity with depth. We find that simulations that have constant porosity with depth have a lower BA for a given crater diameter than those with the same mean porosity, but that vary with depth. We used two different mean porosities (7% and 14%) and found that the BA increases with increasing porosity, similar to simulations with constant porosity. We reproduce the observed anticorrelation between BA and D for D ≲ 100 km only for simulations where the pre-impact porosity is zero or low. Our results support the observation that SPA has lower overall porosity, but higher vertical gradients, giving craters within SPA more-negative BAs than those within the highlands crust. These simulations demonstrate that the BA and porosities reported here are valid for determining general trends only.

**Author(s): Colleen Milbury[3]**, Brandon C. Johnson[2], H. Jay Melosh[3], Gareth S. Collins[1], David M. Blair[2], Jason M. Soderblom[2], Francis Nimmo[5], Roger J. Phillips[4], Carver J. Bierson[5], Maria T. Zuber[2]
**Institution(s):** *1. Imperial College London, 2. Massachusetts Institute of Technology, 3. Purdue University, 4. Southwest Research Institude, 5. UC Santa Cruz*

### 107.10 – Simulated Water Delivery to Lunar Permanently Shadowed Regions

A set of Monte Carlo simulations was run to examine water diffusion across the lunar surface and specifically to the Permanently Shadowed Regions (PSRs). This work extends the results of Schorghofer (2014) to latitudes above 5° from the pole and to specific PSRs and is accomplished using a separately derived model to independently test Schorghofer's (2014) results. The model was validated using the results of Schorghofer (2014) at the 5° latitude line, replicating all of the behaviors of that model, but with slightly different values for the total number of tracer particles arriving and their fractionation.

25 times fewer particles were able to survive to arrive within 1° of the pole, as compared to those that were able to arrive within 5° of the pole. For the PSRs themselves, 1.87% of particles were eventually sequestered within the PSRs by the end of our simulations. Examining the amount of water which could be transported over geological time reveals that sufficient water moves

via migration to (1) supply the hydrogen signals observed by LEND, (Mitrofanov et al., 2012), (2) the frost at Haworth Crater (Gladstone et al., 2012) as well as to explain (3) the high level of water seen in the soils of Cabeus Crater in the LCROSS experiment (Colaprete et al., 2010) without the need to invoke another water supply mechanism.
In all cases, the average time required for migration was small with average arrival times of less than a lunar day following an impact. Substantial differences were observed in the amount of water accreted by the different PSRs with Cabeus Crater accreting by far the most water per square meter. Faustini and the Haworth Lowlands have the next highest delivery, receiving ~60% each as much water as Cabeus per square meter. Shackleton has the lowest water delivery, receiving only ~5% as much water per square meter as Cabeus. The simulated results show a clear latitudinal trend with more water emplaced at lower latitudes. Yet, the data show very little difference between the PSRs in terms of the amount of fractionation taking place and low levels of fractionation overall, considering 100:1 distillation between the impactor and the PSRs.

**Author(s): John Moores[1]**
**Institution(s):** *1. York University*

### 107.11 – The Influence of Surface Roughness on Volatile Transport on the Moon

The Moon and other virtually airless bodies provide distinctive environments for the transport and sequestration of water and other volatiles delivered to their surfaces by various sources. Here, we conduct numerical simulations to investigate the delivery of water to the Moon through comet impacts, focusing on the role of small-scale topography (i.e. surface roughness unresolved by orbital measurements) in the migration and cold-trapping of impact-delivered water. The simulated comet impact generates a transient, collisonally thick water vapor atmosphere that surrounds the Moon for at least several lunar days. During this time, some water is captured by permanently shadowed craters (cold traps) near the lunar poles, where temperatures are sufficiently low that volatiles can remain sequestered over geological time scales. Surface temperature is a critical parameter that determines the residence time of a migrating water molecule on the lunar surface, thereby affecting the rapidity of volatile transport though pressure-driven winds, the susceptibility of migrating molecules to photo-destruction, and the large-scale structure of the impact-generated atmosphere - all of which ultimately affect the rate and magnitude of cold-trapping. The roughness of the lunar surface at small scales, the insulating nature of the lunar regolith and the absence of strong convective heat transport lead to sharp surface temperature gradients: surfaces separated by only a few millimeters can have dramatically different temperatures. Significantly, small-scale roughness gives rise to cold temporary and permanent shadows that may affect the rate at which water migrates to permanent cold traps near the lunar poles and to the temporary shelter of the cold lunar night side. Here, we develop a surface roughness/temperature model, consistent with observed bolometric brightness temperature at larger scales, suitable for simulations of volatile transport on a global scale. We will present a comparison of results from impact-generated atmosphere simulations with and without the surface roughness model in order to understand how small-scale roughness influences transient deposition patterns and the rate and magnitude of cold trap capture.

**Author(s): Parvathy Prem[2]**, Natalia A. Artemieva[1], David B. Goldstein[2], Philip L. Varghese[2], Laurence M. Trafton[2]
**Institution(s):** *1. Planetary Science Institute, 2. The University of Texas at Austin*

### 107.12 – LRO-LAMP Observations of Lunar Exospheric Helium

We present results from Lunar Reconnaissance Orbiter’s (LRO) UV spectrograph LAMP (Lyman-Alpha Mapping Project) campaign to study the lunar atmosphere. Two kinds of off-nadir maneuvers (lateral rolls and pitches towards and opposite the direction of motion of LRO) were performed to search for resonantly scattering species, increasing the illuminated line-of-sight (and hence the signal from atoms resonantly scattering the solar photons) compared to previously reported LAMP “twilight observations” [*Cook & Stern*, 2014]. Helium was the only element distinguishable on a daily basis, and we present latitudinal profiles of its line-of-sight column density in December 2013. We compared the helium line-of-sight column densities with solar wind alpha particle fluxes measured from the ARTEMIS (Acceleration, Reconnection, Turbulence, & Electrodynamics of Moon’s Interaction with the Sun) twin spacecraft. Our data show a correlation with the solar wind alpha particle flux, confirming that the solar wind is the main source of the lunar helium, but not with a 1:1 relationship. Assuming that the lunar soil is saturated with helium atoms, our results suggest that not all of the incident alpha particles are converted to thermalized helium, allowing for a non-negligible fraction (~50 %) to escape as suprathermal helium or simply backscattered from the lunar surface. We also support the finding by *Benna et al.* [2015] and *Hurley et al.* [2015], that a non-zero contribution from endogenic helium, coming from radioactive decay of $^{232}$Th and $^{238}$U within the mantle, is present, and is estimated to be (4.5±1.2) x $10^6$ He atoms $cm^{-2}$ $s^{-1}$. Finally, we compare LAMP-derived helium surface density with the one recorded by the mass spectrometer LACE (Lunar Atmospheric Composition Experiment) deployed on the lunar surface during the Apollo 17 mission, finding good agreement between the two measurements. These LRO off-nadir maneuvers allow LAMP to provide unique coverage of local solar time and latitude of the lunar exospheric helium, allowing for a better understanding of the temporal and spatial structure of the lunar exosphere.

**Author(s): Cesare Grava4**, Kurt D. Retherford4, Dana M. Hurley3, Paul D. Feldman[2], Randy Gladstone4, Thomas K. Greathouse4, Jason C. Cook4, Alan Stern4, Wayne R. Pryor[1], Jasper S. Halekas5, David E. Kaufmann4
**Institution(s):** *1. Central Arizona College, 2. Johns Hopkins University, 3. Johns Hopkins University - Applied Physics Laboratory, 4. Southwest Research Institute, 5. University of Iowa*

## 200 – Pluto System IV--Saving the Best for Last

### 200.01 – Configuration of Pluto's Volatile Ices

We report on near-infrared remote sensing by New Horizons' Ralph instrument (Reuter et al. 2008, Space Sci. Rev. 140, 129-154) of Pluto's $N_2$, CO, and $CH_4$ ices. These especially volatile ices are mobile even at Pluto's cryogenic surface temperatures. Sunlight reflected from these ices becomes imprinted with their characteristic spectral absorption bands. The detailed appearance of these absorption features depends on many aspects of local composition, thermodynamic state, and texture. Multiple-scattering radiative transfer models are used to retrieve quantitative information about these properties and to map how they vary across Pluto's surface. Using parameter maps derived from New Horizons observations, we investigate the striking regional differences in the abundances and scattering properties of Pluto's volatile ices. Comparing these spatial patterns with the underlying geology provides valuable constraints on processes actively modifying the planet's surface, over a variety of spatial scales ranging from global latitudinal patterns to more regional and local processes within and around the feature informally known as Sputnik Planum. This work was supported by the NASA New Horizons Project.

**Author(s): William M. Grundy[2]**, R P Binzel[3], J C Cook[6], D P Cruikshank[4], C M Dalle Ore[4], A M Earle[3], K Ennico[4], D E Jennings[5], C J.A. Howett[6], I R Linscott[8], A W Lunsford[5], C B Olkin[6], A H Parker[6], J Wm Parker[6], S Protopapa[9], D C Reuter[5], K N Singer[6], J R Spencer[6], S A Stern[6], C C.C. Tsang[6], A J Verbiscer[10], H A Weaver[1], L A Young[6], K Berry[11], M W Buie[6], J A Stansberry[7]
**Institution(s):** *1. Johns Hopkins University Applied Physics Laboratory, 2. Lowell Obs., 3. Massachusetts Institute of Technology, 4. NASA Ames Research Center, 5. NASA Goddard Space Flight Center, 6. Southwest Research Institute, 7. Space Telescope Science Institute, 8. Stanford University, 9. University of Maryland, 10. University of Virginia, 11. USGS Astrogeology*

### 200.02 – The Search for Pluto Water

On July 14, 2015, the *New Horizons* spacecraft made its closest approach to Pluto at about ~12,000 km from Pluto's surface. The LEISA (Linear Etalon Imaging Spectral Array) component of the Ralph instrument (Reuter, D.C., Stern, S.A., Scherrer, J., et al. 2008, Space Sci. Rev. 140, 129) obtained spatially resolved near infrared spectra at scales as small as 3 km/pix. LEISA covers the wavelength range 1.25 to 2.5 µm at a spectral resolution (λ/Δλ) of 240, and the 2.1 to 2.25 µm range at a resolution of 560. The observations from this instrument are being used to map the distribution of Pluto's known ices such as $N_2$, $CH_4$, CO and $C_2H_6$ as well as search for $H_2O$-ice. To date, $H_2O$-ice has evaded detection from Earth bound observatories. Observations based on LORRI, the LOng Range Reconnaissance Imager, suggest $H_2O$-ice is a major component of several mountain ranges around the western perimeter of the landmass informally named Tombaugh Regio. If true, $H_2O$-ice may be found in small isolated regions around Pluto. We will present our analysis of all LESIA data of Pluto in hand to search for and understand the distribution of $H_2O$-ice. If found, we will also discuss limits on crystalline vs. amorphous $H_2O$-ice and temperature measurements based on the 1.65 µm crystalline $H_2O$-ice feature. This work was supported by NASA's New Horizons project.

**Author(s): Jason C. Cook5**, Dale P. Cruikshank[3], Cristina M. Dalle Ore [4], Kimberly Ennico[3], William M. Grundy[2], Cathy B. Olkin[5], Silvia Protopapa[6], S. Alan Stern[5], Harold A. Weaver[1], Leslie A. Young[5]
**Institution(s):** *1. John Hopkins University Applied Physics Laboratory, 2. Lowell Observatory, 3. NASA Ames Research Center, 4. SETI Institute, 5. Southwest Research Institute, 6. University of Maryland*

### 200.03 – New Horizons data in the context of prior observations

The New Horizons encounter data have revealed a diverse and complicated surface and atmosphere for Pluto showing strong correlations between geologic features and the albedo and compositional units known from ground- and HST-based observations over the decades prior. This presentation make detailed comparisons between the long time base and low spatial resolution data and the new high resolution stanpshot of Pluto from the flyby. Special emphasis will be placed on the albedo evolution over time with some attention paid to near-infrared spectral signatures. We will compare the albedo maps from mutual event data and two epochs of HST observations against the New Horizons images, after correcting for viewing geometry. Also included will be a discussion of the evolutionary trends in the hemispherically averaged spectral properties from Lowell Observatory and IRTF data against the resolved compositional and spectral maps from New Horizons. The combination of these data sets now permits an unprecedented ability to constrain time-variability on the surface from apparent changes due to viewing geometry and surface inhomogeneities. This work requires a reconcilliation of surface scattering properties that are enabled by the firm determination of the size of Pluto and this will be discussed as well. This work was supported by the NASA New Horizons project.

**Author(s): Marc W. Buie4**, S. Alan Stern[4], Leslie A Young[4], Harold A Weaver[1], Catherine B Olkin[4], Kimberly Ennico[3], Jeffrey M. Moore[3], William M. Grundy[2]
**Institution(s):** *1. JHU/Applied Physics Laboratory, 2. Lowell Observatory, 3. NASA Ames Research Center, 4. Southwest Research Institute*

### 200.04 – Migration of Frosts from High-Albedo Regions of Pluto: what *New Horizons* Reveals

With its high eccentricity and obliquity, Pluto should exhibit seasonal volatile transport on its surface. Several lines of evidence support this transport: doubling of Pluto's atmospheric pressure over the past two decades (Young et al., 2013, *Ap. J.* **766**, L22; Olkin et al., 2015, *Icarus* **246**, 230); changes in its historical rotational light curve, once all variations due to viewing geometry have been modelled (Buratti et al., 2015; *Ap. J.* **804**, L6); and changes in *HST* albedo maps (Buie et al., 2010, *Astron. J.* **139**, 1128). *New Horizons* LORRI images reveal that the region of greatest albedo change is not the polar cap(s) of Pluto, but the feature informally named Tombaugh Regio (TR). This feature has a normal reflectance as high as ~0.8 in some places, and it is superposed on older, lower-albedo pre-existing terrain with an albedo of only ~0.10. This contrast is larger than any other body in the Solar System, except for Iapetus. This albedo dichotomy leads to a complicated system of cold-trapping and thermal segregation, beyond the simple picture of seasonal volatile transport. Whatever the origin of TR, it initially acted as a cold trap, as the temperature differential between the high and low albedo regions could be enormous, possibly approaching 20K, based on their albedo differences and assuming their normalized phase curves are similar. This latter assumption will be refined as the full *New Horizons* data set is returned.
Over six decades of ground-based photometry suggest that TR has been decreasing in albedo over the last 25 years. Possible causes include changing insolation angles, or sublimation from the edges where the high-albedo material impinges on a much warmer substrate.
Funding by the NASA *New Horizons* Project acknowledged.

**Author(s): Bonnie J. Buratti[2]**, S. A. Stern[5], Hal A Weaver[1], Leslie A Young[5], Cathy B Olkin[5], Kimberly Ennico[4], Richard P Binzel[3], Amanda Zangari[5], Alissa M. Earle[3]
**Institution(s):** *1. JHU Applied Physics Lab, 2. JPL, 3. MIT, 4. NASA Ames, 5. SWRI*

### 200.05 – Correlating Pluto's Albedo Distribution to Long Term Insolation Patterns

NASA's New Horizons' reconnaissance of the Pluto system has revealed striking albedo contrasts from polar to equatorial latitudes on Pluto, as well as sharp boundaries for longitudinal variations. These contrasts suggest Pluto undergoes dynamic evolution that drives the redistribution of volatiles. Using the New Horizons results as a template, in this talk we will explore the volatile migration process driven seasonally on Pluto considering multiple timescales. These timescales include the current orbit (248 years) as well as the timescales for obliquity precession (amplitude of 23 degrees over 3 Myrs) and regression of the orbital longitude of perihelion (3.7 Myrs). We will build upon the long-term insolation history model described by Earle and Binzel (2015, Icarus 250, 405-412) with the goal of identifying the most critical timescales that drive the features observed in Pluto's current post-perihelion epoch. This work was supported by the NASA New Horizons Project.

**Author(s): Alissa M. Earle4**, Richard P. Binzel[4], S. Alan Stern[6], Leslie A. Young[6], Bonnie J. Buratti[1], Kimberly Ennico[5], Will M. Grundy[3], Catherine B. Olkin[6], John R. Spencer[6], Hal A. Weaver[2]
**Institution(s):** *1. Jet Propulsion Laboratory, 2. Johns Hopkins University Applied Physics Lab, 3. Lowell Observatory, 4. Massachusetts Institute of Technology, 5. NASA Ames Research Center, 6. Southwest Research Institute*

### 200.06 – A Large Impact Origin for Sputnik Planum

**and Surrounding Terrains, Pluto?**

One of the most prominent features on Pluto discovered by New Horizons is the oval-shaped bright deposit within western Tombaugh Regio (all names used herein are informal). This smooth bright deposit, provisionally identified with frozen nitrogen and methane and informally referred to as Sputnik Planum, is bounded on the northeast by an arcuate scarp (Cousteau Rupes). The smooth bright material there embays what appears to be an eroded plateau 1-2 km high. The arcuate scarp leads to speculation that the deposits formed in an ancient impact basin, but detailed mapping at 2 km pixel scales suggests that this large structure is more complex than any simple impact basin. To the southwest are a series of high peaks and massifs (also embayed by bright material) but these broken massifs have a different morphology from Cousteau Rupes, being both higher and more disrupted. The southern section of this putative 800-km-wide circular structure is completely missing as smooth material extends well to the south of the nominal rim location. A possible analog occurs at the "other End of the Solar System" on Mercury, in Caloris Basin. This 1400-km-wide impact basin is also irregular in shape, with large deviations form circularity, and occasional large massifs along some rim segments. Post-impact smooth plains embay the rim scarp in some areas, though these are likely to be volcanic plains on Mercury. The relief of the rim scarps to the NE and SW and putative evidence for convection within Sputnik Planum suggests that the floor of the deposits lies 1-3 km below the mean surface (pending stereo mapping). This depth is consistent with the filling of an ancient impact basin with ices, deposited either volcanically or atmospherically, although other explanations are also possible. This work was supported by NASA's New Horizons project.

**Author(s): Paul M. Schenk[2]**, William McKinnon[6], Jeffrey Moore[3], Francis Nimmo[5], S. Alan Stern[4], Hal Weaver[1], Kimberly Ennico[3], Cathy Olkin[4], Leslie Young[4]
**Institution(s):** *1. Applied Physics Lab, 2. Lunar and Planetary Inst., 3. NASA Ames Res. Ctr, 4. Southwest Research Institute, 5. UC Santa Cruz, 6. Washington University*

### 200.07 – The Icy Cold Heart of Pluto

The locations of large deposits of frozen volatiles on planetary surfaces are largely coincident with areas receiving the minimum annual influx of solar energy; familiar examples include the polar caps of Earth and Mars. For planets tilted by more than 45 degrees, however, the poles actually receive more energy than some other latitudes. Pluto, with its current obliquity of 119 degrees, has minima in its average annual insolation at +/- 27 degrees latitude, with ~1.5% more energy flux going to the equator and ~15% more to the poles. Remarkably, the fraction of annual solar energy incident on different latitudes depends only on the obliquity of the planet and not on any of its orbital parameters.
Over millions of years, Pluto's obliquity varies sinusoidally from 102-126 degrees, significantly affecting the latitudinal profile of solar energy deposition. Roughly 1Myr ago, the poles received 15% more energy that today while the equator received 13% less. The energy flux to latitudes between 25-35 degrees is far more stable, remaining low over the presumably billions of years since Pluto acquired its current spin properties. Like the poles at Earth, these mid latitudes on Pluto should be favored for the long-term deposition of volatile ices. This is, indeed, the location of the bright icy heart of Pluto, Sputnik Planum.
Reflected light and emitted thermal radiation from Charon increases annual insolation to one side of Pluto by of order 0.02%. Although small, the bulk of the energy is delivered at night to Pluto's cold equatorial regions. Furthermore, Charon's thermal infrared radiation is easily absorbed by icy deposits on Pluto, slowing deposition and facilitating sublimation of volatiles. We argue that the slight but persistent preference for ices to form and survive in the anti-Charon Pluto's heart.

**Author(s): Douglas P. Hamilton[1]**
**Institution(s):** *1. Univ. of Maryland*

### 200.08 – Pluto and Charon Color Light Curves from New Horizons on Approach

On approach to the Pluto system, New Horizons' Ralph Instrument's Multicolor Visible Imaging Camera (MVIC) observed Pluto and Charon, spatially separated, between April 9 and June 23, 2015. In this period, Pluto and Charon were observed to transition from unresolved objects to resolved and their integrated disk intensities were measured in four MVIC filters: blue (400-550 nm), red (540-700 nm), near-infrared (780–975 nm), and methane (860–910 nm). The measurement suite sampled the bodies over all longitudes. We will present the color rotational light curves for Pluto and Charon and compare them to previous (Buie, M. et al. 2010 AJ 139, 1117; Buratti, B.J. et al 2015 ApJ 804, L6) and concurrent ground-based BVR monitoring. We will also compare these data to color images of the encounter hemisphere taken during New Horizons' July 14, 2015 Pluto and Charon flyby, as this data set provides a unique bridge between Pluto & Charon as viewed as astronomical targets versus the complex worlds that early data from New Horizons has revealed them to be. This work was supported by NASA's New Horizons project.

**Author(s): Kimberly Ennico[5]**, C. J.A. Howett[8], C. B. Olkin[8], D. C. Reuter[6], B. J. Buratti[1], M. W. Buie[8], W. M. Grundy[3], A. H. Parker[8], A. M. Zangari[8], R. P. Binzel[4], J. C. Cook[8], D. P. Cruikshank[5], C. M. Dalle Ore[7], A. M. Earle[4], D. E. Jennings[6], I. R. Linscott[9], J. Wm. Parker[8], S. Protopapa[10], K. N. Singer[8], J. R. Spencer[8], S. A. Stern[8], C. C.C. Tsang[8], A. J. Verbiscer[11], H. A. Weaver[2], L. A. Young[8]
**Institution(s):** *1. Jet Propulsion Laboratory, 2. Johns Hopkins University Applied Physics Laboratory, 3. Lowell Observatory, 4. Massachusetts Institute of Technology, 5. NASA Ames Research Center, 6. NASA Goddard Space Flight Center, 7. SETI Institute, 8. Southwest Research Institute, 9. Stanford University, 10. University of Maryland, 11. University of Virginia*

### 200.09D – Pluto's atmosphere from stellar occultations in 2012 and 2013

We present results from two Pluto stellar occultations observed on 18 July 2012 and 04 May 2013, and monitored respectively from five and six sites in South America. Both campaigns involved large telescopes (including the 8.2-m VLT at ESO/Paranal). The high SNR ratios and multi-chord coverage provide amoung the best Pluto atmospheric profiles ever obtained from the ground.
We show that a spherically symmetric, clear (no-haze) and pure $N_2$ atmosphere with a unique temperature profile satisfactorily fits the twelve lightcurves provided by the two events. We find, however, a small but significant increase of pressure of 6% (6-sigma level) between the two dates, with values of 2.16 ± 0.2 and 2.30 ± 0.01 μbar at the reference radius 1275 km, respectively.
We provide atmospheric constrains between 1190 km and 1450 km from Pluto's center, and we determine the temperature profile with accuracy of a few km in vertical scale. Our model shows a stratosphere with strong positive gradient between 1190 km (at 36 K, 11 μbar) and r =1215 km (6.0 μbar), where a temperature maximum of 110 K is reached. Above it is a mesosphere with negative thermal gradient of -0.2 K/km up to 1,390 km (0.25 μbar), at which point, the mesosphere connects itself to a more isothermal upper branch at 81 K. This profile provides (assuming no troposphere) a Pluto surface radius of 1190 ± 5 km, consistent with preliminary values obtained by New Horizons. Currently measured CO abundances are too low to explain the negative mesospheric thermal gradient. We explore the possibility of an HCN (recently detected by ALMA) cooling. This model, however, requires largely supersaturated HCN. Zonal winds and vertical compositional variations of the atmosphere are also unable to explain the observed mesospheric trend.
These events are the last useful ground-based occultations recorded before the 29 June 2015 occultation observed from Australia and New Zealand, and before the NASA's New Horizons flyby of July 2015. This work can serve as a benchmark in the New Horizons context, enabling comparisons between ground-based and space results concerning Pluto's atmospheric structure and temporal evolution.

**Author(s): Alex Dias-Oliveira[12]**, Bruno Sicardy[10], Emmanuel Lellouch[10], Roberto Vieira-Martins[12], Marcelo Assafin[11], Júlio Ignácio Bueno Camargo[12], Felipe Braga-Ribas[23], Altair Gomes-Júnior[11], Gustavo Bendetti-Rossi[12], François Colas[9], Alice Decock[10], Alain Doressoundiram[10], Christophe Dumas[5], Marcelo Emílio[17], Joaquin Fabrega Polleri[13], Ricardo Gil-Hutton[3], Michael Gillon[19], Julien Girard[5], George Hau[5], Valentin Ivanov[4], Emmanuel Jehin[19], Jean Lecacheux[9], Rodrigo Leiva[14], Cecília Lopez-Sisterna[18], Luigi Mancini[8], Jean Manfroid[19], Alain Maury[15], Erick Meza[10], Nicolas Morales[6], Leslie Nagy[15], Cyrielle Opitom[19], José Luiz Ortiz[6], Joe Pollock[1], Françoise Roques[10], Colin Snodgrass[16], Jean François Soulier[2], Audrey Thirouin[7], Leonardo Vanzi[14], Thomas Widemann[10], Daniel Reichart[7], Aaron LaCluyze[21], Joshua B Haislip[21], Kevin Ivarsen[21], Martin Dominik[22], Uffe Jørgensen[20], Jesper Skottfelt[20]
**Institution(s):** *1. Appalachian State University, 2. Association Des 'Etoiles pour Tous, 3. CASLEO-CONICET, 4. ESO, 5. ESO, 6. Instituto de Astrofísica de Andalucía, 7. Lowell Observatory, 8. Max Planck Institute for Astronomy, 9. Observatoire de Paris/IMCCE, 10. Observatoire de Paris/LESIA, 11. Observatório do Valongo/UFRJ, 12. Observatório Nacional, 13. Observatório Panemño, 14. PUC, 15. S.P.A.C.E., 16. The Open University, 17. UEPG, 18. Universidade Nacional de San Juan, 19. Université de Liege, 20. University of Copenhagen, 21. University of North Carolina, 22. University of St Andrews, 23. UTFPR*

## 201 – [3]Venus / Asteroid Dynamics

### 201.01D – The effect of solar flares, coronal mass ejections, and co-rotating interaction regions on the Venusian 557.7 nm oxygen green line

The Venusian 557.7nm OI (1S - 1D) (oxygen green line) nightglow emission is known to be highly temporally variable. The reason for this variability is unknown. We propose that the emission is due to electron precipitation from intense solar storms. For my dissertation, I observed the Venusian green line after solar flares, coronal mass ejections (CMEs), and co-rotating interaction regions from December 2010 to April 2015 using the high resolution Astrophysical Research Consortium Echelle Spectrograph on the Apache Point Observatory 3.5-m telescope. Combining these observation with all other published observations, we find that the strongest detections occur after CME impacts and we conclude electron precipitation is required to produce green line emission. We do not detect emission from the 630.0nm OI (1D - 3P) oxygen red line for any observation.
In an effort to determine the emitting altitude, thereby constraining the possible emission processes responsible for green line emission, and quantify the electron energy and flux entering the Venusian nightside, we conducted analyses of space-based observations of the Venusian nightglow and ionosphere collected by the Venus Express (VEX) spacecraft. We were unable to detect the green line but confirmed that electron energy and flux increases after CME impacts.
In order to determine the effect of storm condition electron precipitation on the Venusian green line, we modeled the Venusian ionosphere using the TRANSCAR model (a 1-D magnetohydrodynamic ionospheric model that simulates auroral emission from electron precipitation) by applying observed electron energies and fluxes. We found that electron energy plays a primary role in producing increased green line emission in the Venusian ionosphere.
Based on observation and modeling results, we conclude that the Venusian green line is an auroral-type emission that occurs after solar storms with the largest intensities observed after CMEs. Post-CME electron fluxes and energies are sufficient to produce the observed green line intensity with the lack of red line emission. We find that O + e is the greatest contributor to the OI (1S) state and is responsible for the observed green line emission.

**Author(s): Candace L. Gray5**, Nancy Chanover5, Tom Slanger[6], Karan Molaverdikhani3, Kerstin Peter[8], Bernd Häusler7, Silvia Tellmann[8], Martin Pätzold[8], Olivier Witasse[1], Pierre-Louis Blelly[2], Glyn Collinson4
**Institution(s):** *1. European Space Research and Technology Centre, 2. Institut de Recherche en Astrophysique et Planétologie , 3. Laboratory for Atmospheric and Space Physics, 4. NASA Goddard Space Flight Center, 5. New Mexico State University, 6. SRI International, 7. Universität der Bundeswehr München, 8. University of Koln*

### 201.02 – Variability of the Venus condensational clouds from analysis of VIRTIS-M-IR observations of the near-infrared spectral windows

The Medium Resolution, Infrared wavelength channel of the Visible and Infrared Thermal Imaging Spectrometer (VIRTIS-M-IR) on the Venus Express spacecraft observed the atmosphere and surface of Venus for 921 orbits following orbit insertion in April 2006 until the failure of the cooling unit in October 2008. The clouds of Venus were long thought to be a uniform sort of perpetual stratocumulus, but near infrared observations by fly-by spacecraft such as Galileo (Near Infrared Mapping Spectrometer) and Cassini (Visible and Infrared Mapping Spectrometer), as well as ground-based observations, indicated a great deal of temporal and spatial inhomogeneity. The nearly three-year lifetime of the VIRTIS-M-IR instrument on Venus Express presents an unprecedented opportunity to quantify these spatial and temporal variations of the Venus clouds. Here, we present the results of an initial quantification of the overall tendencies of the Venus clouds, as measured by variations in the near infrared spectral windows located between wavelengths of 1.0 μm and 2.6 μm. In a companion submission, we also investigate the variations of carbon monoxide and other trace species quantifiable in these data (Tsang and McGouldrick 2015). This work is supported by the Planetary Mission Data Analysis Program, Grant Number NNX14AP94G.

**Author(s): Kevin McGouldrick[2]**, Constantine C. C. Tsang[1]
**Institution(s):** *1. Southwest Research Institute, 2. University of Colorado*

### 201.03 – Thermal structure and minor species distribution of Venus mesosphere by ALMA submm observations

Venus upper atmosphere (70–150 km altitude) is a transition region characterized by a complex dynamics: strong retrograde zonal winds dominate the lower mesosphere while a solar-to-antisolar circulation is observed in the upper mesosphere/lower thermosphere. In addition, photochemical processes play an important role at these altitudes and affect the thermal structure and chemical stability of the entire atmosphere. Sulfur dioxide and water vapor are key species in the photochemical cycles taking place in the troposphere and mesosphere of Venus. They are carried by convective transport, together with the Hadley circulation, up to about 60 km where $SO_2$ is photodissociated and oxydated, leading to the formation of $H_2SO_4$ which condenses in the clouds enshrouding the planet. Previous observations obtained by several instruments on board Venus Express and during ground-based campaigns have shown evidence of strong temporal variations, both on day-to-day as well as longer timescales, of density, temperature and $SO_2$ abundance. Such strong variability is still not well understood.
Submillimeter observations obtained with the Atacama Large Millimeter Array (ALMA) offer the possibility of probing Venus upper mesosphere and of monitoring minor species, winds and the thermal structure. A first set of observations was obtained on November 14, 15, 26 and 27, 2011 during the first ALMA Early Science observation cycle. These observations targeted $SO_2$, SO, HDO and CO transitions around 345 GHz during four sequences of 30 minutes each. The Venus' disk was about 11" with an illumination factor of 90%, so that mostly the dayside of the planet was mapped.
Assuming nominal night-time and dayside CO abundance profiles from Clancy et al. 2013, we retrieved vertical temperature profiles

over the entire disk as a function of latitude and local time for the four days of observation. Temperature profiles were later used to derive the abundances of minor species (HDO, SO, $SO_2$) in each pixel of the disk in order to study their spatial and temporal variability.

**Author(s): Arianna Piccialli[1]**, Raphael Moreno[1], Therese Encrenaz[1], Thierry Fouchet[1], Emmanuel Lellouch[1], Arielle Moullet[2], Thomas Widemann[1]
**Institution(s):** *1. LESIA, Observatoire de Paris, 2. National Radio Astronomy Observatory (NRAO)*

### 201.04 – Observations of Altitude Dependence and Temporal Variation of ClO in the Venus Mesosphere

Analysis of the first observations of ClO in the Venus mesosphere indicate ClO is present above 85 +/-3 km altitude and not below. The retrieved nightside mean abundances show a factor of 2 decrease between observation dates Oct. 23 and Nov. 11, 2015, with change between the two dates evident at more than two sigma confidence. Abundances and altitude distributions are retrieved from submm spectroscopic observations of the 352.88 GHz line of 35ClO (made with the James Clerk Maxwell Telescope - JCMT - located an Mauna Kea, Hawaii).
Detection of ClO in the Venus atmosphere confirms a theory put forward by Yung and DeMore (1982) that the Venus atmosphere is stabilized as $CO_2$ due to chlorine catalytic recombination of CO and O. (Without some form of catalysis, the Venus atmosphere would have 10s of percent CO and $O_2$, but it is in fact 97% $CO_2$ and 3% $N_2$, with only trace amounts of CO and $O_2$.) Detailed retrieval of ClO abundances and altitude distributions (the focus of this talk) provides greater insight to the catalytic process, and to other aspects of Venus atmospheric chlorine chemistry. We compare findings of our quantitave retrieval with predictions of photochemical models, and discuss the implications for chlorine photochemistry of the Venus atmosphere. We also discuss retrieved ClO temporal variation with that of upper mesospheric HCl (Sandor and Clancy, 2012).
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**Author(s): Brad J. Sandor[1]**, R. Todd Clancy[1]
**Institution(s):** *1. Space Science Institute*

### 201.05 – A refined orbit for the satellite of asteroid (107) Camilla

The satellite of the Cybele asteroid (107) Camilla was discovered in March 2001 using the Hubble Space Telescope (Storrs et al., 2001, IAUC 7599). From a set of 23 positions derived from adaptive optics observations obtained over three years with the ESO VLT, Keck-II and Gemini-North telescopes, Marchis et al. (2008, Icarus 196) determined its orbit to be nearly circular.
In the new work reported here, we compiled, reduced, and analyzed observations at 39 epochs (including the 23 positions previously analyzed) by adding additional observations taken from data archives: HST in 2001; Keck in 2002, 2003, and 2009; Gemini in 2010; and VLT in 2011. The present dataset hence contains twice as many epochs as the prior analysis and covers a time span that is three times longer (more than a decade).
We use our orbit determination algorithm Genoid (GENetic Orbit IDentification), a genetic based algorithm that relies on a metaheuristic method and a dynamical model of the Solar System (Vachier et al., 2012, A&A 543). The method uses two models: a simple Keplerian model to minimize the search-time for an orbital solution, exploring a wide space of solutions; and a full N-body problem that includes the gravitational field of the primary asteroid up to 4th order.
The orbit we derive fits all 39 observed positions of the satellite with an RMS residual of only milli-arcseconds, which corresponds to sub-pixel accuracy. We found the orbit of the satellite to be circular and roughly aligned with the equatorial plane of Camilla. The refined mass of the system is (12 ± 1) x 10^18 kg, for an orbital period of 3.71 days.
We will present this improved orbital solution of the satellite of Camilla, as well as predictions for upcoming stellar occultation events.

**Author(s): Myriam Virginia Pajuelo[2]**, Benoit Carry[2], Frederic Vachier[2], Jerome Berthier[2], Pascal Descamp[2], William J. Merline[6], Peter M. Tamblyn[6], Al Conrad[3], Alex Storrs[7], Jean-Luc Margot[8], Frank Marchis[5], Pierre Kervella[4], Julien H. Girard[1]
**Institution(s):** *1. ESO, 2. IMCCE, Observatoire de Paris, 3. Large Binocular Telescope Observatory, 4. LESIA, Observatoire de Paris, 5. SETI Institute, 6. Southwest Research Institute, 7. Towson University, 8. UCLA*

### 201.06 – On the oldest asteroid families in the main belt

Asteroid families are group of minor bodies produced by collisions. Once the parent body is disrupted by a collision and fragments are launched into space, their orbits evolve because of several gravitational and non-gravitational effects, such as diffusion in mean-motion resonances, Yarkovsky and YORP effects, collisional evolution etc. The subsequent dynamical evolution of asteroid family members may cause some of the original fragments to travel beyond the recognizable limits of the asteroid family. Eventually, the whole family will dynamically disperse and no longer be recognizable. Dynamical erosion of asteroid families has been the subject of a few recent studies, mostly focused on smaller asteroid groups.
A natural question that may arise concerns the timescales for dispersion of large families. In particular, what is the oldest still recognizable family in the main belt? Are there any families that may date from the late stages of the Late Heavy Bombardment and that could provide clues on our understanding of the primitive Solar System? In this work we investigate the dynamical stability of seven of the allegedly oldest families in the asteroid main belt, when resonant dynamics, Yarkovsky and stochastic YORP effects, and past changes in the solar luminosity are considered. None of the studied families is estimated to be older than 3.0 Gyr. Results of our numerical simulations show that some of the members of the largest families studied could have survived since 4.2 Gyr, but with a significant depletion in the number of the smallest ($D < 5$ km) family members.

**Author(s): Valerio Carruba[1]**, David Nesvorný[1], Safwan Aljbaae[2], Rita C. Domingos[2]
**Institution(s):** *1. SouthWest Research Institute, 2. UNESP*

### 201.07 – Asteroid Impacts, Crater Scaling Laws, and a Proposed Younger Age for Venus's Surface

A fascinating on-going debate concerns the asteroid sizes needed to form certain large craters. For example, numerical hydrocode models predict that ~12-14 km and ~8 km diameter asteroids are needed to produce craters like Chicxulub (~180 km) and Popigai (~100 km), respectively. The abundance of extraterrestrial Ir/Os measured at well-characterized impact boundaries on land and in oceanic cores, however, predict far smaller projectiles, 4-6 km and 2.5-4 km, respectively (e.g., Paquay et al. 2014; F. Kyte, pers. comm). To test who might be right by proxy, we transformed the near-Earth object (NEO) size distribution (Harris & D'Abramo 2015), where > 90% of the $D > 1$ km asteroids are known, into a model crater size distribution and compared it to the distribution of $D > 20$ km craters formed on the Moon, Mars, and Venus over the last ~1-3 Gyr. Here we kept things simple and assumed that f described the ratio between all crater and asteroid diameters of interest (i.e., f = D_crater / D_proj).
To our surprise, we found f ~ 23-26 produced excellent matches for the crater size distributions on the Moon, Mars, and Venus, despite their differences in gravity, surface properties, impact velocities, etc. These same values work well for the Earth as well. Consider that terrestrial crater production rates derived by Shoemaker (1998) indicate 340 +/- 170 $D > 20$ km craters formed over the last 120 Myr. Using f = 25, we get the same value; a $D > 0.8$ km asteroid makes a $D > 20$ km crater, and they hit Earth every 0.35 Myr on average (e.g., Bottke et al. 2002), for a total of ~340 over 120 Myr. Accordingly, we predict Chicxulub and Popigai were made by D ~ 7 and D ~ 4 km asteroids, respectively, values close to their predicted

sizes from Ir/Os measurements. This result also potentially explains why Chicxulub formed ~65 Myr ago; the interval between D ~ 7 km impacts on Earth is close to this rate.
The NEO model by Bottke et al. (2002) also suggests asteroids hit Venus at roughly the same rate as Earth. Fitting model craters to observations, we estimate Venus' average surface age as ~130 Myr, a lower value than previous predictions. This result, if true, has interesting implications for Venus's evolutionary history.

**Author(s): William Bottke[2]**, Rebecca Ghent3, Sara Mazrouei3, Stuart Robbins[2], David Vokrouhlicky[1]
**Institution(s):** *1. Charles U., 2. Southwest Research Inst., 3. U. Toronto*

### 201.08 – Sesquinary catanae on Phobos from reaccretion of ejected material

Impact ejecta from a planetary satellite can reimpact the target body or nearby companions after an extended period, creating a distinct type of 'sesquinary' impact morphology[1]. We present results of a comprehensive survey of sesquinary ejecta released from the Martian satellite Phobos, ranging from ejecta from the Stickney impact (outcomes of SPH simulations), to just-escaping ejecta particles (Z-model formulation) released from locations at which Phobos both overflows its Roche lobe and is inside that lobe (sub and anti-Mars points). Third body solar perturbations and high-order harmonics terms are implemented in a highly accurate ephemerides formulation to model the dynamical evolution of ejecta in the Mars gravity system, and chart locations of eventual reaccretions for comparison with Phobos crater morphology.
The slowest ejecta is found to reaccrete in multiple low-velocity chain-like clusters similar to catanae observed on Ganymede[2], Callisto[2] and Mars[3], on characteristic timescales of 1-10 years. The morphological similarity to linear pitted chains on Phobos suggests that this formation mechanism may constrain families of grooves that do not fit well to a tidal model for groove origin[4]. Ejecta released from a primordial Phobos orbit about Mars[5] do not result in catanae, implying that these are geologically recent and no older than Phobos's modern orbit. Work is ongoing to construct a more detailed correlation between sesquinary catenae and pitted grooves on Phobos, and possible source craters. Longitudinal and latitudinal variations in the location of the primary cratering event, velocity distributions from 1-10 km craters, orbital position with relation to Mars and conjunctions with Deimos are all treated as free parameters; catanae-like clusters are found in all cases. This persistence suggests that the creation of low-velocity, clustered impact structures from sesquinary ejecta is a relatively frequent process on Phobos; its effect on surface geology has implications for theories surrounding the origin of the families of grooves.
[1] Zahnle et al, 2008, *Icarus*. [2] Melosh & Schenk, 1993, *Nature*. [3] Ferrill et al, 2004, *GSA Today*. [4] Asphaug et al. 2015, *EPSC*. [5] Yoder, 1982, *Icarus*.

**Author(s): Michael Nayak[2]**, Erik Asphaug[1]
**Institution(s):** *1. Arizona State University , 2. University of California, Santa Cruz*

### 201.09 – Surface Evolution from Orbital Decay on Phobos

Phobos, the innermost satellite of Mars, displays an extensive system of grooves that are mostly symmetric about its sub-Mars point. Phobos is steadily spiraling inward due to the tides it raises, and will suffer tidal disruption before colliding with Mars. We calculate the surface stress field of the de-orbiting satellite and show that the first signs of tidal disruption are already present on its surface. Most of Phobos' prominent grooves have an excellent correlation with computed stress orientations. The model predicts an interior that has very low strength on the tidal evolution timescale, overlain by a ~10-100 m exterior shell that has elastic properties similar to lunar regolith.
Shortly after the Viking spacecraft obtained the first geomorphic images of Phobos, it was proposed that stresses from orbital decay cause grooves. But, assuming a homogeneous Phobos, it proved impossible to account for the build-up of failure stress in the exterior regardless of the value assumed for Phobos' rigidity. Hence, the tidal model languished. Here, we revisit the tidal origin of surface fractures with a more detailed treatment that shows the production of significant stress in a surface layer, with a very strong correlation to the geometry of grooves.
Our model results applied to surface observations imply that Phobos has a rubble pile interior that is nearly strengthless. A lunar-like cohesive regolith outer layer overlays the rubble pile interior. This outer layer behaves elastically and can experience significant tidal stress at levels able to drive tensile failure. Fissures can develop as the global body deforms due to increasing tides related to orbital decay. Phobos may have an active and evolving surface; an exciting target for further exploration. The interior predictions of this model can be evaluated by future detailed studies performed by an orbiter or lander.

**Author(s): Terry Hurford4**, Erik Asphaug[1], Joseph Spitale5, Douglas Hemingway7, Alyssa Rhoden[1], Wade Henning4, Bruce Bills3, Simon Kattenhorn[2], Matthew Walker[6]
**Institution(s):** *1. Arizona State University, 2. ConocoPhillips Company, 3. JPL, 4. NASA GSFC, 5. Planetary Science Institute, 6. University of California, Los Angeles, 7. University of California, Santa Cruz*

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## 202 – EPO - Scientists' Showcase

### 202.01 – Science Communication at NASA

Scientists usually excel in a particular discipline, but generally have a difficult time informing and engaging the public about what we do. From climate science to natural hazards risks, our science does affect people's lives. Within NASA, we have started science communications training, focusing on how to tell a clear story about not just what we do, but why we do it. This not only will help us better communicate to our stakeholders and the public, but also hopefully make for better communications within our diverse teams.

**Author(s): Ellen R. Stofan[1]**
**Institution(s):** *1. NASA*

### 202.02 – Confessions of an Accidental E/POnomer, from in Front of the Camera and Behind the Pixels

The various techniques, styles, and venues for popularizing the research outputs from our planetary science community reflect the diversity of the community itself. While some are eloquent public speakers or gifted writers, other colleagues are regularly sought for television appearances or for artwork to illustrate press releases. Whatever the method or medium, the collection of experiences we have had in 'getting the word out' represents a valuable resource pool of ideas and lessons learned from which we can all learn and improve. I will share some of my experiences from working with a number of television productions and magazine editors, with some thoughts on contemporary television production styles. I will also discuss life as both a planetary scientist and digital artist and share some resources that are ready, willing, and quite able to help tell the visual story of your research.

**Author(s): Daniel D. Durda[1]**
**Institution(s):** *1. Southwest Research Inst.*

### 202.03 – Hazardous Asteroids: Cloaking STEM Skills Training within an Attention-Grabbing Science/Math Course

A graduate-level course was designed and taught during the summer months from 2009 – 2015 in order to contribute to the training and professional development of K-12 teachers residing in the Southwest. The teachers were seeking Master's degrees via the New Mexico Institute of Mining and Technology's (NMT's) Masters of Science Teaching (MST) program, and the course satisfied a science or math requirement. The MST program provides opportunities for in-service teachers to enhance their content backgrounds in science, mathematics, engineering, and technology (SMET). The ultimate goal is to assist teachers in

gaining knowledge that has direct application in the classroom. The engaging topic area of near-Earth object (NEO) characterization studies was used to create a fun and exciting framework for mastering basic skills and concepts in physics and astronomy. The objective was to offer a class that had the appropriate science rigor (with an emphasis on mathematics) within a non-threatening format. The course, entitled "Hazardous Asteroids", incorporates a basic planetary physics curriculum, with challenging laboratories that include a heavy emphasis on math and technology. Since the authors run a NASA-funded NEO research and follow-up program, also folded into the course is the use of the Magdalena Ridge Observatory's 2.4-meter telescope so participants can take and reduce their own data on a near-Earth asteroid.
In exit assessments, the participants have given the course excellent ratings for design and implementation, and the overall degree of satisfaction was high. This validates that a well-constructed (and rigorous) course can be effective in receptively reaching teachers in need of basic skills refreshment. Many of the teachers taking the course were employed in school districts serving at-risk or under-prepared students, and the course helped provide them with the confidence vital to developing new strategies for successful teaching.

**Author(s): Eileen V. Ryan[1]**, William H. Ryan[1]
**Institution(s):** *1. NM Tech/MRO*

### 202.04 – Blending Entertainment, Education, and Science in a Modern Digital Planetarium

Students at the University of Arizona have a relatively rare opportunity to learn in a state-of-the-art planetarium. Originally opened as a campus planetarium in 1975, the Flandrau Science Center recently expanded into the digital realm. In 2014 Flandrau's antique Minolta star projector was joined by a full-dome 4K digital projection system powered by a high performance computer cluster. Currently three science courses are taught in the planetarium for non-science majors — stellar astronomy, astrobiology, and planetary science (taught by SJK).
The new digital system allows us to take our classes off the surface of Earth on a journey into the cosmos. Databases from dozens of spacecraft missions and deep-space telescopic surveys are tapped by the software to generate a realistic immersive 3D perspective of the universe, from local planets, satellites and rings to distant stars and galaxies all the way out to the limit of the visible universe. Simple clicks of a mouse allow us to change the orientation, trajectory, and speed of the virtual spacecraft, giving our students diverse views of different phenomena.
The challenge with this system is harnessing the entertainment aspect for educational purposes. The visualization capabilities allow us to artificially enhance certain features and time scales. For example, the sizes of Earth and the moon can be enlarged on-the-fly to help demonstrate phases and eclipses. Polar axes and latitude lines can be added to Earth as it orbits the sun to help convey the reasons for seasons. Orbital paths can be highlighted to allow students to more accurately comprehend the population of near-Earth asteroids.
These new immersive computer-generated visualization techniques have the potential to enhance comprehension in science education, especially for concepts involving 3D spatial and temporal relationships. Whether or not this potential is being realized will require studies to gauge student learning and retention beyond the short-term semester-long course. This work is just beginning.

**Author(s): Stephen J. Kortenkamp[1]**
**Institution(s):** *1. Planetary Science Institute*

### 202.05 – Going Above & Beyond: Astronomy as the Public's Gateway to Science

Many of the world's most pressing scientific issues fall outside the purview of astronomy. Climate change, vaccination, genetic modification, and other similar topics are embroiled in the trenches of an ideological war in the public sphere, which creates a sometimes-insurmountable obstacle to discussion. This talk will describe a show series developed at Fiske Planetarium that uses the public's remarkable appetite for space content as a means for engaging indirectly with these contentious topics. It also promotes the planetarium as a place for interdisciplinary learning and offers the opportunity for the broader population to engage with young scientists in a different light.

**Author(s): Morgan Rehnberg[1]**
**Institution(s):** *1. CU/LASP*

### 202.06 – Investigating Changes in Students' Attitudes Towards Science During an Adaptive Online Astrobiology Course

Online education is an emergent sector of formal education and Arizona State University (ASU) is a leader in offering online courses. One that garners very strong positive feedback on student surveys is Habitable Worlds, which is an interdisciplinary online science course offered every semester since Fall 2011. Primary goals of this course are to teach understanding of scientific reasoning and practices by using principles from trans-disciplinary research in astrobiology. To examine course outcomes we administered the Classroom Undergraduate Research Experience (CURE) survey, which has been previously developed to measure student experiences. Here we use the survey for the first time for an online course. The survey was taken before and after completing the course during the Fall 2014 and Spring 2015 semesters (N = 544). Here, we present students' views of science represented by 22 questions on the survey. For the questions, students responded either "not applicable," "strongly disagree," "disagree," "neutral," "agree," or "strongly agree." In order to interpret the data, we divided the questions into three broader categories for analysis: students' understanding of the scientific process, students' scientific self-efficacy and students' views on science teaching. We study how the sample of students changed their responses to each of the questions as a group by using a paired-samples sign test to gauge the statistical significance of the difference between pre and post responses. We further analyze how individual students changed their responses. For example, we designated a change from "strongly disagree" to "disagree" differently than a change from "agree" to "disagree" since the latter indicated a notable change in the student's opinion. We found statistically significant changes on 12 of the 22 questions. These early results indicate that there are measurable changes on several identified course objectives. By measuring changes that occurred to the whole group of students as well as identifying in detail what type of changes occurred from student to student for each question, we will be able to improve future offerings of the course as well as to make broader conclusions about online science education.

**Author(s): Viranga Perera[1]**, Sanlyn R Buxner3, Lev Horodyskyj[1], Ariel Anbar[1], Steven Semken[1], Chris Mead[1], David Lopatto[2]
**Institution(s):** *1. Arizona State University, 2. Grinnell College, 3. University of Arizona*

### 202.07 – The Arecibo Observatory Space Academy

The Arecibo Observatory Space Academy (AOSA) is a ten (10) week pre-college research program for students in grades 9-12. Our mission is to prepare students for academic and professional careers by allowing them to receive an independent and collaborative research experience on topics related to space and aide in their individual academic and social development. Our objectives are to (1) Supplement the student's STEM education via inquiry-based learning and indirect teaching methods, (2) Immerse students in an ESL environment, further developing their verbal and written presentation skills, and (3) To foster in every student an interest in science by exploiting their natural curiosity and knowledge in order to further develop their critical thinking and investigation skills. AOSA provides students with the opportunity to share lectures with Arecibo Observatory staff, who have expertise in various STEM fields. Each Fall and Spring semester, selected high school students, or Cadets, from all over Puerto Rico participate in this Saturday academy where they receive experience designing, proposing, and carrying out research projects related to space exploration, focusing on four fields: Physics/Astronomy, Biology, Engineering, and Sociology. Cadets get the opportunity to explore their topic of choice while practicing many of the foundations of scientific research with the goal of designing a space settlement, which they present at the NSS-NASA Ames Space Settlement Design Contest. At the end of each semester students present their research to their peers, program mentors, and Arecibo Observatory staff. Funding for this program is provided by NASA SSERVI-LPI: Center for Lunar Science and Exploration with partial support from the Angel Ramos Visitor Center through UMET and management by USRA.

**Author(s): Linda A. Rodriguez-Ford[1]**, Luisa Zambrano-Marin[1], Bryan M. Petty[1], Elizabeth Sternke[1], Andrew M. Ortiz[1], Edgard G. Rivera-Valentin[1]
**Institution(s):** *1. Arecibo Observatory*

### 202.08 – Promoting Diversity in STEM through Active Recruiting and Mentoring: The Pre-Major in Astronomy Program (Pre-MAP) at the University of Washington

The Pre-Major in Astronomy Program (Pre-MAP) is a research and mentoring program for underclassmen and transfer students offered by the University of Washington Astronomy Department since 2005. The primary goal of Pre-MAP is to recruit and retain students from groups traditionally underrepresented in science, technology, engineering, and mathematics (STEM) through early exposure to research. The Pre-MAP seminar is the core component of the program and offers instruction in computing skills, data manipulation, science writing, statistical analysis, and scientific speaking and presentation skills. Students choose research projects proposed by faculty, post-docs and graduate students in areas related to astrophysics, planetary science, and astrobiology. Pre-MAP has been successful in retaining underrepresented students in STEM fields relative to the broader UW population, and we've found these students are more likely to graduate and excel academically than their peers. As of spring 2015, more than one hundred students have taken the Pre-MAP seminar, and both internal and external evaluations have shown that all groups of participating students report an increased interest in astronomy and science careers at the end of the seminar. Several former Pre-MAP students have obtained or are pursuing doctoral and master's degrees in STEM fields; many more work at NASA centers, teaching colleges, or as engineers or data analysts. Pre-MAP student research has produced dozens of publications in peer-reviewed research journals. This talk will provide an overview of the program: the structure of the seminar, examples of projects completed by students, cohort-building activities outside the seminar, funding sources, recruitment strategies, and the aggregate demographic and achievement data of our students. It is our hope that similar programs may be adopted successfully at other institutions.

**Author(s): Edward Schwieterman[1]**, Breanna Binder[1], Michael Tremmel[1], Kristen Garofali[1], Eric Agol[1], Victoria Meadows[1]
**Institution(s):** *1. University of Washington*

### 202.09 – Scientist-Educator Partnerships: the Cornerstone of Astrophysics E/PO

For nearly two decades, NASA has partnered scientists and educators by embedding Education and Public Outreach (E/PO) programs and funding in its science missions and research activities. This enables scientist and educators to work side-by-side in translating cutting-edge NASA science and technology for classrooms, museums, and public venues.

The Office of Public Outreach at the Space Telescope Science Institute (STScI) is uniquely poised to foster collaboration between scientists with content expertise and educators with pedagogy expertise. As home to both Hubble Space Telescope and the future James Webb Space Telescope, STScI leverages the expertise of its scientists to create partnerships with its collocated Education Team to translate cutting-edge NASA science into new and effective learning tools. In addition, STScI is home of the NASA Science Mission Directorate (SMD) Astrophysics Science E/PO Forum, which facilitates connections both within the SMD E/PO community and beyond to scientists and educators across all NASA Astrophysics missions. These collaborations strengthen partnerships, build best practices, and enhance coherence for NASA SMD-funded E/PO missions and programs.

We will present examples of astronomers' engagement in our E/PO efforts, such as NASA Science4Girls.

**Author(s): Bonnie K. Meinke[1]**, Denise A Smith[1], Brandon Lawton[1], Bonnie Eisenhamer[1], Hussein Jirdeh[1]
**Institution(s):** *1. STScI*

## 203 – Centaurs, Trans-Neptunian Objects, and the Inner Oort Cloud

### 203.01 – Rotational properties of the Haumea family members and candidates: Short-term variability

Haumea is one of the largest known Trans-Neptunian Objects (TNOs) with several anomalous characteristics. It is a fast rotator with a double-peak period of 3.92 h. Its spectrum is dominated by water ice features and the high albedo suggests nearly pure water ice on the surface. It has two known satellites and a family of at least ten TNOs with very similar proper orbital parameters and spectral properties. The formation of this peculiar family (Haumea, its two moons and, dynamically related bodies) is not well understood despite various models that have been proposed during the past few years.
In order to improve our understanding of the formation of this family, we have examined the rotational properties of the family members and candidates (i.e. objects with similar proper orbital elements to the family members but without water ice on their surface or without observations to detect surface water). We report new short-term variability for 5 family members and 7 candidates from data collected over the past five years using multiple ground-based facilities. Thanks to our study, all the Haumea family members have a short-term variability study.
From rotational data, assuming fluid-like rubble-pile structure, we constrain ellipsoidal axis ratios for individual objects and set a lower limit to densities. We also compared lightcurve amplitude and rotational frequency distributions for the family members, candidates, and unrelated TNOs to search for additional clues to the progenitor and the formation of this family.

**Author(s): Audrey Thirouin3**, Scott S. Sheppard[1], Keith S. Noll4, Nicholas A. Moskovitz3, Alain Doressoundiram [2]
**Institution(s):** *1. DTM Carnegie Institution for Science, 2. LESIA - Observatory of Paris, 3. Lowell Observatory, 4. NASA-Goddard Space Flight Center*

### 203.02 – Near-Infrared and Optical colors of Trans-Neptunian Objects and Centaurs from Ground-Based Observations in Support of Spitzer Observations

Trans-Neptunian objects and Centaurs are small icy bodies located beyond the orbit of Neptune and between the orbits of Neptune and Jupiter, respectively. These objects are composed of organic material, of silicate minerals and of different ices, including $H_2O$, $CH_4$, $N_2$ and $CH_3OH$. Determining the composition of such object usually requires spectroscopic measurements on large telescopes. However, we can constrain the compositions of these objects by measuring their near-infrared colors that -- in combination with existing data from the Spitzer Space Telescope -- can indicate surface composition.. We will present near-infrared magnitudes and colors of at least 24 trans-Neptunian objects and 3 Centaurs obtained in ground-based observations. We observed with Gemini, UKIRT, and the 90" Bok Telescope on Kitt Peak between 2011 and 2015. The combination of our data with existing Spitzer Space Telescope data enables us to identify spectral slope up to 4.5 µm and provides rough information on spectral bands, which are important clues on the surface composition of our targets. We will present preliminary results on the compositional analysis for select targets. This work was supported by the Spitzer Science Center and NASA's Planetary Astronomy program.

**Author(s): Cassandra Lejoly3**, Michael Mommert3, David Trilling3, Noemi Pinilla-Alonso[2], Josh Emery[2], Chad Melton3, Don McCarthy[1], Craig Kulesa[1]
**Institution(s):** *1. Department of Astronomy - University of Arizona, 2. Department of Earth and Planetary Science - University of Tennessee, 3. Department of Physics and Astronomy - Northern Arizona University*

## 203.03 – The color-magnitude distribution of small Kuiper Belt objects

Occupying a vast region beyond the ice giants is an extensive swarm of minor bodies known as the Kuiper Belt. Enigmatic in their formation, composition, and evolution, these Kuiper Belt objects (KBOs) lie at the intersection of many of the most important topics in planetary science. Improved instruments and large-scale surveys have revealed a complex dynamical picture of the Kuiper Belt. Meanwhile, photometric studies have indicated that small KBOs display a wide range of colors, which may reflect a chemically diverse initial accretion environment and provide important clues to constraining the surface compositions of these objects. Notably, some recent work has shown evidence for bimodality in the colors of non-cold classical KBOs, which would have major implications for the formation and subsequent evolution of the entire KBO population. However, these previous color measurements are few and mostly come from targeted observations of known objects. As a consequence, the effect of observational biases cannot be readily removed, preventing one from obtaining an accurate picture of the true color distribution of the KBOs as a whole.
We carried out a survey of KBOs using the Hyper Suprime-Cam instrument on the 8.2-meter Subaru telescope. Our observing fields targeted regions away from the ecliptic plane so as to avoid contamination from cold classical KBOs. Each field was imaged in both the *g'* and *i'* filters, which allowed us to calculate the *g'*-*i'* color of each detected object. We detected more than 500 KBOs over two nights of observation, with absolute magnitudes from $H$=6 to $H$=11. Our survey increases the number of KBOs fainter than $H$=8 with known colors by more than an order of magnitude. We find that the distribution of colors demonstrates a robust bimodality across the entire observed range of KBO sizes, from which we can categorize individual objects into two color sub-populations -- the red and very-red KBOs. We present the very first analysis of the magnitude distributions of the two color sub-populations.

**Author(s): Ian Wong[1]**, Michael E Brown[1]
**Institution(s):** *1. CALTECH*

## 203.04 – The Outer Solar System Origins Survey: cold classicals beyond the 2:1 resonance

With the 85 characterised discoveries from the first quarter of the ongoing Outer Solar System Origins Survey (OSSOS) with MegaPrime on the Canada-France-Hawaii Telescope, we find that the CFEPS L7 model of Petit et al. 2011 remains an accurate parameterization of the classical Kuiper belt's orbital structure, and the population estimate for the main belt remains unchanged (for 39 AU < a < 47 AU). We independently confirm the existence of substructure within the main classical Kuiper belt. The semi-major axis distribution of the stirred component of the cold classicals must contain a clumped ‘kernel’.
We detect an extension of the cold classical Kuiper belt that continues at least several AU beyond the 2:1 mean motion resonance with Neptune. This extension would have strong cosmogonic implications for the origin of the classical belt's orbital substructure.
We will discuss how the 140 new objects we discovered in the second quarter of OSSOS place further constraints on cold classicals beyond the 2:1 resonance. Our 16-18 month observational arcs and improved astrometric technique continue to achieve extremely high-quality measurements of TNO orbits: fractional semimajor axis uncertainties of our discoveries are consistently in the range 0.01-0.1%, allowing rapid orbital classification.

**Author(s): Michele T Bannister[6]**, J J Kavelaars[6], Brett Gladman5, Jean- Marc Petit[2], Stephen Gwyn3, Kathryn Volk4, Ying- Tung Chen[1], Mike Alexandersen5
**Institution(s):** *1. ASIAA, 2. Institut UTINAM - UMR CNRS, 3. NRC Herzberg, 4. University of Arizona, 5. University of British Columbia, 6. University of Victoria*

## 203.05 – Resonant Trans-Neptunian Populations: Constraints from the first quarter of the Outer Solar System Origins Survey

The first two observational sky "blocks" of the Outer Solar System Origins Survey (OSSOS) have nearly doubled the set of well-characterized observed trans-Neptunian objects (TNOs) that occupy mean motion resonances with Neptune. We describe the 31 securely (plus 8 insecurely) resonant TNOs detected by OSSOS so far and use them to independently verify the resonant population models from the Canada France Ecliptic Plane Survey, with which we find broad agreement. One of the OSSOS blocks described here is well-suited to detecting objects trapped at very low libration amplitudes in Neptune's 3:2 mean motion resonance, a dynamical population of interest in testing the origins of resonant TNOs. We have detected three plutinos (3:2 objects) with libration amplitudes less than 20 degrees, which requires that plutino libration amplitude distribution be extended to lower values. Using the OSSOS detections of 5:2 objects, we confirm that this resonance is more populated than predicted by models of the outer Solar System's early dynamical history; our minimum population estimate shows that just the high eccentricity (e>0.35) portion of the resonance are at least as populous as the 2:1 resonance, and possibly as populated as the 3:2 resonance. The OSSOS 2:1 detections confirm that the 2:1 resonance has a dynamically colder inclination distribution than either the 3:2 or 5:2 resonances. Using the combination of OSSOS and CFEPS detections of 2:1 objects, we constrain the fraction of 2:1 objects in the symmetric mode of libration to be 0.2--0.85 (the rest being asymmetric); we also constrain the ratio of leading to trailing asymmetric librators (a ratio that has been theoretically predicted to vary depending on Neptune's migration history) to be 0.05--0.8 at 95% confidence. These constraints will be improved by future OSSOS blocks.

**Author(s): Kathryn Volk[6]**, Ruth Murray-Clay[8], Brett Gladman7, Samantha Lawler9, Michele Bannister9, J.J. Kavelaars9, Jean-Marc Petit5, Stephen Gwyn4, Mike Alexandersen7, Ying-Tung Chen[1], Patryk Sofia Lykawka[2], Wing Ip3, Hsing Wen Lin3
**Institution(s):** *1. Academia Sinica, 2. Kinki University, 3. National Central University, 4. NRC-Herzberg, 5. Observatoire de Besancon, Universite de Franche Comte, 6. The University of Arizona, 7. University of British Columbia, 8. University of California Santa Barbara, 9. University of Victoria*

## 203.06D – Exploring the Outer Neptune Resonances: Constraints on Solar System Evolution

The long-term evolution of objects in the outer n:1 resonances with Neptune provide clues to the evolutionary history of the Solar System. Based on 4 objects with semi-major axes near the 5:1 resonance, we estimate a substantial and previously unrecognized population of objects, perhaps more significant than the population in the 3:2 (Plutino) resonance. These external resonances are largely unexplored in both observations and dynamical simulations. However, understanding the characteristics and trapping history for objects in these populations is critical for constraining the dynamical history of the solar system. The 4 objects detected in the Canada-France Ecliptic Plane Survey (CFEPS) were classified using dynamical integrations. Three are resonant, and the fourth appears to be a resonance diffusion object, part of a population which exited the resonance through chaotic diffusion. The 3 resonant objects are taken to be representative of the resonant population, so by using these detections and the CFEPS characterization (pointings and detection limits) we calculate a population estimate for this resonance at ~1900(+3300 -1400) objects with Hg<8 [Pike et al.

2015]. This is at least as large as the Plutinos (3:2 resonance) at 90% confidence. The small number of detected objects results in such a large population estimate due to the numerous biases against detecting objects with semimajor axes at ~88AU. The dynamical behavior of the known objects, suggests that the trapping mechanism for the 5:1 resonance is resonance sticking from the scattering objects. Based on our results from the 5:1 resonance, we have begun a project to examine the long term evolution of the other n:1 resonances to determine the importance of resonance diffusion and transfer between libration islands among the scattering-captured members of those populations.

**Author(s): Rosemary E. Pike[6]**, JJ Kavelaars3, Cory J. Shankman[6], Jean-Marc Petit[1], Gladman Brett5, Kat Volk4, Mike Alexandersen[2]
**Institution(s):** *1. Institut UTINAM, 2. Institute of Astronomy & Astrophysics, Academia Sinica, 3. NRC Herzberg, 4. University of Arizona, 5. University of British Columbia, 6. University of Victoria*

### 203.07 – Searching for Extreme Kuiper Belt Objects and Inner Oort Cloud Objects

Since late 2012 we have been performing the largest and deepest survey for distant solar system objects. In the nearly one thousand square degrees we have covered so far we have discovered the object with the most distant perihelion known (2012 VP113), several extreme Kuiper Belt objects with moderate perihelia and large eccentricities, one of the top ten intrinsically brightest Trans-Neptunian objects, an ultra-wide Kuiper Belt binary, one of the most distant known active comets and two active asteroids in the main belt of asteroids. The Kuiper Belt population has an outer edge at about 50 AU. Sedna and our recent discovery, 2012 VP113, are the only known objects with perihelia significantly beyond this edge at about 80 AU. These inner Oort cloud objects obtained their orbits when the solar system was vastly different from now. Thus the dynamical and physical properties of objects in this region offer key constraints on the formation and evolution of our solar system. We will discuss the most recent results of our survey.

**Author(s): Scott S. Sheppard[1]**, Chad Trujillo[2], Dave Tholen3
**Institution(s):** *1. Carnegie Inst. of Washington, 2. Gemini Observatory, 3. University of Hawaii*

### 203.08 – Three steps toward understanding the dynamical structure of the Kuiper belt (and what it means for Neptune's migration)

Much of the dynamical structure of the Kuiper belt can be explained if Neptune migrated over several AU, and/or if Neptune was scattered to an eccentric orbit during planetary instability.
Step 1: An outstanding problem with the previous migration/instability models is that the distribution of orbital inclinations they predict is narrower than the one inferred from observations. Here we perform numerical simulations of the Kuiper belt formation starting from an initial state with Neptune at 20<a_N<30 AU and a dynamically cold outer disk extending from beyond a_N to 30 AU. Neptune's orbit is migrated into the disk on an e-folding timescale 1 < tau < 100 Myr. A small fraction of the disk planetesimals become implanted into the Kuiper belt in the simulations. We find that the inclination constraint implies that Neptune's migration was slow (tau > 10 Myr) and long range (a_N < 25 AU).
Step 2: A particularly puzzling and up-to-now unexplained feature of the Kuiper belt is the so-called `kernel', a concentration of orbits with semimajor axes a=44 AU, eccentricities e=0.05, and inclinations i<5 deg. Here we show that the Kuiper belt kernel can be explained if Neptune's migration was interrupted by a discontinuous change of Neptune's semimajor axis when Neptune reached 28 AU (jumping-Neptune model).
Step 3: The existing migration/instability models invariably predict an excessively large resonant population, while observations show that the non-resonant orbits are in fact more common (e.g., Plutinos in the 3:2 resonance represent only ~1/3 of the main belt population). Here we show that the observed population statistic implies that Neptune's migration was grainy, as expected from scattering encounters of Neptune with massive planetesimals. Our preferred fit to observations suggests that the outer planetesimal disk below 30 AU contained ~2000 bodies with mass comparable to that of Pluto.
Together, these results imply that Neptune's migration was slow, long-range and grainy, and that Neptune radially jumped by ~0.5 AU when it reached 28 AU. This is consistent with Neptune's orbital evolution obtained in the recently developed models of planetary instability/migration (Nesvorny & Morbidelli 2012, AJ 144).

**Author(s): David Nesvorny[1]**
**Institution(s):** *1. SWRI*

### 203.09 – Into the Kuiper Belt: New Horizons Post-Pluto

New Horizons is now beyond Pluto and flying deeper into the Kuiper Belt. In the summer of 2014, a Hubble Space Telescope Large Program identified two candidate Cold Classical Kuiper Belt Objects (KBOs) that were within reach of New Horizons' remaining fuel budget. Here we present the selection of the Kuiper Belt flyby target for New Horizons' post-Pluto mission, our state of knowledge regarding this target and the potential 2019 flyby, the status of New Horizons' targeting maneuver, and prospects for near-future long-range observations of other KBOs.

**Author(s): Alex Harrison Parker[10]**, John Spencer[10], Susan Benecchi[8], Richard Binzel4, David Borncamp[11], Marc Buie[10], Cesar Fuentes5, Stephen Gwyn[6], JJ Kavelaars[6], Keith Noll[1], Jean-Marc Petit7, Simon Porter[10], Mark Showalter9, S Alan Stern[10], Ray Sterner3, David Tholen[2], Anne Verbiscer[12], Hal Weaver3, Amanda Zangari[10]
**Institution(s):** *1. GSFC, 2. IfA, 3. JHU-APL, 4. MIT, 5. NAU, 6. NRC, 7. Observatoire de Besancon, 8. PSI, 9. SETI Institute, 10. Southwest Research Institute, 11. STScI, 12. University of Virginia*

## 204 – Asteroid Radar & Thermal Studies: Microwaved and Served Hot

### 204.01 – Thermal inertia of eclipsing binary asteroids: the role of component shape

Thermal inertia controls the temperature distribution on asteroid surfaces. This is of crucial importance to the Yarkovsky effect and for the planning of spacecraft operations on or near the surface. Additionally, thermal inertia is a sensitive indicator for regolith structure.
A uniquely direct way of measuring thermal inertia is through observations of the thermal response to an eclipse in a binary system, when one component shadows the other. This method was pioneered by Mueller et al. (2010), who observed eclipses in (617) Patroclus using Spitzer IRS. Buie et al. (2015) report observations of a stellar occultation by Patroclus. Their estimate for the system's projected size agrees well with the Spitzer result. However, the occultation revealed that the components are much more oblately shaped than was assumed by Mueller et al.
This prompted us to study the role of component shape in the analysis of thermal eclipse data. Conceivably, the global shape can have a significant impact on the shape and size of the eclipsed area and therefore on its thermal emission. So far, this has not been studied in a systematic way. Using Patroclus and the existing Spitzer data as our test case, we vary the ellipsoidal component shape and determine the resulting best-fit thermal inertia. This will lead to an updated estimate of Patroclus' thermal inertia, along with a potentially more realistic estimate of its uncertainty. Beyond that, our results will inform ongoing and future thermal studies of other eclipsing binary asteroids.

**Author(s): Michael Mueller[1]**, Marlies van de Weijgaert[1]
**Institution(s):** *1. Kapteyn Astronomical Institute, U Groningen*

### 204.02 – Modeling the thermal emission from asteroid 3 Juno using ALMA observations and the KRC thermal model

Asteroid 3 Juno (hereafter referred to as Juno), discovered 1 September 1804, is the 11th largest asteroid in the Main Asteroid Belt (MAB). Containing approximately 1% of the mass in the MAB [1], Juno is the second largest S-type [2].
As part of the observations acquired from Atacama Large Millimeter/submillimeter Array (ALMA) [3], 10 reconstructed images at ~60km/pixel resolution were acquired of Juno [4] that showed significant deviations from the Standard Thermal Model (STM) [5]. These deviations could be a result of surface topography, albedo variations, emissivity variations, thermal inertia variations, or any combination.
The KRC thermal model [6, 7], which has been extensively used for Mars [e.g. 8, 9] and has been applied to Vesta [10] and Ceres [11], will be used to compare model thermal emission to that observed by ALMA at a wavelength of 1.33 mm [4]. The 10 images, acquired over a four hour period, captured ~55% of Juno's 7.21 hour rotation. Variations in temperature as a function of local time will be used to constrain the source of the thermal emission deviations from the STM.
This work is supported by the NASA Solar System Observations Program.
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**Author(s): Timothy N. Titus3**, Jian-Yang Li2, Arielle Moullet1, Mark V. Sykes2
**Institution(s):** *1. National Radio Astronomy Observatory, 2. Planetary Science Institute, 3. U.S. Geological Survey*

### 204.03 – Characterizing Asteroid Thermal Properties through the Laboratory Study of Meteorites

Asteroid thermal diffusivity is critical to understanding its thermal evolution, and thermal inertia determines its behavior under Yarkovsky effects. These properties are both functions of thermal conductivity, heat capacity, and density. Thermal conductivity and heat capacity both vary with temperature, while thermal conductivity and density are strongly influenced by microporosity. Our survey of low-temperature (175K) heat capacities includes more than 130 meteorites, supplemented by precision temperature-sensitive heat capacities for 6 individual samples. Heat capacities (175K) range from 350 J/kgK for unweathered iron meteorites to 530 J/kgK, with most chondrites between 480 and 520 J/kgK. Heat capacities for unweathered ordinary chondrite falls are within 5% of theoretical models, and as a function of temperature fit a theoretical curve of $C_p=A+BT+CT^{(-2)}+DT^{(-0.5)}$ between 77 and 300 K, and are consistent with mineral data between 20 and 300 K. (Values for A,B,C,D vary by meteorite type.)
Thermal conductivities are strong functions of porosity and, below 90 K, strong functions of temperature. Laboratory measurements of several meteorites indicate that between 90 and 300 K, most thermal conductivities vary little with temperature. Below 90 K, thermal conductivity drops off strongly as temperature decreases. Above 2% porosity and 90 K, thermal conductivities correlate linearly with the inverse of porosity. Pore geometry and orientation also affects thermal conductivity; thermal conductivity differs noticeably for the same meteorite sample depending on the direction of heat flow.
Given these relations and meteorite data, thermal diffusivity and thermal inertia can be derived over a range of porosities and temperatures for most asteroids. We see that porosity greatly influences both thermal diffusivity and thermal inertia. Even as little as 20% porosity can reduce thermal diffusivity by two orders of magnitude from the nonporous case.

**Author(s): Robert J. Macke3**, Guy J. Consolmagno3, Cyril P. Opeil1, Daniel T. Britt2
**Institution(s):** *1. Boston College, 2. University of Central Florida, 3. Vatican Observatory*

### 204.04 – The Spherical Brazil Nut Effect and its Significance to Asteroids

Asteroids are intriguing remnant objects from the early solar system. They can inform us on how planets formed, they could possibly impact the earth in the future, and they likely contain precious metals; for those reasons, there will be future exploration and mining space missions to them. Telescopic observations and spacecraft data have helped us understand basic properties such as their size, mass, spin rate, orbital elements, and their surface properties. However, their interior structures have remained elusive. In order to fully characterize the interiors of these bodies, seismic data will be necessary. However, we can infer their interior structures by combining several key factors that we know about them: 1). Past work has shown that asteroids between 150 m to 10 km in size are rubble-piles that are a collection of particles held together by gravity and possibly cohesion. 2). Asteroid surfaces show cratering that suggests that past impacts would have seismically shaken these bodies. 3). Spacecraft images show that some asteroids have large protruding boulders on their surfaces. A rubble-pile object made of particles of different sizes and that undergoes seismic shaking will experience granular flow. Specifically, a size sorting effect known as the Brazil Nut Effect will lead larger particles to move towards the surface while smaller particles will move downwards. Previous work has suggested that this effect could possibly explain not only why there are large boulders on the surfaces of some asteroids but also might suggest that the interior particles of these bodies would be organized by size. Previous works have conducted computer simulations and lab experiments; however, all the particle configurations used have been either cylindrical or rectangular boxes. In this work we present a spherical configuration of self-gravitating particles that is a better representation of asteroids. Our results indicate that while friction is not necessary for the Brazil Nut Effect to take place, it aids the sorting process after a certain energy threshold is met. Even though we find that the outer layers of asteroids could possibly be size sorted, the inner regions are likely mixed.

**Author(s): Viranga Perera1**, Alan P Jackson1, Erik Asphaug1, Ronald-Louis Ballouz2
**Institution(s):** *1. Arizona State University, 2. University of Maryland*

### 204.05 – An Investigation of 2D Electrostatic Dust Levitation about Bennu

Electrostatic dust levitation has been hypothesized to occur near the surface of asteroids, due to the interaction of the solar wind plasma and UV radiation with the asteroids' surfaces and their near-zero surficial gravity. Dust levitation could provide a mechanism to move regolith across the surface of an asteroid. Our preliminary investigations have identified grains sizes and the altitudes at which grains may levitate considering a semi-analytical 1D plasma model. However, our initial semi-analytical plasma model was not well-suited to the complex terminator region, where the surface transitions between positive (dominated by photoemission) and negative (in the plasma wake) potentials. In this analysis, we use a new 2D treecode-based plasma simulation to more accurately model the plasma environment about a simplified circular cross-section of the asteroid Bennu. We investigate the altitudes and grain sizes where electrostatic levitation could occur at Bennu. The improved plasma model will allow more accurate predictions of dust levitation and deposition, particularly in the terminator and wake regions that could not be characterized be earlier plasma models.

**Author(s): Christine Hartzell[2]**, Michael Zimmerman[1]
**Institution(s):** *1. Johns Hopkins University Applied Physics Laboratory, 2. University of Maryland*

### 204.06D – On physical properties of planetary surfaces studied by modeling radar scattering

After decades of post-discovery characterization and orbital refinement of near-Earth objects using planetary radars, extensive literature describing the radar scattering properties of various objects of the Solar System has become available. At the same time, there is a shortage of work on what the observed values imply about the physical properties of the planetary surfaces. Our goal is to fill part of this gap.
We investigate, which physical properties of a planetary surface or small body affect the radar echo and how. All of the work will be carried out by modeling electromagnetic scattering with the primary focus in the backscattering direction. As all models are only simplifications of the real world, it is necessary to study, which models are the best analogies to observations. Moreover, the number of scattering scenarios is near infinite, but numerical resources are limited. Due to the limitations of specific codes, several different codes are used.
The simulations reveal, in the backscattering direction, polarization enhancement at certain bands of sizes and refractive indices. By studying spherical inhomogeneous particles, we found that the electric permittivity defines the phase shift caused by the scatterer, and hence, the depolarizing capability of the scatterer. By using large, irregular particles as the scatterers, a systematic effect of the absorption on the radar observables can be seen, which leads to a semi-analytic, novel form of the radar scattering laws. By using small (wavelength-scale) irregular particles as internal or external diffuse medium inside or on the surface of a very large particle, radar scattering can be simulated very realistically. The results mainly support the current understanding of the effects of the surface geometry, the electric permittivity, and multiple scattering. We also explain how the electric permittivity can affect the radar albedo and circular-polarization ratio by phase shift and absorption. In addition, we show that, as the polarization is very sensitive to the scatterer geometry, simplifications made in the choice of the geometry can have unprecedented effects.

**Author(s): Anne Virkki[1]**, Karri Muinonen[1]
**Institution(s):** *1. University of Helsinki*

### 204.07 – Radar imaging of binary near-Earth asteroid (357439) 2004 BL86

We report radar imaging of near-Earth asteroid 2004 BL86 obtained at Goldstone, Arecibo, Green Bank, and elements of the Very Long Baseline Array between 2015 January 26-31. 2004 BL86 approached within 0.0080 au on January 26, the closest known approach by any object with an absolute magnitude brighter than ~19 until 2027. Prior to the encounter, virtually nothing was known about its physical properties other than its absolute magnitude of 19, which suggested a diameter within a factor of two of 500 m. 2004 BL86 was a very strong radar target that provided an outstanding opportunity for radar imaging and physical characterization. Delay-Doppler images with range resolutions as fine as 3.75 m placed thousands of pixels on the object and confirmed photometric results reported by Pravec et al. (2015, CBET 4063) that 2004 BL86 is a binary system. During the observations, the asteroid moved more than 90 deg and provided a range of viewing geometries. The bandwidth was relatively narrow on Jan. 26, reached a maximum on Jan. 27, and then narrowed on Jan. 28, a progression indicating that the subradar latitude moved across the equator during those days. The images reveal a rounded primary with an equatorial diameter of ~350 m, evidence for ridges, possible boulders, and a pronounced angular feature ~100 m in diameter near one of the poles. Images from Jan. 26 show arcs of radar-bright pixels on the approaching and receding limbs that extend well behind the trailing edge in the middle of the echo. This is the delay-Doppler signature of an oblate shape seen at least a few tens of degrees off the equator. A rough estimate for the diameter of the secondary is ~70 m and its narrow bandwidth is consistent with the 14-h orbital period reported by Pravec et al. (2015). The images are suitable for 3D shape, pole, orbit, and mass estimation. The observations utilized new data taking equipment at Green Bank to receive X-band (8560 MHz, 3.5 cm) transmissions from the 70 m DSS-14 facility, and, for the first time, transmissions using a new C-band (7190 MHz, 4.2 cm) radar at the 34 m DSS-13 antenna at the Goldstone complex.

**Author(s): Lance A. M. Benner[2]**, Marina Brozovic[2], Jon D. Giorgini[2], Patrick A. Taylor[1], Ellen S. Howell[1], Michael W. Busch[4], Michael C. Nolan[1], Joseph S. Jao[2], Clement G. Lee[2], H. Alyson Ford[3], Frank D. Ghigo[3]
**Institution(s):** *1. Arecibo Observatory, 2. JPL, 3. NRAO, 4. SETI Institute*

### 204.08 – Radar observations of near-Earth asteroid (436724) 2011 UW158 using the Arecibo, Goldstone, and Green Bank Telescopes

Near-Earth asteroid (436724) 2011 UW158 made a close approach to the Earth on 2015 July 19 at a distance of 0.016 au (6.4 lunar distances). We observed it between July 13-26 using the Arecibo S-band (2380 MHz, 12.5 cm) radar, the Goldstone X-band (8560 MHz, 3.5 cm) radar, and the Green Bank Telescope (GBT). Arecibo delay-Doppler observations achieved range resolutions as fine as 7.5 m. At the GBT, we used a newly installed radar backend to record the radar echoes, which improved signal-to-noise ratios (SNRs) two-fold relative to monostatic reception at the 70-m DSS-14 antenna at Goldstone. The higher SNRs allowed us to obtain images with range resolutions comparable to those at Arecibo that reveal the asteroid's surface topography with great detail. The visible extents of the asteroid in the radar images suggest an elongated object with dimensions of about 600 x 300 m. The shape of the object is angular with a facet on one side that spans the entire length of the asteroid. Three parallel radar-bright features are visible when the asteroid is oriented broadside and may represent ridges. These features cause unusually large brightness variations in the echo as the asteroid rotates. There are other radar-bright regions that suggest small-scale (tens of meters) topography. Repetition of the leading edge profiles in the images indicates a spin period of ~37 minutes, which is consistent with the period that was previously reported using lightcurves (B. Gary, T. Lister, H. K. Moon, P. Pravec, and B. D. Warner, pers. comm.). This spin period is unusually fast among asteroids its size and suggests that the object has relatively high cohesive strength. 2011 UW158 has a relatively low delta-V for spacecraft missions and is on NASA's Near-Earth Object Human Accessible Targets Study list.

**Author(s): Shantanu P Naidu[2]**, Lance A. M. Benner[2], Marina Brozovic[2], Jon D Giorgini[2], Joseph S Jao[2], Michael W Busch[4], Patrick A Taylor[1], James E Richardson[1], Edgard G Rivera-Valentin [1], Linda A Ford[1], Frank D Ghigo[3], Adam Kobelski[3]
**Institution(s):** *1. Arecibo Observatory, 2. Jet Propulsion Laboratory, California Institute of Technology, 3. NRAO, 4. SETI Institute*

### 204.09 – Potentially Hazardous Asteroid (85989) 1999 JD6: Radar, Infrared, and Lightcurve Observations and a Preliminary Shape Model

We report observations of potentially hazardous asteroid (85989) 1999 JD6, which passed 0.048 AU from Earth (19 lunar distances) during its close approach on July 25, 2015. During eleven days between July 15 and August 4, 2015, we observed 1999 JD6 with the Goldstone Solar System Radar and with Arecibo Observatory's planetary radar, including bistatic reception of some Goldstone echoes at Green Bank. We obtained delay-Doppler radar images at a wide range of latitudes, with range resolutions varying from 7.5 to 150 meters per pixel, depending on the observing conditions. We acquired near-infrared spectra from the NASA InfraRed Telescope Facility (IRTF) on two nights in July 2015, at wavelengths from 0.75 to 5.0 microns, showing JD6's thermal emission. We also obtained optical lightcurves from Ondrejov Observatory (in 1999), Table Mountain Observatory (in 2000), and Palmer Divide Station (in 2015). Previous observers had suggested that 1999 JD6 was most likely an elongated object, based on its large lightcurve amplitude of 1.2 magnitudes (Szabo et al. 2001; Polishook and

Brosch 2008; Warner 2014). The radar images reveal an elongated peanut-shaped object, with two lobes separated by a sharp concavity. JD6's maximum diameter is about two kilometers, and its larger lobe is approximately 50% longer than its smaller lobe. The larger lobe has a concavity on its end. We will present more details on the shape and rotation state of 1999 JD6, as well as its surface properties from optical and infrared data and thermal modeling.

**Author(s): Sean E. Marshall4**, Ellen S. Howell7, Marina Brozović5, Patrick A. Taylor1, Donald B. Campbell4, Lance A. M. Benner5, Shantanu P. Naidu5, Jon D. Giorgini5, Joseph S. Jao5, Clement G. Lee5, James E. Richardson1, Linda A. Rodriguez-Ford1, Edgard G. Rivera-Valentin1, Frank Ghigo8, Adam Kobelski8, Michael W. Busch10, Petr Pravec2, Brian D. Warner3, Vishnu Reddy9, Michael D. Hicks5, Jenna L. Crowell11, Yanga R. Fernandez11, Ronald J. Vervack6, Michael C. Nolan7, Christopher Magri12, Benjamin Sharkey13, Brandon Bozek14
**Institution(s):** *1. Arecibo Observatory, 2. Astronomical Institute, Academy of Sciences of the Czech Republic, 3. Center for Solar System Studies, 4. Cornell University, 5. Jet Propulsion Laboratory, 6. Johns Hopkins University / Applied Physics Laboratory, 7. Lunar and Planetary Laboratory / University of Arizona, 8. National Radio Astronomy Observatory, 9. Planetary Science Institute, 10. SETI Institute, 11. University of Central Florida, 12. University of Maine at Farmington, 13. University of Minnesota, 14. University of Texas*

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## 205 – Titan's Atmosphere

### 205.01 – Seasonal variations in Titan's stratosphere observed with Cassini/CIRS after the northern spring equinox

Since 2004, Cassini has made more than 110 Titan flybys, observing its atmosphere with instruments including the Cassini Composite InfraRed Spectrometer (CIRS). We know from CIRS observations that the global dynamics drastically changed after the northern spring equinox that occurred in August 2009 ([1], [2], [3], [4]). The pole-to-pole middle atmosphere dynamics (above 100 km) experienced a global reversal in less than 2 years after the equinox [4], while the northern hemisphere was entering spring. This new pattern, with downwelling at the south pole, resulted in enrichment of almost all molecules inside the southern polar vortex, while a persistent enhancement due to the former northern winter subsidence is still seen in the north pole region. According to General Circulation Model calculations, this single circulation cell pattern should remain until 2025.
We will present new 2015 CIRS limb observations analysis. We will show that many species ($C_2H_2$, HCN, $HC_3N$, $C_6H_6$, $C_4H_2$, $CH_3CCH$, $C_2H_4$) are now highly enriched near the south pole, by factors ~100 at 500 km compared to just a few years ago. Such large middle atmospheric enrichments were never observed before and are similar to in situ results from INMS at 1000 km [5].
We will also show that the north pole displays for the first time since the beginning of the Cassini mission, a depletion of molecular gas mixing ratios at altitudes higher than 300 km, while deeper levels remains enriched compared to mid-latitude regions.
References:
[1] Teanby, N., et al., Nature, 491, pp. 733-735, 2012.
[2] Achterberg et al., DPS 46, abstract 102.07,Tucson, 2014.
[3] Coustenis et al., DPS 46, abstract 102.46, Tucson, 2014.
[4] Vinatier et al., Icarus, 250, 95-115, 2015.
[5] Cui et al., Icarus, 200, 581-615, 2009.

**Author(s): Sandrine Vinatier2**, Bruno Bézard2, Nick Teanby4, Sébastien Lebonnois1, Richard Achterberg6, Nicolas Gorius5, Andrei Mamoutkine3, F. Michael Flasar3
**Institution(s):** *1. Laboratoire de Météorologie Dynamique, 2. LESIA, Obs. de Paris-Meudon, 3. NASA Goddard Space Flight Center, 4. School of Earth Science, University of Bristol, 5. The Catholic University of America, 6. University of Maryland*

### 205.02 – Post-equinox evolution of Titan's south-polar stratosphere

Since northern spring equinox in mid-2009, Titan's atmosphere has demonstrated dramatic changes in temperature (Achterberg et al 2014), composition (Teanby et al 2012, Vinatier et al 2015, Coustenis et al 2015), and aerosol/ice distribution (de Kok et al 2014, Jennings et al 2015, West et al 2015). Changes have been greatest at the southern winter pole, which continues to enter deeper into Titan's shadow following the 2009 equinox. Observational highlights include development of a south polar hot-spot, nitrile ice clouds, dense condensate clouds, and extreme trace gas concentrations.
Here we use recent infrared spectral limb observations by Cassini/CIRS to determine the evolution of temperature and composition of the south polar region since equinox. Our observations show that the south polar hot-spot initially observed following equinox has now disappeared and been replaced by extremely low temperatures throughout the stratosphere, suspected to be due to enhanced radiative cooling. There also appears to be an unusual distribution of nitrile species, which suggests trace gases are now escaping the newly formed winter vortex. Thus providing clues to the underlying circulation. The new observations will be presented and implications for Titan's polar atmospheric dynamics discussed.
Achterberg et al (2014), DPS46, 102.07, Tucson.
Coustenis et al (2015), Icarus (in press).
de Kok et al (2014), Nature, 514, 65-67.
Jennings et al (2015), ApJL, 804, L34.
Teanby et al (2012), Nature, 491, 732-735.
Vinatier et al (2015), Icarus, 250, 95-115.
West et al (2015), Icarus (in press).

**Author(s): Nicholas A Teanby5**, Sandrine Vinatier2, Remco de Kok4, Conor A Nixon3, Patrick GJ Irwin1
**Institution(s):** *1. AOPP Oxford University, 2. LESIA-Observatoire de Paris, 3. NASA Goddard Space Flight Center, 4. SRON Netherlands Institute for Space Research, 5. University of Bristol*

### 205.03 – ALMA Spectroscopy of Titan's Atmosphere: First Detections of Vinyl Cyanide and Acetonitrile Isotopologues

Studies of Titan's atmospheric chemistry provide a unique opportunity to explore the origin and evolution of complex organic matter in primitive planetary atmospheres. The Atacama Large Millimeter/submillimeter Array (ALMA) is a powerful new telescope, well suited to the study of molecular emission from Titan's stratosphere and mesosphere. Here we present early results from our ongoing study to exploit the large volume of Titan data taken using ALMA in Early Science Mode (during the period 2012-2014). Combining data from multiple ALMA Band 6 observations, we obtained high-resolution mm-wave spectra with unprecedented sensitivity, enabling the first detection of vinyl cyanide ($C_2H_3CN$) in Titan's atmosphere. Initial estimates indicate a mesospheric abundance ratio with respect to ethyl cyanide ($C_2H_5CN$) of $[C_2H_3CN]/[C_2H_5CN] = 0.31$. In addition, we report the first detections on Titan of the $^{13}C$ and $^{15}N$-substituted isotopologues of acetonitrile ($^{13}CH_3CN$ and $CH_3C^{15}N$). Radiative transfer models and possible chemical formation pathways for these molecules will be discussed.

**Author(s): Martin Cordiner1**, Maureen Y Palmer3, Conor A Nixon1, Steven B Charnley1, Michael J Mumma1, Pat G. J. Irwin5, Nick A Teanby4, Zbigniew Kisiel2, Joseph Serigano1
**Institution(s):** *1. NASA Goddard Space Flight Center, 2. Polish Academy of Sciences, 3. St. Olaf College, 4. University of Bristol, 5. University of Oxford*

### 205.04 – Observations of CO in Titan's Atmosphere Using ALMA

The advent of the Atacama Large Millimeter/submillimeter Array (ALMA) has provided a powerful facility for probing the atmospheres of solar system targets at long wavelengths (84-720 GHz) where the rotational lines of small, polar molecules are prominent. In the dense, nitrogen-dominated atmosphere of Titan,

photodissociation of molecular nitrogen and methane leads to a wealth of complex hydrocarbons and nitriles in small abundances. Past millimeter/submillimeter observations, including ground-based observations as well as those by the Composite Infrared Spectrometer (CIRS) aboard the Cassini spacecraft, have proven the significance of this wavelength region for the derivation of vertical mixing profiles, latitudinal and seasonal variations, and molecular detections. Previous ALMA studies of Titan have presented mapping and vertical column densities of hydrogen isocyanide (HNC) and cyanoacetylene ($HC_3N$) (Cordiner et al. 2014) as well as the first spectroscopic detection of ethyl cyanide ($C_2H_5CN$) in Titan's atmosphere (Cordiner et al. 2015).
Here, we report several submillimetric observations of carbon monoxide (CO) and its isotopologues $^{13}CO$, $C^{18}O$, and $C^{17}O$ in Titan's atmosphere obtained with flux calibration data from the ALMA Science Archive. We employ NEMESIS, a line-by-line radiative transfer code, to determine the stratospheric abundances of these molecules. The abundance of CO in Titan's atmosphere is determined to be approximately 50±1 ppm, constant with altitude, and isotopic ratios are determined to be approximately $^{12}C/^{13}C$ = 90, $^{16}O/^{18}O$ = 470, and $^{16}O/^{17}O$ = 2800. This report presents the first spectroscopic detection of $C^{17}O$ in the outer solar system, detected at >11σ confidence. This talk will focus on isotopic ratios in CO in Titan's atmosphere and will compare our results to previously measured values for Titan and other bodies in the Solar System. General implications for the history of Titan from measurements of CO and its isotopologues will be discussed.

**Author(s): Joseph Serigano[1]**, Conor A. Nixon[2], Martin Cordiner[2], Patrick G. J. Irwin[4], Nicholas Teanby[5], Steven B. Charnley[2], Johan E. Lindberg[2], Anthony J. Remijan[3]
**Institution(s):** *1. Johns Hopkins University, 2. NASA Goddard Space Flight Center, 3. National Radio Astronomy Observatory, 4. Oxford University, 5. University of Bristol*

### 205.05 – Search for methane isotope fractionation due to Rayleigh distillation on Titan

Kinetic fractionation of methane isotopes on Titan may be diagnostic of the temperatures where methane is evaporating from the surface and condensing in the atmosphere. We describe the equilibrium fractionation that is expected to result in a depletion of $CH_3D$ in the gas, and speculate about the magnitude of this depletion. We search for spatial variation in $CH_3D$ using near-IR spectra obtained with Keck NIRSPAO (Ádámkovics et al., 2015) and describe some limitations of the current methane line assignments near 1.55μm in HITRAN2012. After performing a rudimentary empirical correction to our radiative transfer model, we perform retrievals of the $CH_3D$ abundance. Preliminary results from this work suggest that $CH_3D/CH_4$ is globally uniform to within ~10%; that is, variation in $CH_3D$ abundance of more than 10% of the nominal value would be detectable in our existing observations. Improvements to both the observations and models are suggested, and we discuss the limitations of our methodology.

**Author(s): Mate Adamkovics[1]**, Jonathan L. Mitchell[2]
**Institution(s):** *1. University of California, 2. University of California*

### 205.06 – Titan Aerosol Formation as a Sink for Stable Carbon and Nitrogen Isotopes

Stable isotope ratios of major elements can be used to infer much about local- and global-scale processes on a planet. On Titan, aerosol production is a significant sink of carbon and nitrogen in the atmosphere, and isotopic fractionation of these elements may be introduced during the advanced organic chemistry that leads to the condensed phase products. Several stable isotope pairs, including $^{12}C/^{13}C$ and $^{14}N/^{15}N$, have been measured *in situ* or probed spectroscopically by Cassini-borne instruments, space telescopes, or through ground-based observations. However, the effect of a potentially critical pathway for isotopic fractionation – organic aerosol formation and subsequent deposition onto the surface of Titan – has not been considered due to insufficient data regarding fractionation during aerosol formation. To better understand the nature of this process, we have measured the isotopic fractionation associated with the formation of Titan aerosol analogs via far-UV irradiation of several methane ($CH_4$) and nitrogen ($N_2$) mixtures.
Our initial results probed the fractionation of the aerosol product, relative to the reactant gases, as a function of $CH_4$ abundance [1]. Our results show that the direction of carbon isotope fractionation during aerosol formation is in contrast to the expected result if the source of the fractionation is a kinetic isotope effect. The resultant fractionation in nitrogen favored the light ($^{14}N$) isotope in the aerosol, with N/C ratios varying from 0.13 – 0.31. Ongoing work includes probing the effects of pressure and temperature on the direction and magnitude of the stable isotope fractionation. We will present results alongside interpretation of the driving processes, as well as implications for Titan if similar fractionation occurred during aerosol formation in the atmosphere.
[1] Sebree, J.A., Stern, J.C., Mandt, K.E., Domagal-Goldman, S.D., and Trainer, M.G.: $^{13}C$ and $^{15}N$ Fractionation of $CH_4/N_2$ Mixtures during Photochemical Aerosol Formation: Relevance to Titan, Icarus, in press, 2015, doi:10.1016/j.icarus.2015.04.016.

**Author(s): Melissa G Trainer[1]**, Jennifer C. Stern[1], Joshua A. Sebree[3], Thomas J. Gautier[1], Javier A. Fuentes[1], Shawn D. Domagal-Goldman[1], Kathleen E. Mandt[2]
**Institution(s):** *1. NASA Goddard Space Flight Center, 2. Southwest Research Institute, 3. University of Northern Iowa*

### 205.07 – New results from the analyses of the solid phase of the NASA Ames Titan Haze Simulation (THS) experiment

In Titan's atmosphere, a complex chemistry occurs at low temperature between $N_2$ and $CH_4$ that leads to the production of heavy organic molecules and subsequently solid aerosols. The Titan Haze Simulation (THS) experiment was developed at the NASA Ames COSmIC facility to study Titan's atmospheric chemistry at low temperature. In the THS, the chemistry is simulated by plasma in the stream of a supersonic expansion. With this unique design, the gas is cooled to Titan-like temperature (~150K) *before* inducing the chemistry by plasma, and remains at low temperature in the plasma (~200K). Different $N_2$-$CH_4$-based gas mixtures can be injected in the plasma, with or without the addition of heavier molecules, in order to monitor the evolution of the chemical growth.
Following a recent in situ mass spectrometry study of the gas phase that demonstrated that the THS is a unique tool to probe the first and intermediate steps of Titan's atmospheric chemistry at low temperature (Sciamma-O'Brien et al., Icarus, *243,* 325 (2014)), we have performed a complementary study of the solid phase. The findings are consistent with the chemical growth evolution observed in the gas phase. Grains and aggregates form in the gas phase and can be jet deposited onto various substrates for ex situ analyses. Scanning Electron Microscopy images show that more complex mixtures produce larger aggregates, and that different growth mechanisms seem to occur depending on the gas mixture. They also allow the determination of the size distribution of the THS solid grains. A Direct Analysis in Real Time mass spectrometry analysis coupled with Collision Induced Dissociation has detected the presence of aminoacetonitrile, a precursor of glycine, in the THS aerosols. X-ray Absorption Near Edge Structure (XANES) measurements also show the presence of imine and nitrile functional groups, showing evidence of nitrogen chemistry. Infrared and μIR spectra of samples deposited on KBr and Si substrates show the presence of more aromatic functional groups for more complex gas mixtures, and allowed the determination of the samples' thickness. These complementary studies show the potential of THS to better understand Titan's chemistry and the origin of aerosol formation.

**Author(s): Ella Sciamma-O'Brien[1]**, Kathleen T. Upton[2], Jesse L. Beauchamp[2], Farid Salama[1]
**Institution(s):** *1. NASA Ames Research Center, 2. Noyes Laboratory of Chemical Physics and the Beckman Institute - Caltech*

### 205.08 – Aerosol properties in Titan's upper

**atmosphere from UVIS airglow observations**

Multiple Cassini observations reveal that the abundant aerosol particles in Titan's atmosphere are formed at high altitudes, particularly in the thermosphere [1]. They subsequently fall towards the lower atmosphere, and in their path, their size, shape, and population change in reflection to the variable atmospheric conditions.

Although multiple observations can help us retrieve information for the aerosol properties in the lower atmosphere [2], we have limited knowledge for their properties in the altitude range between their formation region in the thermosphere, and the upper region of the main haze layer. UVIS is one of a few instruments that can probe this part of the atmosphere and allow for the retrieval of the aerosol properties.

Here we analyze observations of atmospheric airglow that demonstrate the signature of $N_2$ emissions and light scattering from aerosol particles, at different altitudes above 500 km [3]. We fit these observations with a combined model of $N_2$ airglow [4] and atmospheric scattering by gases and aerosols that allows us to separate the pure scattering component and retrieve the aerosol size (distribution) and density. We particularly focus on observations from the T32 flyby that probed high southern latitudes in 2007 and combine good altitude resolution with high signal to noise ratio. We combine these with observations at different phase angles and observing geometry conditions (nadir vs. limb) in order to set better constraints on the aerosol properties. Our preliminary results demonstrate an increase in the average particle size with decreasing altitude in the atmosphere, from about 10 nm at 800 km to ~50 nm at 500 km, and an extinction profile at 185 nm wavelength, similar to the profile derive from UVIS occultation measurements at lower latitudes [5].

[1] Lavvas et al. 2013. PNAS, doi/10.1073/pnas.1217059110, and references therein.
[2] Tomasko et al. 2008, PSS, 56, p.669; Bellucci et al. 2009, Icarus 201, p.198
[3] Ajello et al. 2008, GRL, 35, L06102.
[4] Lavvas et al. 2015. Icarus, 260, p.29.
[5] Koskinen et al. 2011. Icarus, 216, p.507.

**Author(s): Panayotis Lavvas[2]**, Tommi Koskinen5, Emilie Royer4, Pascal Rannou[1], Robert A West3
**Institution(s):** *1. GSMA, 2. GSMA/CNRS, 3. JPL, 4. LASP, 5. University of Arizona*

### 205.09 – Retrievals of Aerosol and Hydrocarbon Abundances in the Atmosphere of Titan from Cassini UVIS Stellar Occultation Measurements

We present retrievals of haze optical properties and hydrocarbon abundances in the atmosphere of Titan from Cassini UVIS stellar occultation observations of the upper atmosphere above 300 km. These measurements focus on the extinction in the far ultraviolet (FUV) wavelengths between 140 and 190 nm and include data from multiple Titan flybys across several latitudes and longitudes. Coherent structures in the optical depth profile are seen to vary by tens of kilometers in altitude across different latitudes, while also varying temporally on time scales of months and years. Comparisons of these extinction estimates with the results of our aerosol microphysics model suggest that processes aside from sedimentation, diffusional transport, and Brownian coagulation are taking place. The UVIS spectrographs also provide measurement of the scattered solar spectrum, which can be used to calculate the real part of the aerosol index of refraction. At the same time, the phase angle distribution and absolute flux of the scattered spectrum, in combination with the extinction, can be used to estimate other physical properties of the scattering particles. Thus, our results provide valuable constraints for models of Titan photochemistry and haze formation throughout this region of the upper atmosphere.

**Author(s): Siteng Fan[1]**, Joshua A. Kammer4, Peter Gao[1], Mao-Chang Liang3, Donald E. Shemansky[2], Yuk L. Yung[1]
**Institution(s):** *1. Division of Geological and Planetary Sciences, California Institute of Technology, 2. Planetary and Space Science Division, Space Environment Technologies, 3. Research Center for Environmental Changes, Academia Sinica, 4. Southwest Research Institute*

## 207 – Harold C. Urey Prize: No Photon Left Behind: How Modern Spectroscopy is Transforming Planetary Sciences, Geronimo Villanueva (NASA Goddard Space Flight Center)

### 207.01 – No photon left behind: How modern spectroscopy is transforming planetary sciences

The advent of sensitive high-resolution spectrometers and modern analytical spectroscopic tools is opening new windows in the exploration of planetary atmospheres. High-resolution infrared spectrometers with broad spectral coverage at ground-based observatories (e.g., Keck, IRTF, VLT) and arrays of radio telescopes with state of the art receivers (e.g., ALMA) now permit the exploration of the kinematics, composition and thermal structure of a broad range of planetary sources with unprecedented precision. These, combined with the advent of comprehensive spectroscopic databases containing billions of lines, robust radiative transfer models, and unprecedented available computational power, are transforming the way we investigate planetary atmospheres.

Such advances have allowed us to obtain the first mapping of water D/H on Mars (Villanueva et al. 2015), to obtain one of the most comprehensive searches for organics in the Martian atmosphere (Villanueva et al. 2013), and to obtain the first measurement of water D/H of a periodic comet (Villanueva et al. 2009).

In this talk, I will present the current frontiers in the exploration of planetary atmospheres and how the synergies between future space (e.g., ExoMars 2016, JWST) and ground astronomical assets (e.g., TMT, E-ELT) will transform our understanding of the composition, stability and evolution of the atmospheres in the Solar System and beyond.

Villanueva, G.L., et al. 2009. *Astrophys. J. Lett.* 690 (1). pp. L5–L9.
Villanueva, G.L., et al. 2013. *Icarus* 223 (1). pp. 11–27.
Villanueva, G.L., et al. 2015. *Science* 348 (6). pp. 218–221.

**Author(s): Geronimo Luis Villanueva[1]**
**Institution(s):** *1. NASA - Goddard Space Flight Center*

## 208 – Changing Perspectives on Mercury and the Moon, Brett Denevi (Johns Hopkins, APL)

### 208.01 – Changing Perspectives on Mercury and the Moon

Airless, cratered, and not so different in size, the Moon and Mercury form a natural pair in the inner Solar System. For decades after the 1974 and 1975 Mariner 10 flybys of Mercury, with little compositional information, no concrete evidence for volcanism, and images of less than half of the planet, it was thought that Mercury's surface may be similar to the lunar highlands: an ancient anorthositic flotation crust subsequently shaped mainly by impact cratering. However, observations from the recently completed MESSENGER mission to Mercury have upended our view of the innermost planet, revealing, for example, a crust that may be rich in graphite and that has been extensively resurfaced by volcanic activity, and geologic activity that may continue today to produce enigmatic "hollows" – a crust very different from that of the Moon. Meanwhile, the Moon has undergone its own revolution, as data from recent spacecraft such as the Lunar Reconnaissance Orbiter reveal sites of silicic volcanism indicative of complex differentiation in the mantle, tectonic activity that may be ongoing, recent volcanic activity that alters the paradigm that volcanism died on the Moon over a billion years ago, and evidence that the early chronology of the inner Solar System may not be as well known as once thought. As our views of these two bodies evolve, a new understanding of their differences informs our knowledge of the variety of processes and styles of planetary evolution, and their similarities point to commonalities among all airless bodies.

**Author(s): Brett W. Denevi[1]**
**Institution(s):** *1. Johns Hopkins University Applied Physics Laboratory*

## 209 – Vesta and Ceres by the Light of Dawn, Christopher Russell (UC, Los Angeles)

### 209.01 – Vesta and Ceres by the light of Dawn

Ceres and Vesta are the most massive bodies in the main asteroid belt. They both appear to be intact protoplanets whose growth may have been drastically altered by the concomitant formation of Jupiter.. These two bodies have witnessed 4.6 Ga of solar system history, much, but not all, of which has been recorded in their surfaces. Dawn's objective is to interview these two witnesses to learn as much as possible about the early epoch. These bodies are protoplanets, our best archetypes of the early building blocks of the terrestrial planets. In particular, siderophile elements in the Earth's core were probably first segregated in Vesta-like bodies, and its water was likely first condensed in Ceres-like bodies.
Many of the basaltic achondrites originated from a common parent body. Dawn verified that Vesta was consistent with that parent body. hence strengthening geochemical inferences from these samples on the formation and evolution of the solar system and supporting hypotheses for their delivery from Vesta to Earth. Ceres has not revealed itself with a meteoritic record. While the surface is scarred with craters, it is probable that the ejecta from the crater-forming event created little competent material from the icy crust and any such ejected projectiles that reached Earth might have disintegrated upon entry into the Earth's atmosphere.
Ceres' surface differs greatly from Vesta's. Plastic or fluidized mass wasting is apparent, as are many irregularly shaped craters, including many polygonal crater forms. There are many central-pit craters possibly caused by volatilization of the crust in the center of the impact. There are also many central-peak craters, which were made by rebound or pingo-like formation processes. Bright deposits dot the landscape, which are possibly salt-rich, suggesting fluvial activity beneath the crust. Observations of the brightest spots on Ceres could suggest sublimation from the surface of the bright area, which may be water vapor driven, as Herschel observations suggest. Ceres is not only the most massive body in the asteroid belt but also possibly the most active.

**Author(s): Christopher T. Russell[1]**
**Institution(s):** *1. UC, Los Angeles*

## 210 – Pluto System

### 210.01 – New Horizons disk-integrated approach photometry of Pluto and Charon

Approach and cruise observations of Pluto and Charon by NASA's New Horizons LOng Range Reconnaissance Imager ("LORRI") allow monitoring of Pluto not only at phase angles beyond Earth's 2 degree limit, but present a near constant sub-observer latitude of 43 degrees. However, the creation of light curves and solar phase curves of the pair prove to be an interesting challenge. Early images of the pair from July 2013 are barely resolved and have low signal, while later images show the pair clearly resolved and at sufficient resolution. Just at the Pluto approaches the signal level and image quality of prior HST images, surface features become resolved, rendering disk integrated photometry increasingly difficult and inaccurate, with the largest discrepancies found at longitudes which show the intersection of features informally named Tombaugh Regio ("the heart") and Cthulhu Macula ("the whale").
Now, post flyby, accurate knowledge of the radius and the shapes of surface features and their patterns of dark and light, allow for the creation of custom PSFs created from flyby maps. Using these maps, we present disk-integrated approach photometry, a solar phase curve and estimate Hapke parameters, taking into account the sub-observer position.
This work was supported by the NASA New Horizons Project.

**Author(s): Amanda M. Zangari4**, Marc W. Buie4, Bonnie J. Buratti[1], Anne J. Verbiscer5, C. J. A. Howett4, H. A. Weaver[2], Catherine B. Olkin4, Kimberly Ennico3, Leslie A. Young4, S. A. Stern4
**Institution(s):** *1. Jet Propulsion Laboratory, California Inst. of Technology, 2. Johns Hopkins University Applied Physics Laboratory , 3. NASA Ames Research Center, 4. SwRI, 5. University of Virginia*

### 210.02 – On the Departure from Isothermality of Pluto's Volatile Ice due to Local Insolation and Topography

Pluto's atmosphere is known to be supported by the vapor pressure of ices that are volatile at low temperature, primarily $N_2$ and secondarily $CH_4$ and CO. The atmospheric bulk is regulated by the globally average temperature of the ice, which is determined by a radiative balance between the diurnally average insolation absorbed globally by the volatile ice and the global volatile ice thermal radiation. This bulk is sufficient that Pluto's atmosphere is close to hydrostatic equilibrium, though this may not remain so as Pluto continues to move towards aphelion. With the weight of the atmosphere currently distributed evenly around the body, the ice temperature is expected to be globally isothermal in absence of topographic variations, due to the transport of latent heat from regions of high insolation to low insolation through sublimation and condensation. Images returned from the New Horizons spacecraft show topographical features, including mountain ranges that extend above 3.5 km, with albedo variations that suggest a topographical dimension or dependence of the volatile ice deposits. In general, the conditions often applied to a volatile atmosphere of hydrostatic equilibrium and vapor-solid phase equilibrium are approximations that may not always both be appropriate. This is particularly the case in the presence of topography when the atmospheric lapse rate differs from the wet adiabat. We present our results of an investigation of the effect of variable insolation and topography on Pluto's local ice temperature assuming an atmosphere close to hydrostatic equilibrium.

**Author(s): Laurence M. Trafton[2]**, John A. Stansberry[1]
**Institution(s):** *1. Space Telescope Science Institute, 2. Univ. of Texas at Austin*

### 210.03 – New Horizons and Hubble Space Telescope Photometry of Nix and Hydra

New Horizons has provided the first spatially-resolved images of Pluto's small satellites, enabling the characterization of albedo and scattering properties across their surface. Application of photometric models to yield the physical properties of airless planetary surfaces requires observations spanning the broadest possible range of viewing and illumination geometries, from full disk to thin crescent. While New Horizons observed the Pluto system at phase angles no smaller than 15°, full-disk Hubble Space Telescope images (HST Program 13367, M. Buie, PI) at phase angles between 0.06° and 1.7° constrain the phase function near opposition. Together with New Horizons disk-resolved images, we use the near-opposition phase function to test whether ejecta exchange (Stern 2009, Icarus 199, 571) affects photometric properties. With direct measurements of small satellite sizes from New Horizons, we can determine the disk-integrated geometric albedo by extrapolating the HST observations to zero phase. New Horizons observations at larger phase angles reveal surface roughness and directional scattering properties. Finally we place the photometric properties of Pluto's small satellites in context with those of similar size in other planetary systems. This work was supported in part by the NASA New Horizons Project.

**Author(s): Anne J. Verbiscer[8]**, Marc W. Buie[7], Richard P. Binzel[4], Marina Brozovic[1], Kimberly Ennico[5], William M. Grundy[3], Robert Jacobson[1], Cathy B. Olkin[7], Mark R. Showalter[6], John R. Spencer[7], Sol Alan Stern[7], Hal A. Weaver[2], Leslie A. Young[7]
**Institution(s):** *1. Jet Propulsion Laboratory, 2. Johns Hopkins University Applied Physics Laboratory, 3. Lowell Observatory, 4. Massachusetts Institute of Technology, 5. NASA Ames Research Center, 6. SETI Institute, 7. Southwest Research Institute, 8. University of Virginia*

### 210.04 – Long Wavelength Observations of Thermal Emission from Pluto and Charon with ALMA

Long wavelength observations of Pluto can determine atmospheric temperatures, abundances, and vertical distributions for those molecules that have transitions at these wavelengths. In addition, observations of both Pluto and Charon can elucidate their surface and subsurface temperatures and surface compositions (and distribution, with enough resolution). We have used the Atacama Large Millimeter Array (ALMA) to observe the CO and HCN in the atmosphere of Pluto, and to observe thermal emission from the two bodies, where the resolution is enough to separate them (but not enough to resolve each individually). We report here on the thermal emission observations, and separately at this meeting on the CO [1] and HCN [2] observations. We observed the Pluto/Charon system with ALMA on June 12 and 13, 2015, at a wavelength of ~0.86 mm. Both days provide separate observations of the thermal emission from Pluto and Charon. We find a preliminary value of the brightness temperature of the two bodies of 35 K and 46 K with variation of less than 1 K between the two days and SNR of > 300 for Pluto and > 100 for Charon. This is similar to previous observations of the separate thermal emission of the two bodies with the Submillimeter Array (SMA) [3] and Very Large Array (VLA) [4]. We will discuss the implications of these measured brightness temperatures and the apparent lack of significant variation between the two days (longitudes).
[1] Gurwell et al., this meeting. [2] Lellouch et al., this meeting. [3] Gurwell & Butler, BAAS 37, 2005. [4] Butler et al. BAAS 43, 2010.

**Author(s): Bryan J. Butler[5]**, Mark Gurwell[3], Emmanuel Lellouch[6], Arielle Moullet[5], Raphael Moreno[6], Dominique Bockelee-Morvan[6], Nicolas Biver[6], Thierry Fouchet[6], Darek Lis[2], Alan Stern[8], Leslie Young[8], Eliot Young[8], Hal Weaver[4], Jeremie Boissier[1], John Stansberry[7]
**Institution(s):** *1. Institut de Radio-Astronomie Millimétrique, 2. Caltech, 3. Harvard-Smithsonian Center For Astrophysics, 4. JHU APL, 5. NRAO, 6. Observatoire de Paris , 7. STScI, 8. SWRI*

### 210.05 – The Radii and Oblateness of Pluto and Charon: Preliminary Results from the 2015 New Horizons Flyby

We present preliminary results for the radii and oblateness of Pluto and Charon. Accurate determinations of the mean radii of Pluto and Charon are important for establishing their densities and bulk composition. A fossil bulge, if present, would place constraints on the thermal and orbital evolution of these bodies [1,2]. The New Horizons LORRI imaging system [3] has provided global images of Pluto and Charon, with best resolutions of 3.8 and 2.3 km/pix, respectively. Three separate approaches have been used to determine mean radii and oblateness from the images, two using a threshold DN value [4,5] and one using a maximum gradient method. These approaches were validated using synthetic images having a range of photometric functions. Tradeoffs between the limb center location and the derived shape in individual images can be reduced by combining limb pixel locations obtained from different imaged rotational phases.
This work was supported by NASA's New Horizons project.
[1] Robuchon & Nimmo, Icarus 216, 426, 2011. [2] McKinnon & Singer, DPS 46, abs. no. 419.07, 2014. [3] Cheng et al., SSR 140, 189, 2008. [4] Dermott & Thomas, Icarus 73, 25, 1988. [5] Thomason & Nimmo, LPSC 46, abs. no. 1462, 2015.

**Author(s): Carey M. Lisse[1]**, Francis Nimmo[5], William B. McKinnon[6], Orkan M. Umurhan[2], Marc W. Buie[4], Tod R. Lauer[3], James H. Roberts[1], S. Alan Stern[4], Hal A. Weaver[1], Leslie A. Young[4], Kimberly Ennico-Smith[2], Cathy B. Olkin[4]
**Institution(s):** *1. Johns Hopkins Univ. Applied Physics Lab, 2. NASA ARC, 3. NOAO, 4. SwRI, 5. UCSC, 6. Washington University, St. Louis*

### 210.06 – Geomorphological Mapping of Sputnik Planum and Surrounding Terrain on Pluto

The New Horizons flyby of Pluto in July 2015 has provided the first few close-up images of the Kuiper belt object, which reveal it to have a highly diverse range of terrains, implying a complex geological history. The highest resolution images that have yet been returned are seven lossy 400 m/pixel frames that cover the majority of the prominent Plutonian feature informally named Sputnik Planum (all feature names are currently informal), and its surroundings. This resolution is sufficient to allow detailed geomorphological mapping of this area to commence. Lossless versions of all 15 frames that make up the mosaic will be returned in September 2015, and the map presented at DPS will incorporate the total area covered by these frames.
Sputnik Planum, with an area of ~650,000 km$^2$, is notable for its smooth appearance and apparent total lack of impact craters at 400 m/pixel resolution. The Planum actually displays a wide variety of textures across its expanse, which includes smooth and pitted plains to the south, polygonal terrain at its center (the polygons can reach tens of kilometers in size and are bounded by troughs that sometimes feature central ridges), and, to the north, darker polygonal terrain displaying patterns indicative of glacial flow. Within these plains there exist several well-defined outcrops of a mottled, light/dark unit that reach from several to tens of kilometers across. Separating Sputnik Planum from the dark, cratered equatorial terrain of Cthulhu Regio on its south-western margin is a unit of chaotically arranged mountains (Hillary Montes); similar mountainous units exist on the south and western margins. The northern margin is bounded by rugged, hilly, cratered terrain (Cousteau Rupes) into which ice of Sputnik Planum appears to be intruding in places. Terrain of similar relief exists to the east, but is much brighter than that to the north. The southernmost extent of the mosaic features a unit of rough, undulating terrain (Pandemonium Dorsa) that displays very few impact craters at 400 m/pixel resolution.
This work was supported by the NASA New Horizons project.

**Author(s): Oliver White[1]**, Alan Stern[2], Hal Weaver[3], Cathy Olkin[2], Kimberly Ennico[1], Leslie Young[2], Jeff Moore[1]
**Institution(s):** *1. NASA Ames Research Center, 2. Southwest Research Institute, 3. The Johns Hopkins University Applied Physics Laboratory*

### 210.07 – Probing Pluto's Underworld : Predicted Ice Temperatures from Microwave Radiometry Decoupled from Surface Conditions

The Pluto dwarf planet has been successfully observed in July 2015 by the New Horizons spacecraft (NASA) during a close-targeted flyby which reavealed surprising and fascinating landscapes. While data are still being downlinked on the ground, we propose to present a prediction of the observation of the Radio Science Experiment experiment (REX) that occured on July 14, 2015 and aimed at measuring the microwave brightness temperature of Pluto's night side.
Present models admit a wide range of 2015 surface conditions at Pluto and Charon, where the atmospheric pressure may undergo dramatic seasonal variation and for which measurements have been performed by the New Horizons mission. One anticipated observation is the microwave brightness temperature, heretofore anticipated as indicating surface conditions relevant to surface-atmosphere equilibrium. However, drawing on recent experience with Cassini observations at Iapetus and Titan, we call attention to the large electrical skin depth of outer solar system materials such as methane, nitrogen or water ice, such that this observation may indicate temperatures averaged over depths of several or tens of meters beneath the surface.

Using a seasonally-forced thermal model to determine microwave emission we predict that the southern hemisphere observations (in the polar night in July 2015) of New Horizons should display relatively warm effective temperatures of about 40 K. This would reflect the deep heat buried over the last century of summer, even if the atmospheric pressure suggests that the surface nitrogen frost point may be much lower. We will present our predictions and discuss their impact for the interpretation of the REX measurements.

**Author(s): Alice Le Gall[2]**, Ralph Lorenz[1], Cedric Leyrat3
**Institution(s):** *1. APL, 2. LATMOS, 3. LESIA*

### 210.08 – The visible spectrum of Pluto: secular and longitudinal variation

Continuous near-infrared spectroscopic observations during the last 30 years enabled the characterization of the Pluto's surface and the study of its variability. Nevertheless, only few data are available in the visible range, where the nature of the complex-organics can be studied.
For this reason, we started an observational campaign to obtain the Pluto's relative reflectance in the visible range, with the aim of characterizing the different components of its surface, and providing ground based observations in support of the *New Horizons* mission. We observed Pluto on six nights in 2014, with the imager/spectrograph ACAM@WHT (La Palma, Spain). We obtained six spectra in the 0.40 – 0.93 μm range, that covered a whole Pluto's rotational period (6.4 days).
To study longitudinal variations, we computed for all the spectra the spectral slope, and the position and the depth of the methane ice absorption bands. Also, to search for secular or seasonal variations we compared our data with previously published results. All the spectra present a red slope, indicating the presence of complex organics on Pluto's surface, and show the methane ice absorption bands between 0.73 and 0.90 μm. We also report the detection of the $CH_4$ absorption band at 0.62 μm, already detected in the spectra of Makemake and Eris. The measurement of the band depth at 0.62 μm in the new spectra of Pluto, and in the spectra of Makemake and Eris, permits us to estimate the Lambert coefficient, not measured yet at this wavelength, at a temperature of 30 K and 40 K.
We find that all the $CH_4$ bands present a blue shift. This shift is minimum at the Charon-facing hemisphere, where the $CH_4$ is also more abundant, indicating a higher degree of saturation of $CH_4$ in the $CH_4$:$N_2$ dilution at this hemisphere.
Comparing with data in the literature, we found that the longitudinal and secular variations of the parameters measured in our spectra are in accordance with previous results and with the distribution of the dark and bright material as showed by the Pluto's albedo maps from *New Horizons*.
In 2015, new observations were run quasi-simultaneously with the New Horizons flyby at 10 different Pluto longitudes (July 3 to 14). The data are currently being reduced.

**Author(s): Vania Lorenzi[2]**, Noemí Pinilla-Alonso[1], Joshua P. Emery[1], Javier Licandro3, Dale P. Cruikshank[6], Will Grundy4, Richard P. Binzel5
**Institution(s):** *1. Department of Earth & Planetary Sciences, University of Tennesse, 2. Fundación Galileo Galilei - INAF, 3. Instituto Astrofisico de Canarias, IAC, 4. Lowell Observatory, 5. Massachusetts Institute of Technology, 6. NASA Ames Research Center*

### 210.09 – New rotationally resolved spectra of Pluto-Charon from 350 - 900 nm

We are using the 11-meter Southern African Large Telescope (SALT) to acquire high-resolution rotationally resolved visible spectra of Pluto-Charon. We use the Robert Stobie Spectrograph (RSS) to observe Pluto-Charon from 350 nm to 900 nm. At 500 nm, resolution is 0.05 nm (R ~ 10,0000) and SNR per spectral resolution element is ~ 500.
We planned observations for 13 dates during June-September 2014, and 13 more dates during June-September 2015. The observations for each season were spaced so as to equally sample Pluto's 6.5-day rotational period. As of the abstract submission, we have data from 11 nights (2014) and 9 nights (2015) in hand. Most of the observations were taken with observations of solar-type star HD 146233 to determine the surface reflectivity.
Our results will provide constraint on the composition and spatial distribution of material on Pluto's surface, enabling comparison to previous epochs and near-infrared results, and giving a ground-truth for New Horizons' July 2015 flyby. In addition, our data will allow us to search for new spectral features in the range 350 nm to 600 nm, at a sensitivity substantially higher than previously published searches.

**Author(s): Henry B. Throop[2]**, Will Grundy[1], Cathy B Olkin4, Leslie A Young4, Amanda A Sickafoose3
**Institution(s):** *1. Lowell Observatory, 2. PSI, 3. South African Astronomical Observatory, 4. Southwest Research Institute*

### 210.10 – Spectroscopy of Pluto's Surface from 2.8 - 3.6 μm during the New Horizons Flyby

Spectroscopy of Pluto in the 1 - 2.5 μm range has produced key results over the past two decades: identification of nitrogen, CO, methane and ethane ices, longitudinal variability in the concentrations of these ices, evidence of dissolved vs. pure methane and nitrogen ices, and the surface temperature and crystalline state of nitrogen ice (e.g., Douté et al., 1999; Holler et al., 2014). Only a few spectra have been published at wavelengths from 2.5 - 5 μm (e.g., Protopapa et al., 2008; Olkin et al. , 2007), but these few L- and M-band spectra changed our interpretation of Pluto's surface: the depth of the 3.3 μm methane band precludes significant regions of pure of nitrogen ice, the slope of the methane band at 3.1-3.2 μm is sensitive to the fraction of pure methane vs. methane that is diluted in nitrogen frost, and an absorption feature at 4.67 μm needs an identified source (but could be due to CO, CH3D or other constituent). The LEISA instrument on New Horizons obtained spectra of Pluto's surface at wavelengths between 1.25 - 2.5 μm. To complement the spacecraft instrumentation, we observed Pluto's disk-integrated spectra from 2.8 - 3.6 μm on two half-nights (12-JUL-2015 and 14-JUL-2015 (UT)) using the NIRSPEC spectrograph at the W.M. Keck Observatory. Conditions were excellent throughout most of the observing run, with seeing under 0.5" at K. We will compare our results to observations obtained in 2001 with the same instrument and report on evidence for surface constituents that have been found at shorter wavelengths.
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Holler, B.J. et al., "Evidence for longitudinal variability of ethane ice on the surface of Pluto." Icarus 243, 104-110 (2014)

**Author(s): Eliot F. Young[2]**, Leslie A. Young[2], Henry Roe[1], Bryan J. Holler3
**Institution(s):** *1. Lowell Observatory, 2. Southwest Research Inst., 3. University of Colorado*

### 210.11 – Glacial Flow on and onto Sputnik Planum

Sputnik Planum (SP)[1,2] is the high albedo apparently crater-free western portion of Tombaugh Regio imaged in July by the New Horizons LORRI instrument. The relatively high resolution (400 m/pix) LORRI mosaics of the northern portions of the planum bordered by the Cousteau Rupes (CR) scarp reveal surface patterns highly suggestive of viscous flow dynamics. Spectroscopic measurements of SP taken by the New Horizons LEISA instrument also indicate that SP is a region containing a significant amount of CO[2]. It has also been long known that CO and $N_2$ are associated with one another on SP[3-4]. Taken together these observations suggest the possibility that the high albedo material on SP is a volatile ice mix possibly flowing atop a bedrock-like substrate. The apparent notable lack of craters on SP strongly suggests that the flow processes act on relatively fast geologic timescales. Using the known properties of various volatile ice mixtures in the temperature range of interest, we formulate and implement a numerical landform evolution model in order to examine a number of hypothetical evolutionary scenarios for SP and its environs. This

work was supported by NASA's New Horizons project.
[1] All place names on Pluto and Charon are informally known as such as of the writing of this abstract. [2] Stern, S. A. et al. 2015 Science. [3] Grundy & Buie 2001 Icarus 153, 248. [4] Grundy et al. 2013 Icarus 223, 710.

**Author(s): O. M Umurhan3**, J. M. Moore3, W. B. McKinnon7, A. D. Howard6, F. Nimmo5, W. Grundy2, S. A. Stern4, H. Weaver1, C. Olkin4, K. Ennico3, L. A. Young4
**Institution(s):** *1. Johns Hopkins University Applied Physics Laboratory, 2. Lowell Observatory, 3. NASA-Ames Research Center, 4. Southwest Research Institute, 5. University of California, Santa Cruz, 6. University of Virginia, 7. Washington University St. Louis*

## 210.12 – A Central Flash at an Occultation of a Bright Star by Pluto Soon Before New Horizons' Flyby

From the Mt. John Observatory, New Zealand, we were so close to the center of the occultation path on 29 June 2015 UTC that we observed a modest central flash from the focusing of starlight from a 12th-magnitude star. The star was one of the brightest ever in our years of continual monitoring that started in 2002. At the time of Pluto's perihelion in 1989, it was feared from models that Pluto's atmosphere might collapse by now, a motivation for the timely launch of New Horizons; some models now allow Pluto to retain its atmosphere throughout its orbit.
We used our frame-transfer CCD at 10 Hz with GPS timing on the 1-m McLellan telescope of Canterbury U. We also observed with a Lowell Obs. infrared camera on the "AAVSO" 0.6-m Optical Craftsman telescope; and obtained 3-color photometry at a slower cadence on a second 0.6-m telescope. We coordinated with the overflight of SOFIA and its 2.5-m telescope, which benefited from last-minute astrometry, and the Auckland Observatory's and other ground-based telescopes.
Our light curves show a modest central flash; our tentative geometrical solution shows that we were only about 50 km from the occultation path's centerline. The flash is from rays lower than otherwise accessible in Pluto's atmosphere. Our light curves, at such high cadence that we see spikes caused by atmospheric effects that we had not seen so well since our 2002 Mauna Kea occultation observations, show that Pluto's atmosphere had not changed drastically since our previous year's observations. Our data provide a long-term context for New Horizon's highly-detailed observations of Pluto's atmosphere in addition to providing a chord for the geometrical solution that includes SOFIA's observations.
Our observations were supported by NASA Planetary Astronomy grants NNX12AJ29G to Williams College, NNX15AJ82G to Lowell Observatory, and NNX10AB27G to MIT, and by the National Research Foundation of South Africa. We are grateful to Alan Gilmore, Pam Kilmartin, Robert Lucas, and Carolle Varughese for assistance at Mt. John. We thank the AAVSO for use of the AAVSOnet 0.6-m telescope and Arne Henden for assistance.

**Author(s): Jay M. Pasachoff7**, Bryce A. Babcock7, Rebecca F. Durst7, Christina H. Seeger7, Stephen E. Levine1, Amanda S. Bosh2, Amanda A. Sickafoose2, Michael J. Person2, Fumio Abe4, Daisuke Suzuki5, Masayuki Nagakane6, Paul J. Tristam3
**Institution(s):** *1. Lowell Obs., 2. MIT, 3. Mt. John U. Obs., 4. Nagoya U., 5. Notre Dame, 6. Osaka U., 7. Williams College*

## 210.13 – Placing SOFIA in the central flash for the 29 June 2015 Pluto Occultation

We report on the astrometry prediction process carried out for the 29 June 2015 occultation of an 11.9 magnitude star by Pluto. The occultation star, UCAC2 139-209445 was first identified in 2013 as a good candidate for an occultation to be observed with Stratospheric Observatory for Infrared Astronomy (SOFIA) due to the circumstances of the event. In addition, the event's proximity to the New Horizons encounter with Pluto made the event even more timely. We were awarded time on SOFIA for the Pluto occultation in 2014. From mid-2014 up through the night of the occultation, we tracked Pluto's position. We collected astrometric data from four telescopes: the SARA-CT telescope located in Cerro Tololo International Observatory, Chile; the Lowell Observatory 42-inch Hall telescope; the Lowell Observatory 4.3-m Discover Channel Telescope, both in Flagstaff, AZ; and the USNO 1.55-m Kaj Strand telescope in Flagstaff, AZ. The objective of the astrometric observations was to improve the prediction enough to place the aircraft within the central flash zone (approximately ±75 km, 5mas, from the center line of the Pluto shadow).
The prediction uncertainties included those of the star position and proper motion, Pluto ephemeris offset, potential zone-dependent offsets in the reference catalog, unknown stellar duplicity, and center-of-mass to center-of-light offsets. Over the two years since we identified this event as promising, we worked to steadily decrease each of the sources of uncertainty.
We communicated prediction updates to the SOFIA flight planning team. We provided a pre-take-off update, which was then followed by a later in-flight update that necessitated a change in the flight plan of 320 km. The crew were able to implement this change and SOFIA was able to capture the central flash of this event (Bosh et al., and Person et al., this conference).

**Author(s): Carlos A. Zuluaga2**, Amanda S. Bosh2, Michael J. Person2, Stephen E. Levine1, Len P. Bright1, Hugh C. Harris3, Trudy Tilleman3, Thanawuth Thanathibodee2, Luke W. Weisenbach2
**Institution(s):** *1. Lowell Observatory, 2. Massachusetts Institute of Technology, 3. U.S. Naval Observatory*

## 210.14 – Constraints on Pluto's Hazes from 2-Color Occultation Lightcurves

The controversial question of aerosols in Pluto's atmosphere first arose in 1988, when features in a Pluto occultation lightcurve were alternately attributed to haze opacity (Elliot et al. 1989) or a thermal inversion (Eshleman 1989). A stellar occultation by Pluto in 2002 was observed from several telescopes on Mauna Kea in wavelengths ranging from R- to K-bands (Elliot et al. 2003). This event provided compelling evidence for haze on Pluto, since the mid-event baseline levels were systematically higher at longer wavelengths (as expected if there were an opacity source that scattered more effectively at shorter wavelengths). However, subsequent occultations in 2007 and 2011 showed no significant differences between visible and IR lightcurves (Young et al. 2011). The question of haze on Pluto was definitively answered by direct imaging of forward-scattering aerosols by the New Horizons spacecraft on 14-JUL-2015. We report on results of a bright stellar occultation which we observed on 29-JUN-2015 in B- and H-bands from both grazing and central sites. As in 2007 and 2011, we see no evidence for wavelength-dependent extinction. We will present an analysis of haze parameters (particle sizes, number density profiles, and fractal aggregations), constraining models of haze distribution to those consistent with and to those ruled out by the occultation lightcurves and the New Horizons imaging.
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**Author(s): Kara Hartig2**, T. Barry15, C. Y. Carriazo1, A. Cole12, D. Gault4, B. Giles12, D. Giles15, K. M. Hill12, R. R. Howell14, G. Hudson9, B. Loader9, J. A. Mackie1, C. B. Olkin10, P. Rannou11, J. Regester3, A. Resnick1, T. Rodgers8, B. Sicardy6, M. F. Skrutskie13, A. J. Verbiscer13, L. H. Wasserman5, C. R. Watson7, E. F. Young10, L. A. Young10, M. W. Buie10, M. Nelson13
**Institution(s):** *1. Amherst College, 2. Brown University, 3. Greensboro Day School, 4. Kuriwa Observatory, 5. Lowell Observatory, 6. Paris Observatory, 7. Pomona College, 8. Princeton Instruments, 9. Royal Astronomical Society of New Zealand, 10. Southwest Research Inst., 11. Université Reims Champagne-Ardenne, 12. University of Tasmania, 13. University of Virginia, 14. University of Wyoming, 15. Western Sydney Amateur Astronomy Group*

**210.15 – The State of Pluto's Bulk Atmosphere at the Time of the New Horizons Encounter**

On 29-JUL-2015, our team - plus many critical amateur astronomers - observed a stellar occultation by Pluto from sites in Australia and New Zealand. This event was remarkable for two reasons: it preceded the New Horizons flyby of Pluto by just two weeks, and the occulted star was about 10x brighter than Pluto itself, by far the brightest Pluto occultation event observed to date. The separation of ground sites spanned nearly 900 km with respect to the central chord, allowing a good geometric solution for the shadow path. The lightcurves show some inflection points and broad "fangs" that are characteristic of perturbations in the temperature profile. Preliminary fits show that the temperature profile derived from a 2006 occultation (Young et al. 2008) reproduces the 29-JUN-2015 lightcurves well. Assuming a surface radius of 1187 km for Pluto, we find that the surface pressure is 18 +/- 3 µbar. This pressure indicates that Pluto's surface has not yet started to cool down, despite a decrease in absorbed solar flux of more than 17% since perihelion in 1988. A surface pressure of 18 µbar would correspond to a nitrogen ice surface temperature of 38.0 K.

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**Author(s): Aaron C. Resnick[1]**, T Barry[15], M.W. Buie[11], C.Y. Carriazo[1], A. Cole[12], D. Gault[4], B. Giles[12], D. Giles[15], K. Hartig[2], K. Hill[12], R.R. Howell[14], G. Hudson[9], B. Loader[9], J. Mackie[1], M. Nelson[13], C. Olkin[11], J. Register[3], T. Rodgers[8], B. Sicardy[6], M. Skrutskie[13], A. Verbiscer[13], L. Wasserman[5], C. Watson[7], E. Young[11], L. Young[11], A. Zalucha[10]

**Institution(s):** *1. Amherst College, 2. Brown University, 3. Greensboro Day School, 4. Kuriwa Observatory, 5. Lowell Obersvatory, 6. Paris Observatory, 7. Pomona College, 8. Princeton Instruments, 9. Royal Astronomical Society of New Zealand, 10. SETI, 11. SwRI, 12. University Of Tasmania, 13. University of Virginia , 14. University of Wyoming, 15. Western Sydney Amateur Astronomy Group*

**210.16 – Predictions for the escape of $CH_4$ from Pluto**

Observations of Pluto's extended atmosphere by the New Horizons/ALICE instrument have the potential to constrain models of energy-limited escape from planetary atmospheres. Such models have wide applicability, ranging from dwarf planets in the solar system to giant extrasolar planets, but the opportunities to test them in actual atmospheres are limited. We adapted a multi-species escape model from close-in extrasolar planets to calculate the escape rates of $CH_4$ and $N_2$ from Pluto. In the absence of escape, $CH_4$ should overtake $N_2$ as the dominant species below the exobase. Theory suggests, however, that Pluto's atmosphere undergoes rapid escape that leads to a nearly constant $CH_4$ mixing ratio of about 1 % below the exobase, with $CH_4$ escaping at a rate that is only 5-10 % of the $N_2$ escape rate. Simultaneous observations of the $N_2$ and $CH_4$ profiles in the upper atmosphere, together with our model, can be used to test if this is the case and infer an estimate of the mass loss rate.

**Author(s): Tommi Koskinen[1]**, Justin T Erwin[1], Roger V Yelle[1]

**Institution(s):** *1. Lunar and Planetary Laboratory*

**210.17 – Radiative equilibrium and escape of Pluto's atmosphere**

Observations of Pluto's extend atmosphere by the New Horizons spacecraft motivate an update to our modeling effort on Pluto's atmosphere. New Horizons observations have already improved our constraints on planet radius and surface pressure, which are key to modeling the atmospheric structure. We model the radiative conductive equilibrium in the lower atmosphere combined with the UV driven escape model of the upper atmosphere. The non-LTE radiative transfer model in the lower atmosphere include heating and cooling by $CH_4$, CO, and HCN. The escape model of the upper atmosphere is updated to include diffusion and escape of each molecular component. These results will be used to aid in the analysis and better understanding of the full atmospheric structure.

**Author(s): Justin Erwin[1]**, Tommi T Koskinen[1], Roger V Yelle[1]

**Institution(s):** *1. Lunar and Planetary Lab, UA*

**210.18 – Pluto's atmosphere in 2015 from high-resolution spectroscopy**

Pluto's thin N2/CH4 atmosphere is in vapor-pressure equilibrium with ices on its surface. The atmosphere evolves seasonally with the varying insolation pattern on Pluto's heterogenous surface, perhaps even largely freezing out to the surface during the coldest portion of Pluto's year. We use high-resolution (R≈25,000-50,000) near-infrared spectroscopy to resolve atmospheric methane absorption lines from Pluto's continuum spectra, as well as separate Pluto's atmospheric lines from the telluric spectrum. In addition to measuring the abundance and temperature of Pluto's atmospheric CH4, with broad wavelength coverage we are able to search for the inevitable products of N2/CH4 photochemistry. In 2015 we are undertaking an intensive campaign using NIRSPEC at Keck Observatory and IGRINS (Immersion Grating INfrared Spectrometer) at McDonald Observatory to coincide with the New Horizons Pluto encounter. We will report initial results from this 2015 campaign and compare the state of Pluto's atmosphere at the time of the New Horizons encounter with earlier years.

**Author(s): Henry G. Roe[1]**, Jason C. Cook[2], Gregory N. Mace[4], Bryan J. Holler[3], Leslie A Young[2], Jacob N McLane[4], Daniel T. Jaffe[4]

**Institution(s):** *1. Lowell Obs., 2. SwRI, 3. University of Colorado, Boulder, 4. University of Texas at Austin*

**210.19 – 12 years of Pluto surface's evolution investigated with radiative transfer modeling**

The evolution of Pluto's surface through time, due to surface - atmosphere interactions, remains unknown. New Horizons will provide very high spatial resolution data of its surface state but only as a snapshot. Furthermore, this evolution during the last decades is supposed to be fast due to the recent passage of Pluto through its perihelion (1989). Ground based survey data over a long period of time are thus crucial to understand the long-term evolution of the dwarf planet surface.

IRTF/SpeX reflectance spectra of Pluto have been acquired during 13 years (2001-2013) between 0.8-2.4 µm (Grundy et al., 2013; Grundy et al., 2014). This set of data present the opportunity to monitor possible changes of the surface in terms of geographical distribution and segregation between different chemical species that are known to be present at the surface in an icy state ($N_2$, $CH_4$ and CO, Owen et al., 1993, Douté et al., 1999). These variations are recorded through changes in the infrared absorption bands of the different ices. A study based on band criteria variation (Grundy et al., 2013) showed that $CH_4$ absorption bands are increasing through time, whereas $N_2$ and CO absorptions bands are decreasing (Grundy et al. 2014). However, quantitative interpretation of these data needs further investigation and detailed radiative transfer modeling.

We used the bidirectional reflectance model of Douté & Schmitt (1998) to fit the IRTF/SpeX spectral data. This model takes into account a possible stratification of chemical species, a phenomenon that is likely to occur on Pluto where $CH_4$ is supposed to accumulate on a sublimating molecular mixture of $N_2$-$CH_4$-CO (Douté et al., 1999). Different modelings take into account pure $CH_4$ ice, a molecular mixture of $N_2$-$CH_4$-CO, tholins and water ice. We modeled the grand average spectra and then allowed the parameters to vary around the average values to model individual spectra and get quantitative variations of the different species.

Preliminary results of these modelings will be presented in terms of longitudinal and temporal variations. This study could provide a useful precursor for the analysis of the spatially resolved New Horizon hyper spectral data acquired by the RALPH/Leisa instrument.

**Author(s): Sylvain Philippe[1]**, Bernard Schmitt[1], William Grundy[2], Silvia Protopapa[4], Cathy Olkin[3]
**Institution(s):** *1. Institut de Planétologie et d'Astrophysique de Grenoble, 2. Lowell Observatory, 3. Southwest Research Institute , 4. University of Maryland*

### 210.20 – Modeling the seasonal evolution of the surface distribution of N2, CH4 and CO ices on Pluto to interpret New Horizons observations

The distribution of nitrogen, methane and carbon monoxide ices on Pluto as observed by New Horizons is controlled by the intense seasonal cycle and possibly by some internal sources. To better understand the seasonal processes, we have developed a detailed model of the ices cycles derived from a full Global Climate Model (GCM, see Forget et al., this issue) but in which the transport by the atmosphere is parametrized, based on reference GCM simulations. This allows to simulate the seasonal ices cycles on Pluto for thousands of years.
The resulting distribution primarily depends on the seasonal thermal inertia used for the different ices, and is affected by the assumed topography as well. As observed, it is possible to form permanent deposits in the equatorial regions, with possible longitudinal variations depending on the topography. In particular, we will discuss how the elevation of the anti-Charon point, which is not random since its location is the output of the Pluto-Charon tidal locking process, may explain the formation of the Tombaugh Regio ice deposits.

**Author(s): Tanguy Bertrand[1]**, François Forget[1]
**Institution(s):** *1. Laboratoire de Météorologie Dynamique / UPMC*

### 210.21 – Pluto Photochemical Models for the New Horizons Flyby

We have designed a state-of-the-art 1-D chemistry-transport model for Pluto's atmosphere as a prelude to New Horizons' flyby on July 14, 2015 and as a tool with which to analyze and understand the data gathered by the New Horizons spacecraft. Prior to the close encounter, many atmospheric properties remain unknown. Our model demonstrates the sensitivity of hydrocarbon and HCN profiles to the eddy mixing strength in the lower atmosphere. When the New Horizons data arrive, this model stands primed to aid the characterization of Pluto's atmospheric chemistry and dynamics. If atmsopheric measurements have been obtained/released by the time of this presentation, we will show a comparison between our model and the data.

**Author(s): Michael L Wong[1]**, Randy Gladstone[3], Michael E Summers[2], Yuk L Yung[1]
**Institution(s):** *1. California Institute of Technology, 2. George Mason University, 3. Southwest Research Institute*

### 210.22 – Pluto: Modeling of 3-D Atmosphere-Surface Interactions

Atmosphere-surface interactions on Pluto are of great importance to creating and maintaining the atmospheric variations and heterogeneous surface that have been observed by New Horizons and two decades' prior work. Publicly released images/data from New Horizons contain numerous fascinating surface features and constrasts. Insights into their origin, maintenance, and/or evolution may be gleaned through multidisciplinary climate modeling. Some results from such modeling will be presented, with an emphasis on shorter-timescale interactions.

**Author(s): Timothy I. Michaels[1]**
**Institution(s):** *1. SETI Institute*

### 210.23 – Mass loss from the atmosphere of Pluto

Molecules can escape readily from the atmosphere of Pluto. Hydrodynamic escape is a process that drives large scale escape. The process was generally believed to produce rather small isotopic fractionation. Here, we show that the escape highly fractionates the isotopic composition of nitrogen. The process preferentially selects lighter species, with an escape probability ~30% higher for the lighter isotopologue. This fractionation factor is higher than the fractionations occurring in most of known processes in modifying the distributions of molecules in the planetary atmospheres. The validity of the model can be tested against the upcoming data, mainly nitrogen abundance in the outer atmosphere of Pluto, from the *New Horizons*. The property of the selection can significantly modify the isotopic composition of the atmosphere, leaving the present-day atmosphere isotopically heavier than the ancient one. This also impacts the current view of the evolution of planetary atmospheres. Venus, for example, may not need that much mass loss, in order to explain the current D/H ratio.

**Author(s): Mao-Chang Liang[1]**, Chien-Chang Yen[1], Ronald Taam[1]
**Institution(s):** *1. Academia Sinica*

### 210.24 – Long-term Simulations of Pluto's Atmosphere and Surface as a Coupled System

Previous work has modeled either Pluto's atmosphere or surface/subsurface as separate entities. In reality, these two regions should be coupled energetically and physically because of the accumulation, sublimation, and transport of volatiles (here, N2). Simulation results over multi-Pluto years are presented from a general circulation model that has both detailed atmospheric and surface/subsurface modules. As the initial model conditions that will ultimately reproduce the observed surface pressures from New Horizons, stellar occultation data, and spectroscopic observations are not known, by trial and error the model is initialized with different surface pressures and amounts of surface ice (collectively known as the volatile inventory). This "brute force" method is now a viable strategy given the ongoing development of the Pluto general circulation model (based on the MIT general circulation model dynamical core; Zalucha & Michaels 2013) and modern supercomputing power. The coupled atmosphere and surface/subsurface model is run until a yearly repeatable frost cycle occurs (if at all). Surface coverage of volatiles and surface pressure will be presented from the various scenarios. Ancillary variables such temperature (of both the atmosphere and surface/subsurface) and wind direction and magnitude will also be shown for cases of particular interest.

**Author(s): Angela M. Zalucha[1]**
**Institution(s):** *1. SETI Institute*

### 210.25 – Extended Neutral Cloud around Pluto's Orbit

Recent studies estimate the approximate escape rate of molecular nitrogen from Pluto as well as its ionization rate. In this study, we focus on the implications of this escaping nitrogen and the resulting extended neutral cloud around Pluto's orbit by simulating the escaping nitrogen with a numerical model. Several unknown parameters are varied, including the dependence of Pluto's production rate on orbital distance and the distribution of speeds at which nitrogen is escaping Pluto.

**Author(s): Evan Sidrow[1]**, F Bagenal[1]
**Institution(s):** *1. University of Colorado - Boulder*

### 210.26 – Pluto, Near and Far: PEPSSI Measurements of Energetic Particles During the New Horizons Flyby and Investigating a Pluto Torus of Circumsolar Neutral Gas

The energetic particle environment at Pluto has been unknown, and little modeled, until this year's historic encounter by the New Horizon (NH) spacecraft on 14 July 2015. The first energetic particle observations, made with the Pluto Energetic Particle Spectrometer Science Investigation (PEPSSI) instrument, were downlinked in August 2015. There are variations in the intensities of suprathermal (~3-30 keV/nucleon) ions that are associated with a combination of the position of the spacecraft relative to Pluto, the look direction of PEPSSI, and (potentially) temporal evolution in the system. We present the results of the near encounter with Pluto, to as close as ~11.6 $R_p$ (1 $R_p$ = 1187 km), which, early analysis shows, include large intensity variations associated with Pluto. We also present the concept of a neutral gas torus surrounding the Sun, aligned with Pluto's orbit, and place observational constraints on it based primarily on comparison of NH measurements with a 3-D Monte Carlo model adapted from analogous satellite tori surrounding Saturn and Jupiter. Such a torus, or perhaps partial torus, could result from neutral $N_2$ escaping from Pluto's exosphere. Unlike other more massive planets, gaseous neutrals escape Pluto readily via Jeans escape (i.e., owing to the high thermal speed relative to the escape velocity). These neutrals are not directly observable by NH but, once ionized to $N_2^+$ or $N^+$ via photolysis or charge exchange, are picked up by the solar wind, ultimately reaching ~50 keV or more, making these pickup ions detectable by PEPSSI. This work was supported by NASA's New Horizons project.

**Author(s): Matthew Eric Hill[2]**, Peter Kollmann[2], Ralph L McNutt[2], H Todd Smith[2], Fran Bagenal[6], Lawrence E Brown[2], Heather A Elliott[5], Dennis K Haggerty[2], Mihaly Horanyi[6], Stamatios M Krimigis[2], Martha Kusterer[2], Carey M Lisse[2], David J McComas[5], Marcus Piquette[6], Darrell Strobel[1], Jamey Szalay[6], Jon Vandegriff[2], Eric Zirnstein[5], Kimberly Ennico[3], Cathy B Olkin[4], Harold A Weaver[2], Leslie A Young[4], S A Stern[4]
**Institution(s):** *1. Johns Hopkins University, 2. Johns Hopkins University Applied Physics Laboratory, 3. NASA Ames Research Center, 4. Southwest Research Institute, 5. Southwest Research Institute, 6. University of Colorado*

### 210.27 – Crystalline and amorphous $H_2O$ on Charon

Charon, the largest satellite of Pluto, is a gray-colored icy world covered mostly in $H_2O$ ice, with spectral evidence for $NH_3$, as previously reported (Cook et al. 2007, Astrophys. J. 663, 1406–1419; Merlin, et al. 2010, Icarus, 210, 930; Cook, et al. 2014, AAS/Division for Planetary Sciences Meeting Abstracts, 46, #401.04). Images from the New Horizons spacecraft reveal a surface with terrains of widely different ages and a moderate degree of localized coloration. The presence of $H_2O$ ice in its crystalline form (Brown & Calvin 2000 Science 287, 107-109; Buie & Grundy 2000 Icarus 148, 324-339; Merlin et al, 2010) along with $NH_3$ is consistent with a fresh surface.
The phase of $H_2O$ ice is a key tracer of variations in temperature and physical conditions on the surface of outer Solar System objects. At Charon's surface temperature $H_2O$ is expected to be amorphous, but ground-based observations (e.g., Merlin et al. 2010) show a clearly crystalline signature. From laboratory experiments it is known that amorphous $H_2O$ ice becomes crystalline at temperatures of ~130 K. Other mechanisms that can change the phase of the ice from amorphous to crystalline include micro-meteoritic bombardment (Porter et al. 2010, Icarus, 208, 492) or resurfacing processes such as cryovolcanism.
New Horizons observed Charon with the LEISA imaging spectrometer, part of the Ralph instrument (Reuter, D.C., Stern, S.A., Scherrer, J., et al. 2008, Space Science Reviews, 140, 129). Making use of high spatial resolution (better than 10 km/px) and spectral resolving power of 240 in the wavelength range 1.25-2.5 µm, and 560 in the range 2.1-2.25 µm, we report on an analysis of the phase of $H_2O$ ice on parts of Charon's surface with a view to investigate the recent history and evolution of this small but intriguing object.
This work was supported by NASA's New Horizons project.

**Author(s): Cristina M. Dalle Ore[4]**, Dale P. Cruikshank[3], Will M. Grundy[2], Kimberly Ennico[3], Catherine B. Olkin[5], S. Alan Stern[5], Leslie A. Young[5], Harold A. Weaver[1]
**Institution(s):** *1. Johns Hopkins University Applied Physics Laboratory, 2. Lowell Observatory, 3. NASA Ames Reseach Center, 4. SETI Institute, 5. Southwest Research Institute*

### 210.28 – Charon Quandaries

Recent data from *New Horizons* have revealed Charon as a dynamic world, with an apparently young surface experiencing geological processes. Tectonic features include a chasm seen on Charon's terminator, and cliffs or troughs that belt the moon. The 'mountain-in-a-moat' seen in LORRI images appears emplaced in a depression, also suggesting an active process. These raise the questions: How hot is Charon's interior? Are temperatures sufficient for liquid (i.e., > 176 K, the water-ammonia eutectic)? How close to the surface are these temperatures reached? How thick is Charon's crust? We will report our calculations of these quantities.
Following [1,2], we hypothesize that Charon formed from a circumplutonian disk after a giant impact. Unlike in the 'intact moon' scenario, a Charon accreted from a disk is everywhere > 100 K, and its outermost surface is > 250 K, possibly leading to full differentiation into rocky core and ice mantle [2]. We suggest that contraction of Charon due to its cooling from this hot initial state to its present-day surface temperature ≈ 50 K might lead to tectonic features like those seen on Mercury [3]. We calculate the thermal history of Charon using our published codes [4,5]. We find temperatures today at the base of the ice mantle are cold (< 100 K), but that ice at sufficient depth in the core should melt, producing liquid. It is unclear whether this liquid could reach the surface from the core, but it may do so via processes described by [6]. This would have implications for cryovolcanism, resurfacing, and the 'mountain-in-a-moat'. We will discuss the results of our modeling and our interpretation of New Horizons data at the meeting.
**References**: [1] Canup, R (2005) *Science* 207, 546-550. [2] Desch, SJ (2015) *Icarus* 246, 37-47. [3] Byrne, P, Klimczak, C, Celal Sengor, AM, Solomon, SC, Watters, TR & Hauck, SA (2014) *Nature Geosci.* 7, 301-307.[4] Desch, SJ, Cook, JC, Doggett, TC & Porter, SB. (2009) *Icarus* 202, 694-714. [5] Neveu, M, Desch, SJ & Castillo-Rogez, JC (2015) *J. Geophys. Res. E* 120, 123-154. [6] Neveu, M, Desch, SJ, Shock, EL & Glein, CR (2015) *Icarus* 246, 48-64.

**Author(s): Steven Desch[1]**, Marc Neveu[1]
**Institution(s):** *1. Arizona State Univ.*

### 210.29 – Determination of the System Mass and the Individual Masses of the Pluto System from New Horizons Radio Tracking

One objective of the New Horizons Radio Science Experiment REX is the determination of the system mass and the individual masses of Pluto and Charon. About four weeks of two-way radio tracking centered around the closest approach of New Horizons to the Pluto system were processed. Major problems during the processing were caused by the small net forces of the spacecraft thruster activity, which produce extra Δv on the spacecraft motion superposed onto the continuously perturbed motion caused by the attracting forces of the Pluto system. The times of spacecraft thruster activity are known but the applied Δv needs to be specifically adjusted. No two-way tracking was available for the day of the flyby, but slots of REX one-way uplink tracking are used to cover the most important times near closest approach, e.g. during occultation entries and exits. This will help to separate the individual masses of Pluto and Charon from the system mass.

**Author(s): Matthias Hahn[5]**, Martin Pätzold[5], Tom Andert[2], Michael K. Bird[5], Leonard G. Tyler[1], Ivan Linscott[1], Dave P. Hinson[1], Alan Stern[6], Hal Weaver[3], Cathrin Olkin[6], Leslie Young[6], Kimberly Ennico[4]
**Institution(s):** *1. Department of Electrical Engineering, Stanford University, 2. Institut für Satellitentechnik und Weltraumnutzung, Universität der Bundeswehr München, 3. Applied Physics Laboratory, Johns Hopkins University, 4. NASA Ames Research Center, 5. Rheinisches Institut für Umweltforschung an der Universität zu Köln, Abt. Planetenforschung, 6. Southwest Research Institute*

### 210.30 – The Infrared Spectra and Absorption Intensities of Amorphous Ices: Methane and Carbon Dioxide

Our research group is carrying out new IR measurements of icy solids relevant to the outer solar system and the interstellar medium, with an emphasis on amorphous and crystalline ices below ~70 K. Our goal is to add to the relatively meager literature on this subject and to provide electronic versions of state-of-the-art data, since the abundances of such molecules cannot be deduced without accurate reference spectra and IR band strengths. In the past year, we have focused on two of the simplest and most abundant components of icy bodies in the solar system - methane ($CH_4$) and carbon dioxide ($CO_2$). Infrared spectra from ~ 4500 to 500 $cm^{-1}$ have been measured for each of these molecules in μm-thick films at temperatures from 10 to 70 K. All known amorphous and crystalline phases have been reproduced and, for some, presented for the first time. We also report measurements of the index of refraction at 670 nm and the mass densities for each ice phase. Comparisons are made to earlier work where possible. Electronic versions of our new results are available at http://science.gsfc.nasa.gov/691/cosmicice/ constants.html.

**Author(s): Perry A. Gerakines[1]**, Reggie L. Hudson[1], Mark J. Loeffler[1]
**Institution(s):** *1. NASA GSFC*

### 210.31 – Revisiting the 1988 Pluto Occultation

In 1988, Pluto's atmosphere was surmised to exist because of the surface ices that had been detected through spectroscopy, but it had not yet been directly detected in a definitive manner. The key to making such a detection was the stellar occultation method, used so successfully for the discovery of the Uranian rings in 1977 (Elliot et al. 1989; Millis et al. 1993) and before that for studies of the atmospheres of other planets.
On 9 June 1988, Pluto occulted a star, with its shadow falling over the South Pacific Ocean region. One team of observers recorded this event from the Kuiper Airborne Observatory, while other teams captured the event from various locations in Australia and New Zealand. Preceding this event, extensive astrometric observations of Pluto and the star were collected in order to refine the prediction.
We will recount the investigations that led up to this important Pluto occultation, discuss the unexpected atmospheric results, and compare the 1988 event to the recent 2015 event whose shadow followed a similar track through New Zealand and Australia.

**Author(s): Amanda S. Bosh[2]**, Edward W. Dunham[1], Leslie A. Young3, Steve Slivan4, Linda L. Barba née Cordella[2], Robert L. Millis[1], Lawrence H. Wasserman[1], Ralph Nye[1]
**Institution(s):** *1. Lowell Observatory, 2. MIT, 3. Southwest Research Institute, 4. Wellesley College*

### 210.32 – Voyager IRIS Measurements of Triton's Thermal Emission: Impllications for Pluto?

The New Horizons Pluto encounter data set includes unique observations obtained using the Radio Science experiment to measure the night-side thermal emission at centimeter wavelengths, well beyond the emission peak (in the 70 to 100 micron range). 26 years ago the Voyager 2 Infrared Interferometer Spectrometer (IRIS) obtained spectra in the 30 - 50 micron wavelength range to try and detect thermal emission from Pluto's sibling, Triton. Conrath etal. (1989) analyzed 16 of the IRIS spectra of Triton's dayside and derived a weak limit of 36 K - 41 K. We have analysed those, and an additional 75 spectra, to refine the limits on the temperature of Triton's surface, and to explore diurnal differences in the thermal emission. Triton results from other Voyager instruments provide important constraints on our interpretation of the IRIS data, as do Spitzer measurements of Pluto's thermal emission.
For unit-emissivity, average temperature is 34 K, inconsistent with the pressure of Triton's atmosphere (13 - 19 microbar), the presence of beta-phase nitrogen ice on the surface, and the likely presence ofwarm regions on the surface. The atmospheric pressure requires nitrogen ice temperatures of 37.4 K - 38.1 K, which in turn requires emissivity of 0.31--0.53. Such a low emissivity in this spectral region might be expected if the surface is dominated by nitrogen or methane ice. Averages of data subsets show evidence for brightness temperature variations across Triton's surface. Surprisingly, the data seem to indicate that Triton's nightside equatorial region was warmer than on the dayside.
These Voyager results for Triton provide a useful context for interpreting New Horizons and ALMA observations of emission from Pluto in the sub-millimeter and centimeter region. JWST will be capable of detecting Triton's and Pluto's 10 - 28 micron thermal emission, although scattered light from Neptune may be an issue for the Triton. Combined with new capabilities of ALMA to measure the sub-millimeter emission (and even resolve the disks of Pluto and Triton), it seems possible that we may gain significant new insights into the thermal properties of these bodies in the coming decade.

**Author(s): John A. Stansberry[2]**, John Spencer[1], Ivan Linscott3
**Institution(s):** *1. Southwest Research Institute, 2. Space Telescope Science Institute, 3. Stanford University*

### 210.33 – Exploring potential Pluto-generated neutral tori

The NASA New Horizons mission to Pluto is providing unprecedented insight into this mysterious outer solar system body. Escaping molecular nitrogen is of particular interest and possibly analogous to similar features observed at moons of Saturn and Jupiter. Such escaping $N_2$ has the potential of creating molecular nitrogen and N (as a result of molecular dissociation) tori or partial toroidal extended particle distributions. The presence of these features would present the first confirmation of an extended toroidal neutral feature on a planetary scale in our solar system. While escape velocities are anticipated to be lower than those at Enceladus, Io or even Europa, particle lifetimes are much longer in Pluto's orbit because as a result of much weaker solar interaction processes along Pluto's orbit (on the order of tens of years). Thus, with a ~248 year orbit, Pluto may in fact be generating an extended toroidal feature along it orbit.
For this work, we modify and apply our 3-D Monte Carlo neutral torus model (previously used at Saturn, Jupiter and Mercury) to study/analyze the theoretical possibility and scope of potential Pluto-generated neutral tori. Our model injects weighted particles and tracks their trajectories under the influence of all gravitational fields with interactions with other particles, solar photons and Pluto collisions. We present anticipated $N_2$ and N tori based on current estimates of source characterization and environmental conditions. We also present an analysis of sensitivity to assumed initial conditions. Such results can provide insight into the Pluto system as well as valuable interpretation of New Horizon's observational data.

**Author(s): Howard T. Smith[1]**, Matthew Hill[1], Peter KollMann[1], Ralph McHutt[1]
**Institution(s):** *1. Johns Hopkins Applied Physics Lab*

### 210.34 – Visible-band (390-940nm) monitoring of the Pluto absorption spectrum during the New Horizons encounter

Whilst Earth-based observations obviously cannot compete with New Horizons' on-board instrumentation in most regards, the New Horizons data set is essentially a snapshot of Pluto in July 2015. The New Horizons project team therefore coordinated a broad international observing campaign to provide temporal context and to take advantage of the once-in-a-lifetime opportunity to directly link our Earth-based view of Pluto with "ground truth" provided by in situ measurements. This both adds value to existing archival data sets and forms the basis of long term, monitoring as we watch Pluto recede from the Sun over the coming years. We present visible-band (390-940nm) monitoring of the Pluto absorption spectrum over the period July - October 2015 from the Liverpool Telescope (LT). In particular we wished to understand the well-known 6-day fluctuation in the methane ice absorption spectrum which is observable from Earth in relation to the never-before-available high resolution maps of the Pluto surface. The LT is a fully robotic 2.0m optical telescope that automatically and dynamically schedules observations across 30+ observing programmes with a broad instrument suite. It is ideal for both reactive response to dynamic events (such as the fly-by) and long term, stable monitoring with timing constraints individually optimised to the science requirements of each programme. For example past studies of the observed CH4 absorption variability have yielded ambiguity of whether they were caused by real physical changes or geometric observation constraints, in large part because of the uneven time sampling imposed by traditional telescope scheduling.

**Author(s): Robert J Smith[1]**, Jonathan M Marchant[1]
**Institution(s):** *1. Astrophysics Research Institute, Liverpool John Moores University*

### 210.35 – Photos from Inside Pluto: Historic Images from the New Horizons Encounter with Pluto

NASA's New Horizons mission flew past Pluto on July 14, 2015. In the months and weeks leading up to the encounter, over 200 mission personnel were located at JHU APL and directly involved in the planning and operations of the flyby. Several members of the team were given special permission to document photographically this historic event. These photos have been collected into a public archive which allows the general public to see the intimate and normally hidden 'behind the scenes' views of an operating spacecraft team, through times of elation, times of stress, public celebrations, and private moments.
We present here a variety of these photos spanning May (the beginning of detailed hazards searches) through the end of July. The entire archive will be available online and accessible to the public.
We thank JHU-APL for arranging special permission for the photographers (HBT, CSS, JS, SJR, DC). All photos are used courtesy NASA/SwRI/JHUAPL and the individual photographers.

**Author(s): Henry B. Throop3**, John Spencer4, Stuart J Robbins4, Constantine Tsang4, Dale Cruikshank[2], S. Alan Stern4, Harold Weaver[1], Peter Bedini[1], Andrew Calloway[1]
**Institution(s):** *1. JHU-APL, 2. NASA Ames, 3. PSI, 4. SwRI*

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## 211 – Centaurs, Trans-Neptunian Objects, and the Inner Oort Cloud

### 211.01 – Search for Binary Trojans

We have reexamined 41 Trojan asteroids observed with the Hubble Space Telescope (HST) to search for unresolved binaries. We have identified one candidate binary with a separation of 53 milliarcsec, about the width of the diffraction limited point-spread function (PSF). Sub-resolution-element detection of binaries is possible with HST because of the high signal-to-noise ratio of the observations and the stability of the PSF. Identification and confirmation of binary Trojans is important because a Trojan Tour is one of five possible New Frontiers missions. A binary could constitute a potentially high value target because of the opportunity to study two objects and to test models of the primordial nature of binaries. The potential to derive mass-based physical information from the binary orbit could yield more clues to the origin of Trojans.

**Author(s): Keith S. Noll[2]**, W. M. Grundy[1], E. L. Ryan4, S. D. Benecchi3
**Institution(s):** *1. Lowell Obs., 2. NASA GSFC, 3. PSI, 4. U MD*

### 211.02 – A long term study of Centaur 174P/Echeclus

Centaur 174P/Echeclus was discovered by the Spacewatch program on March 3, 2000 and initially labelled (60558) 2000 EC 98 . On December 30, 2005, a surprising cometary outburst was discovered with the 5-m Mount Palomar Observatory telescope. This outburst corresponded to a change in the overall visual magnitude from about 21 to about 14. At that time (60558) 2000 EC 98 was located at 13.07 au to the Sun and was subsequently renamed with a cometary designation. This outburst lasted a few months and, one year later, no coma could be detected. Another secondary outburst happened in 2011 and lasted also a few months. This target was at its perihelion (5.82 au) on April 22, 2015.
We present new observational data obtained with the 2.5-m Nordic Optical Telescope during the 2011 outburst and in July 2013, and with the robotic 2-m Liverpool telescope on April 27, 2014, August 13, 2014 and June 1, 2015. We also found archive observational data obtained on December 22, 2005.
These archive images point out the extremely high level of the 174P/Echeclus activity during the first outburst. The R-magnitude and Afrho parameter of the target were estimated to 14.8 and 56000±3000 cm respectively. During the second outburst, in 2011, the activity level of the Centaur was lower, the R-Afrho parameters were 1200±100 cm and 480±70 cm in June and July respectively. The dust production rates needed to produce the observed comae were approximately 700 $kg.s^{-1}$ in 2005 and between 10 and 20 $kg.s^{-1}$ in 2011 assuming the average grain geometric albedo of 0.1 and low outflow velocities of the dust, less than 10 $m.s^{-1}$. A possible scenario of the dust coma formation for the first outburst will also be proposed using a Monte Carlo modeling.
Before the outburst the lightcurve amplitude was 0.24 magnitude in the R-band with a rotation period of 26.80 h (if a double-peaked lightcurve is assumed). The observational data obtained after the outburst with the NOT do not permit to detect any clear variation in the apparent magnitude at the level of about 0.1 magnitude. The different possible explanations for this change will be discussed as well as an analysis of the outbursts themselves.

**Author(s): Philippe Rousselot[1]**, Pavlo Korsun[2], Irina Kulyk[2], Jean-Marc Petit[1], Aurélie Guilbert-Lepoutre[1]
**Institution(s):** *1. Institut UTINAM, 2. Main Astronomical Observatory of NAS*

### 211.03 – Variability and Lightcurves Studies in the Outer Solar System Origins Survey

Lightcurves provide a powerful mechanism for learning about the history of the collisional and/or gravitational processes acting on small bodies since the formation, and subsequent migration, of our solar nebula. At the extremes, they can provide constraints on the material properties (and interior structure) of individual objects and perhaps in quantity can provide information about their source populations. Our project consists of two datasets: (1) the Outer Solar System Origins Survey (OSSOS) discovery and recovery magnitudes, and (2) observations from a 6-hour pilot study on a subset of (17) OSSOS objects using the Subaru and Hyper Suprime-Cam (HSC) instrument. The OSSOS objects span a full range of sizes, from as large as several hundreds of km to as small as a few tens of km in diameter. Because of the telescope diameter and the wide field of view of HSC, we are able to obtain measurements on multiple objects covering a range of magnitudes with a single telescope pointing within the first two years following object discovery. The OSSOS survey is well calibrated photometrically and as such we use the very sparce sampling in the discovery and recovery magnitudes to identify which objects might have the largest amplitude lightcruves, indicating that they are likely elongated or in potentially interesting spin states. We then select the HSC fields containing these objects and the highest density of surrounding objects to obtain more densely sampled lightcurves. In this way we optimize the telescope time and the potential scientific return. We will present our analysis of the OSSOS dataset and some preliminary results from HSC.

**Author(s): Susan D. Benecchi[2]**, Ying-Tung Chen[1], Meg Schwamb[1], Shiang-Yu Wang[1], Matthew Lehner[1], Mike Alexandersen[1]
**Institution(s):** *1. Institute of Astronomy & Astrophysics at Academia Sinica, 2. Planetary Science Institute*

### 211.04 – Photometry of Scattered Disk Objects at 3.6 µm and 4.5 µm

Scattered disk objects (SDO) are some of the most interesting of the estimated 100,000 icy bodies located in the outer Solar System. SDOs have been gravitationally disturbed and scattered by the orbital migration of Neptune. The surface compositions of these objects provide a window into formation conditions and dynamics of the outer Solar System. Characterization of volatiles and organic materials, in particular, provide important constraints on formation conditions and subsequent surface processing of these objects. We measured fluxes of 36 SDOs at 3.6 µm and 4.5 µm using the Infrared Array Camera (IRAC) aboard the *NASA Spitzer Space Telescope* in order to characterize volatiles and organics on their surfaces. Albedos calculated from these fluxes are combined with broadband albedos from ground-based observations at shorter wavelengths (V, R, I, J, H, K bands, spanning 0.55 – 2.22 µm) to provide spectrophotometry from 0.5 to 4.5 µm. Much of those ground-based data are from previously published literature. However, we have also conducted new ground-based Y, J, H, K observations of several of the targets. Sizes and visible geometric albedos, which are required to convert IRAC fluxes to geometric albedos, were extracted from published literature when available and computed from absolute magnitudes otherwise. The resulting spectrophotometry of these 36 SDOs shows a wide range of surface compositions. Several of the SDOs we observed show red visible and near-infrared spectral slopes and strong absorptions at 3.6 µm and 4.5 µm. These absorption features suggest the presence of complex organics. Other SDOs appear red as well but show only moderate absorptions at 3.6 µm and 4.5 µm. Moderate absorption features at these wavelengths may indicate a mixture of $H_2O$ ice and refractory material on the surface. Finally, some objects show no absorption at 3.6 and 4.5 µm, most likely characteristic of silicate dust. We will discuss implications of these findings in terms of surface composition and possible origins.

**Author(s): Chad Mellton[2]**, Joshua P Emery[2], Noemi Pinilla-Alonso[2], Michael Mommert[1], Cassandra Lejoly[1], David E Trilling[1]
**Institution(s):** *1. Northern Arizona University, 2. University of Tennessee, Knoxville*

### 211.05 – A Chemical and Dynamical Link Between Red Centaur Objects and the Cold Classical Kuiper Belt

We present new B-V, V-R, and B-R colors for 32 Centaurs objects using the 4.3-meter Discovery Channel Telescope (DCT) near Happy Jack, AZ and the 1.8-meter Vatican Advanced Technology Telescope on Mt. Graham, AZ. Combining these new colors with our previously reported colors, we now have optical broad-band colors for 58 Centaur objects.
Application of the non-parametric Dip Test to our previous sample of only 26 objects showed Centaurs split into gray and red groups at the 99.5% confidence level, and application of the Wilcoxon Rank Sum Test to the same sample showed that red Centaurs have a higher median albedo than gray Centaurs at the 99% confidence level (Tegler et al., 2008, Solar System Beyond Neptune, U Arizona Press, pp. 105-114).
Here we report application of the Wilcoxon Rank Sum Test to our sample of 58 Centaurs. We confirm red Centaurs have a higher median albedo than gray Centaurs at the 99.7% level. In addition, we find that red Centaurs have a lower median inclination angle than gray Centaurs at the 99.5% confidence level. Because of their red colors and lower inclination angles, we suggest red Centaurs originate in the cold classical Kuiper belt. We thank the NASA Solar System Observations Program for its support.

**Author(s): Stephen C. Tegler[1]**, William Romanishin[2], Guy Consolmagno3
**Institution(s):** *1. Northern Arizona University, 2. University of Oklahona, 3. Vatican Observatory*

### 211.06 – Constraints to the Cold Classical KBO population from HST observations of faint objects

The size distribution of the known Kuiper Belt Objects has been described by a double power law, with a break at R magnitude 25. There are two leading interpretations to this break: 1) It is the result of the collisional evolution among these KBOs, with the objects smaller than the break being the population most affected by collisional erosion. 2) The size distribution break is primordial, set during the Kuiper Belt formation.
The low inclination Kuiper Belt Objects, the Cold Classical population, is thought to have been dynamically isolated since the formation of the Solar System, and thus only collisions between Cold Classicals would have affected their size distribution. If the size distribution is collisional, it probes parameters of the Kuiper Belt history: strengths of the bodies, impact energies and frequency, and the the number of objects. If the distribution is primordial, it reveals parameters of the Kuiper Belt accretion, as well as limits on its subsequent collisional history.
In this work, we obtained new HST observations of 5 faint Cold Classicals, which we combine with previous HST observations, to examine the distribution of two properties of the smallest KBOs: colors and binary fraction. These two properties can differentiate between a primordial and a collisional origin of the size distribution break. If the smaller bodies have been through extensive collisional evolution, they will have exposed materials from their interiors, which has not been exposed to weathering, and thus should be bluer than the old surfaces of the larger bodies. An independent constraint can be derived from the fraction of binary objects: the angular momentum of the observed binaries is typically too high to result from collisions, thus a collisionally-evolved population would have a lower binary fraction, due to the easier separation of binaries, compared to the disruption of similar-sized bodies, and the easier disruption of the binary components, due to the smaller size.
We will present the constraints to the color and binary fraction distributions we are measuring from these observations, which probe the smallest KBOs currently observable.

**Author(s): Paulo F. Penteado[2]**, David Trilling[2], William Grundy[1]
**Institution(s):** *1. Lowell Observatory, 2. Northern Arizona University*

### 211.07 – Quantifying the Infrared Spectra of Icy Methanol - A New Investigation for Solar System Objects

The presence and abundances of organic molecules in extraterrestrial settings, such as on TNOs, can be determined using infrared (IR) spectroscopy, but significant challenges exist. Although reference IR spectra for organics under relevant conditions are vital for such work, for many molecules the data needed either do not exist or exist only in fragmentary form. In this presentation we describe new laboratory results for a three-element molecule, methanol ($CH_3OH$), which has been reported to be present in planetary and interstellar ices. Near- and mid-IR spectra at various ice thicknesses and temperatures are presented, band strengths are calculated, and optical constants are derived. Results are compared to those of earlier workers, the influence of assumptions found in the literature is explored, and possible revisions to the literature are described. Although IR spectra of solid $CH_3OH$ has been reported by many low-temperature laboratory-astrochemistry groups over the past 25 - 30 years, our work appears to be the first that aims to determine the densities, refractive indices, and resulting mid-IR band strengths and optical constants of both the amorphous and crystalline phases of methanol. The majority of the laboratory work in this project was done by Tatiana Tway, who was supported by a summer internship through the DREAM2 program, which in turn is supported by a grant from NASA's SSERVI program.

**Author(s): Reggie L. Hudson[2]**, Tatiana Tway[1], Perry Gerakines[2]
**Institution(s):** *1. Delaware Valley University, 2. NASA Goddard Space Flight Center*

### 211.08 – Trans-Neptunian Objects Transiently Stuck in Neptune's Mean Motion Resonances: numerical simulations of the current population

Inferring from observational data, it is well known that a large population of objects orbits the Sun in mean motion resonance with Neptune with semi-major axes in the range a=30-100AU. Many of these objects were likely caught into resonances by planetary migration---either smooth or stochastic---approximately 4 billion years ago. Some, however, scattered off Neptune and become transiently stuck in more recent events. The goal of this project is to form a testable model of the transient sticking population through numerical simulation. We calculate the relative likelihood of resonance sticking from the current scattering disk into a range of resonances. We confirm that transiently stuck objects are most prevalent in n:1 resonances, followed by n:2, n:3 and so on. The integrated time that objects spend stuck in resonance increases for resonances with longer orbital periods. We calculate the expected distribution of libration amplitudes for resonance angles of stuck objects and comment on implications for the origins of distant resonance populations.

**Author(s): Tze Yeung Mathew Yu[2]**, Ruth Murray-Clay[2], Kathryn Volk[1]
**Institution(s):** *1. The University of Arizona, 2. University of California, Santa Barbara*

### 211.09 – Dynamical Constraints on the Existence of a 9th Planet Residing in the Inner Oort Cloud

The discovery of Sedna, a decade ago, on a highly eccentric orbit beyond the Kuiper belt challenged our understanding of the Solar System. With a perihelion of 76 AU, Sedna is well beyond the reach of the gas-giants and could not be scattered onto its highly eccentric orbit from interactions with Neptune alone. Sedna's aphelion at ~1000 AU is too far from the edge of the Solar System to feel the perturbing effects of passing stars or galactic tides in the present-day solar neighborhood. Some other mechanism likely no longer active in the Solar System today is required to emplace Sedna on its orbit. Sedna's presence predicts a population of icy bodies on similar orbits residing past the Kuiper belt in what has been called the Inner Oort Cloud.
The recent discovery of 2012 VP113 on a similar orbit to Sedna confirmed the presence of the Inner Oort Cloud and identified a possible alignment of the argument of perihelion for objects with orbits detached from Neptune. Based on the expected precession frequency, the arguments of perihelion should be randomly distributed. The existence of a planet beyond 200 AU has been suggested as a possible mechanism to actively control and lock the argument of perihelion of these orbits. We use new dynamical modeling to further investigate this hypothesis and explore the possible orbital configurations and physical properties of such a body residing beyond Neptune. We will also discuss the implications of the presence of a ninth planet for the Solar System's formation and for the current Inner Oort Cloud.

**Author(s): Megan E. Schwamb[2]**, Ramon Brasser[1], Zhi-Wei Zhang [2]
**Institution(s):** *1. Earth-Life Science Institute (ELSI), Tokyo Institute of Technology, 2. Institute of Astronomy & Astrophysics, Academia Sinica (ASIAA)*

### 211.10 – Property of Kozai Dynamics of Inner Oort Cloud Objects with a Hypothetical Planet Beyond Neptune

The origin of a number of Trans-Neptunian objects (TNOs) with large perihelion and semi-major axis are difficult to explain by current models. In addition to Sedna, these include 2010 GB174 (Chen et al., 2013) and 2012 VP113 (Trujillo and Sheppard, 2014) which might represent members of the Inner Oort Cloud objects (IOCOs). One thing of particular interest has to do with the clustering of the argument of perihelion (ω) of the discovered IOCSs near 340$^{0}$. Trujillo and Sheppard (2014) suggested that this effect could be caused by the Kozai mechanism induced by a distant planet. We have performed parametric studies of the orbital motion of hypothetical IOCOs under the influence of this distant planet. Our preliminary results indicate that this distant planet with a perihelion distance of about 150 AU, if exists, should have a mass larger than 2 Earth masses. The observed clustering in the argument of perihelion at around 340$^{0}$ can not be reproduced by our simulations. Instead, the distribution of ω of the test particles in the inner Oort cloud is characterized by concentration around 0 $^{0}$ or 180$^{0}$ and, on the other hand, 90$^{0}$ or 270$^{0}$ (for smaller perihelion and lower inclination).

**Author(s): Zong-Fu Sie[1]**, Hsing-Wen Lin[1], Wing-Huen Ip[1]
**Institution(s):** *1. Institute of Astronomy,NCU*

### 211.11 – Deep Surveys for Inner Oort Cloud Objects

We are undertaking two deep wide-field surveys to discover extremely distant solar system objects. While our target solar system population is the Inner Oort Cloud objects such as 2012 VP113 and Sedna, we are also sensitive to other populations with high perihelia such as the Scattered Kuiper Belt Objects and the highest perihelion Kuiper Belt Objects which have similar arguments of perihelion to the Inner Oort Cloud Objects. These unusual populations are thought to consist primarily of highly eccentric objects which spend most of their orbits hundreds or thousands of AU from the sun. Large aperture telescopes are needed to reach the faintness limits, red magnitudes of 23.5 to 25, required for detection of even the large members of the population. In addition, wide fields of view are also needed since the sky density of the detectable members of the populations approach 1 in 100 square degrees even with large telescopes.
Our primary discovery instruments are the Dark Energy Camera (DECam) on the 4 meter Blanco Telescope at the Cerro Tololo Inter-American Observatory and Hyper Suprime-Cam (HSC) on Subaru Telescope at Maunakea. Each of these instruments has a tremendously wide field of view considering the size of the telescope they are mounted on. DECam has a field of view of about 3 square degrees and HSC has a field of view of about 1.75 square degrees. We will present our survey progress in terms of sky area covered and new objects discovered and highlight some of our more interesting findings.

**Author(s): Chadwick A. Trujillo[2]**, David J Tholen3, Scott S Sheppard[1]
**Institution(s):** *1. Carnegie Inst., 2. Gemini Obs., 3. Univ. Hawaii*

### 211.12 – Results from the Pan-STARRS-1 Outer Solar System Key Project

As part of the Pan-STARRS-1 Outer Solar System Key Project, we have completed two searches of the full data set obtained by the Pan-STARRS-1 Science Consortium. The data set spans more than three years and covers the full sky north of -30 degrees declination. Our two searches employ different algorithms and between them are sensitive to slow-moving objects with magnitudes brighter than approximately r=22.5 and heliocentric distances of 25-250 AU. We present the details of our search pipeline, the results of our surveys, and plans for future surveys with the ongoing Pan-STARRS-1+Pan-STARRS-2 system.

**Author(s): Matthew J. Holman[2]**, Ying-Tung Chen3, Hsing-Wen Lin4, Michael Lackner[1], Matthew J Payne[2], Charles Alcock[2]
**Institution(s):** *1. Harvard University, 2. Harvard-Smithsonian, CfA, 3. IAA, Academia Sinica, 4. National Central University*

### 211.13 – The IMACS Occultation Survey

We report the results of our extended campaign to search for occultations of background stars by small (sub-km) Kuiper belt objects (KBOs) using the IMACS instrument on the Magellan Telescope.
We implemented a novel shutterless continuous readout mode on the IMACS instrument, with custom-made aperture masks, permitting simultaneous high-speed (~40 Hz) photometry for numerous stars, while minimizing the effects of stellar crowding and sky background. Observing in the southern hemisphere allows us to target the intersection of the ecliptic and galactic planes, where hundreds of stars can be monitored with a single field of view.
We observed for a total of ~28 hours spread over eight nights, obtaining over 10,000 star-hours of light curves with per-point SNR > 10. This represents an order of magnitude increase in star hours compared to the previous best ground-based survey by Bianco et al. (2009). Our results allow us to place strong constraints on the surface density of sub-km objects in the Kuiper-Belt, as well as to complement the HST FGS results of Schlichting et al. (2009, 2012).

**Author(s): Matthew John Payne[2]**, Matthew Holman[2], Charles Alcock[2], David Osip[1], Hilke Schlichting3
**Institution(s):** *1. Carnegie, 2. Harvard-Smithsonian, 3. MIT*

### 211.14 – The Outer Solar System Origins Survey (OSSOS): a status update

OSSOS is a 560 hour imaging survey using MegaPrime on the CFHT designed to produce a well characterized sample of Kuiper belt objects whose orbital and physical properties will provide useful constraints on the evolutionary history of the outer solar system. Started in 2013, this 4 year project has now entered the

finally year of survey operation. With 1/2 (84 square degrees) of the observation fully analyzed, OSOSS has detected and tracked 219 TNOs brighter than our typical flux limit of r' ~ 24.5. This is 30% more detections than the entire Canada-France Ecliptic Plane Survey (CFEPS), a precursor project.
Based on the first quarter of the survey the OSSOS project confirms the CFEPS-L7 orbital model of the orbital structure of the TNO population (Petit et al., 2011) and has provided additional evidence of complex structure in the size distribution of scatterin TNOs (Shankman et al., 2015). A number of the OSSOS science teams are presenting results at this meeting: Bannister et al., Benecchi et al., Fraser et al., Volk et al. on a variety of aspects of the orbital and physical properties the OSSOS detected samples. Here we present a summary of the current status of the survey: field locations, basic characterization, detection rates and some global detection statistics.
More details on the OSSOS project are available from our web site: www.ossos-survey.org

**Author(s): J. J. Kavelaars[2]**, Michele T. Bannister[2], Brett Gladman[5], Jean-Marc Petit[3], S. Gwyn[2], Ying-Tung Charles Chen[1], Mike Alexandersen[1], Kat Volk[4]
**Institution(s):** *1. IAA, Academia Sinica , 2. National Research Council of Canada, 3. Observatoire de Besancon, 4. University of Arizona, 5. University of British Columbia*

### 211.15 – Col-OSSOS: Colours of the Outer Solar System Origins Survey

The surfaces of trans-Neptunian objects (TNOs) are poorly understood. Other than the large objects which exhibit signatures of various ices, very little has been discerned about the compositions of most TNOs. In recent years, some concrete knowledge about the distribution of surface colours of small TNOs has come to light. It is now generally accepted that small TNOs fall into at least three classes of object based on their surface colours and albedo. TNO surface type is also correlated with dynamical class, with certain types of TNO being found primarily in certain regions of the outer Solar System. This correlation presents the intriguing idea that the surfaces of TNOs contain information on more than composition, but as well hold the key to understanding the dynamical processes that lead to the giant planets violently dispersing the protoplanetesimal disk and populating the Kuiper Belt region. It is around this idea that the Col-OSSOS survey is predicated. This 4 year program which started in 2014B is simultaneously using the Gemini-North and Canada-France-Hawaii telescopes to gather near simultaneous u, g, r, and J spectral photometry of all targets in the Outer Solar System Origins Survey (OSSOS) brighter than r'=23.5 (~140 expected). The focus of Col-OSSOS is completeness and consistency, with the same SNR=25 being reached in all bands, for all targets brighter than our depth limit.
Col-OSSOS will provide a combined compositional-dynamical map from which key hypotheses about the Solar System's cosmogony can be tested. For example, by mapping the fraction of TNOs with cold-classical like surface colours, we will be able to determine how much of the belt was populated by dynamical scattering versus sweep-up from Neptune. Further, we will be able to constrain the compositional homogeneity of the protoplanetesimal disk. The surfaces of TNOs must reflect that homogeneity; a heterogeneous disk will result in a clumpy colour distribution with many unique types, while a homogeneous disk will result in a smooth distribution of colours with only a few distinct types. Here we will present preliminary results and report on the initial progress of the survey.

**Author(s): Wesley Cristopher Fraser[6]**, Michele Bannister[9], Rosemary Pike[9], Megan Schwamb[2], Michael Marrset[1], JJ Kavelaars[3], Susan Benecchi[5], Audrey Delsanti[1], Audrey Guilbert-Lepoutre[4], Alex Parker[7], Nuno Peixinho[8], Peirre Vernazza[1], Shiang-Yu Wang[2]
**Institution(s):** *1. CNRS - Laboratoire d'Astrophysique de Marseille, 2. Institute of Astronomy & Astrophysics at Academia Sinica, 3. NRC - Herzberg, 4. Observatoire de Besancon, 5. Planetary Science Institute, 6. Queen's University, Belfast, 7. Southwest Research Institute, 8. University of Antofogasta, 9. University of Victoria*

### 211.16 – Status of the Transneptunian Automated Occultation Survey (TAOS II)

The Transneptunian Automated Occultation Survey (TAOS II) will aim to detect occultations of stars by small (~1 km diameter) objects in the Kuiper Belt and beyond. Such events are very rare (<$10^{-3}$ events per star per year) and short in duration (~200 ms), so many stars must be monitored at a high readout cadence. TAOS II will operate three 1.3 meter telescopes at the Observatorio Astronómico Nacional at San Pedro Mártir in Baja California, México. With a 2.3 square degree field of view and a high speed camera comprising CMOS imagers, the survey will monitor 10,000 stars simultaneously with all three telescopes at a nominal readout cadence of 20 Hz. Construction of the site began in the fall of 2013. We present here an update on the status of the TAOS II survey, including the site development, camera fabrication, and project schedule.

**Author(s): Matthew J Lehner[1]**, Shiang Yu Wang[1], Mauricio Reyes-Ruiz[3], You Hua Chu[1], William Lee[4], Zhi Wei Zhang[1], Kem H Cook[1], Timothy Norton[2], Andrew Szentgyorgyi[2], Charles Alcock[2]
**Institution(s):** *1. Academia Sinica Institute of Astronomy and Astrophysics, 2. Harvard-Smithsonian Center for Astrophysics, 3. Instituto de Astronomia, Universidad Nacional Autonoma de Mexico, 4. Instituto de Astronomia, Universidad Nacional Autonoma de Mexico*

### 211.17 – Pan-STARRS 1 discoveries of new Neptune Trojans: Preliminary results

Neptune Trojans are a well-known probe of the dynamical environment of the outer solar system. However, given the small number of known Neptune Trojans, many questions remain: the total number, the size distribution, and the orbital distribution of Neptune Trojans are all still unclear.
Pan-STARRS 1 (PS1) survey provides a chance to comprehensively investigate the properties of Neptune Trojan population. In this study we present our preliminary results of a PS1 search for new Neptune Trojans. We report several candidates. At least one unstable L5 trojan has been confirmed. The preliminary orbital distribution of Neptune Trojan populations shows a possible L4/L5 distribution asymmetry from the combination of our new candidates and the known Neptune Trojans.

**Author(s): Hsing-Wen Lin[3]**, Yin Tung Chen[2], Matthew J. Holman[1], Wing-Huen Ip[3]
**Institution(s):** *1. Harvard-Smithsonian Center for Astrophysics, 2. Institute of Astronomy and Astrophysics, Academia Sinica, 3. Institute of Astronomy, National Central University*

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## 212 – Spiraling in on Ceres and Vesta Redux

### 212.01 – Spikes in High-Energy Electrons at Ceres: Evidence for a Bow Shock?

Strong, regular spikes in counts, suggestive of electrons, were measured by by the Dawn's Gamma Ray and Neutron Detector (GRaND) when Dawn was in Survey orbit about Ceres in June 2015. The source of the spikes was tentatively identified as energetic electrons (up to 100 keV). Individual spikes lasted up to an hour and were superimposed on more gradual variations attributed to energetic ion interactions. The spikes occurred during a period of intense solar activity associated with sunspot AR2371.

The fact that they were seen at the same location on three successive orbits over a 10 day period suggests that the events are associated with Ceres. Fermi-acceleration of the solar wind electrons could explain the dramatic increase in the electron counts. If a bow shock were present at Ceres, electrons could be reflected back into the solar wind and travel along the magnetic field line tangent to the shock and encounter the spacecraft. If a bow shock is confirmed, this would have considerable implications for the existence of an exosphere at Ceres, its characteristics, and possible origins. The observations to date allow such an atmosphere to be transitory.

**Author(s): Michaela Villarreal[2]**, Christopher T Russell[2], Thomas Prettyman[1], Naoyuki Yamashita[1], William Feldman[1]
**Institution(s):** *1. Planetary Science Institute, 2. UCLA*

### 212.02 – Spectral modeling of Ceres VIR data from Dawn: Method and Result

The Dawn spacecraft [1] is at Ceres, the closest of the IAU-defined dwarf planets to the Sun. This work focuses on the interpretation of Ceres' surface composition based on the data from the VIR instrument [2] onboard Dawn. The Visible InfraRed (VIR) mapping spectrometer combines high spectral and spatial resolution in the VIS (0.25-1mm) and IR (1-5mm) spectral ranges. VIR will provide a very good coverage of the surface during its orbital mission at Ceres.
In order to model the measured spectra, we have utilized Hapke's radiative transfer model [3], which allows estimation of the mineral composition, the relative abundances of the spectral end-members, and the grain size. Optical constants of the spectral end-members are approximated by applying the methodology described in [4] to IR spectra reflectance obtained from the RELAB database.
The observed spectra of Ceres surface are affected by a thermal emission component that prevents direct comparison with laboratory data at longer wavelengths. Thus to model the whole wavelength range measured by VIR, the thermal emission is modeled together with the reflectance. Calibrated spectra are first cleaned by removing artefacts. A best fit is obtained with a least square optimization algorithm. For further details on the method, see reference [5].
The range 2.5 - 2.9 µm is severely hindered by Earth's atmosphere, but it contains a strong absorption band that dominates the IR Ceres' spectrum. Thanks to the VIR instrument we can obtain a compositional model for the whole IR range [6]. We used several different combinations of materials hypothesized to be representative of the Ceres' surface including phyllosilicates, ices, carbonaceous chondrites and salts. The results will be discussed.
**Acknowledgements** This work is supported by the Italian Space Agencies and NASA. Enabling contributions from the Dawn Instrument, Operations, and Science Teams are gratefully acknowledged.
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**Author(s): Andrea Raponi[2]**, M.C. De Sanctis[2], M. Ciarniello[2], F.G. Carrozzo[2], E. Ammannito[2], F. Capaccioni[2], M.T. Capria[2], A. Frigeri[2], S. Fonte[2], M. Giardino[2], A. Longobardo[2], G. Magni[2], S. Marchi[2], E. Palomba[2], C.M. Pieters[1], F. Tosi[2], D. Turrini[2], F. Zambon[2], C.A. Raymond3, C.T. Russell4
**Institution(s):** *1. Department of Earth, Environmental, and Planetary Sciences Brown University, 2. IAPS - INAF, 3. Jet Propulsion Laboratory, California Institute of Technology, 4. University of California Los Angeles, Earth Planetary and Space Sciences*

### 212.03 – First Geological Mapping Investigation of the Kerwan Hemisphere of Ceres (0-180°E), from NASA's Dawn Mission

The Dawn Science team divided the surface of Ceres into quadrangles, in order to facilitate systematic geological mapping, which is a tool used to methodically observe and interpret the surfaces of planetary bodies. Here we present a geological map of the Kerwan hemisphere of Ceres (0-180°E), which we assemble from a combination of quadrangle-scale geological maps. Ceres' Kerwan hemisphere is dominated by smooth plains, which surround the 284-km-diameter Kerwan crater. The smooth material has a lower abundance of craters than other parts of the Kerwan hemisphere, and may suggest that regional resurfacing has occurred. The current topography data also indicates that broad, positive topography features are present within Kerwan crater. In addition, there are ejecta deposits surrounding Haulani and Dantu craters, which are distinctive in photometrically corrected mosaics and color composite mosaics. These ejecta deposits may contribute to the #1 and #2 bright albedo regions observed by Li et al. (2006) with the Hubble Space Telescope. In the northern region, there are homogeneously distributed impact craters, most of which are circular, shallow, flat-floored and contain central mounds. Polygonal craters are also observed, which may provide inferences about the target materials in which they formed. In the southern region there are numerous craters containing central mounds and smooth material in their interiors. For example, the 129-km-diameter Zadeni crater contains a broad central mound. Moreover, lobate deposits are found in numerous craters in the Kerwan hemisphere, which are likely formed by mass wasting. Ongoing work will include the development of a detailed geological history and the use of crater morphologies to infer the composition and physical properties of the sub-surface. Currently, our geological mapping is based on Approach (~1.3 km/pixel) and Survey (~400 m/pixel) mosaics of clear and color filter data from the Dawn spacecraft's Framing Camera. In addition, shape models derived from Framing Camera data are used as a mapping aid. Dawn will begin the High Altitude Mapping Orbit (HAMO) in mid-August, and our geological mapping will then incorporate the higher resolution HAMO mosaics (~140 m/pixel).

**Author(s): Jennifer E. C. Scully4**, David A. Williams[1], Scott C. Mest7, Debra L. Buczkowski9, Ralf Jaumann[2], Carol A. Raymond4, Christopher T. Russell[10], Thomas Roatsch[2], Frank Preusker[2], Ryan Park4, Andreas Natheus[6], Martin Hoffmann[6], Michael Schafer[6], Thomas Platz[6], Paul M. Schenk5, Simone Marchi[8], David P. O'Brien7, Maria C. De Sanctis3
**Institution(s):** *1. Arizona State University, 2. German Aerospace Center (DLR), 3. Institute of Astrophysics and Space Planetology, 4. Jet Propulsion Laboratory, California Institute of Technology, 5. Lunar and Planetary Institute, 6. Max Planck Institute for Solar System Research, 7. Planetary Science Institute, 8. Southwest Research Institute, 9. The Johns Hopkins University Applied Physics Laboratory, 10. University of California Los Angeles*

### 212.04 – First Geological Mapping Investigation of the Occator Hemisphere of Ceres (180°-360°E), from NASA's Dawn Mission

The Dawn Science team divided the surface of Ceres into quadrangles, in order to facilitate systematic geological mapping, which is a tool used to methodically observe and interpret the surfaces of planetary bodies. Here we present a geological map from 180° - 360°E longitude of Ceres, which we assemble from a combination of quadrangle-scale geological maps. Geologic units are characterized based on physical attributes such as albedo, morphology, structure, color, and topography, and are related to geologic processes such as volcanism, tectonism, impact cratering, deposition, and weathering. This hemisphere is dominated by a heavily cratered terrain, with both fresh-looking and putatively-relaxed craters evident. Also evident is Occator crater and the feature known as Spot 5, the brightest of the "bright spots" on Ceres. Linear structures are prevalent, but whether they are formed due to impact stresses or by internal activity has not yet been determined. However, the numerous polygonal craters suggest significant sub-surface fracturing. Color data indicates considerable compositional diversity, specifically around Spot 5, as well as around some of the other craters and associated with some of the linear structures. Variations in crater abundance in different parts of this hemisphere suggest that some type of resurfacing might have occurred. Domical, positive relief features are present in some of the craters; a 5 km high feature informally known as "the pyramid" is also identified. Determining the processes by which these topographically high features formed is of major interest in this mapping effort. Ongoing work will include the development of a detailed geological history and the use of crater morphologies to infer the composition and physical properties of the sub-surface. Currently, our geological mapping is based on Approach (~1.3 km/p) and Survey (~400 m/p) mosaics of clear and color filter data from the Dawn spacecraft's Framing Camera. In addition, shape models derived from Framing Camera data are used as a mapping aid. Dawn will begin the High Altitude Mapping Orbit (HAMO) in mid-August, and our geological mapping will then incorporate the higher resolution HAMO mosaics (~140 m/p).

**Author(s): Debra Buczkowski4**, David Williams1, Scott Mest8, Jennifer E. C. Scully3, Ralf Jaumann2, Chris T. Russell10, Carol Raymond3, Thomas Roatsch2, Frank Preusker2, Ryan Park3, Andreas Nathues6, Martin Hoffmann6, Michael Schäfer6, Thomas Platz6, Paul M. Schenk5, Simone Marchi9, David P. O'Brien8, M. Cristina De Sanctis7
**Institution(s):** *1. Arizona State University, 2. DLR, 3. Jet Propulsion Laboratory, Calitfonia Institute of Technology, 4. Johns Hopkins University Applied Physics Laboratory, 5. Lunar and Planetary Institute, 6. MPI for Solar System Research, 7. National Institute of Astrophysics, 8. Planetary Science Institute, 9. Southwest Research Institute, 10. UCLA*

### 212.05 – Origin Hypotheses for Kilometer-Scale Mounds on Dwarf Planet Ceres

The Dawn Framing Camera has revealed numerous domical to conical features on Ceres, which may have relevance to the presence and history of near-surface ice. These features fall into two broad classes, large domes 10s to >100 km in diameter exhibiting 1-5 km of positive relief, and small mounds <10 km in diameter exhibiting sub-kilometer relief. Here, we propose three hypotheses for the origin of the ~150 small mounds identified thus far, and discuss morphological observations that could support each hypothesis as higher resolution data becomes available.
**Hypothesis 1:** Kilometer-scale mounds are produced by localized eruption of cryomagma or hydrothermal material. Observational tests: Kilometer and sub-kilometer scale albedo variations; sub-kilometer flow features on individual mounds; localized vents; conical or domical shape. Challenge: Features are smaller than convective plumes expected from thermal evolution modeling.
**Hypothesis 2:** Kilometer-scale mounds are analogous to terrestrial and martian pingos, which grow by drawing liquid water through a silicate matrix as a freezing front propagates downward. Observational tests: Mounds occurring on smooth material that floods or embays large-scale features; little or no local albedo variation; no small flows associated with individual mounds; domical or ring-shape; concentric or radial fractures on dome, or central depression. Challenge: Small Cerean mounds observed thus far are an order of magnitude larger than terrestrial or martian pingos.
**Hypothesis 3:** Kilometer-scale mounds are rootless cones analogous to features observed on the surface of volcanic flows in volatile-rich regions of Earth and Mars. Rootless cones are produced when layers of fluid material inundate a region; localized devolatilization of a layer mobilizes clasts to form cone-shaped deposits. Observational tests: Mounds on smooth material that floods or embays large-scale features; conical, not domical, profile; large central depressions; cones in organized spatial patterns; no small-scale flows. Challenge: Low gravity environment and/or cryolava composition may be incompatible with this process.
In addition to morphological observations, VIR data will help distinguish between these hypotheses.

**Author(s): Hanna G Sizemore5**, Thomas Platz5, Britney E. Schmidt3, Jennifer E. C. Scully4, Christopher T. Russell7, Scott C. Mest5, David A. Crown5, Mark V. Sykes5, Kynan H. G. Hughson7, Heather T. Chilton3, David A. Williams1, Carle M. Pieters2, Simone Marchi6, Bryan Travis5, Carol A. Raymond4
**Institution(s):** *1. Arizona State University, 2. Brown University, 3. Georgia Institute of Technology, 4. Jet Propulsion Laboratory, 5. Planetary Science Institute, 6. Southwest Research Institute, 7. University of California Los Angeles*

### 212.06 – Common Mountain-Building Processes on Ceres and Pluto?

The Dawn Framing Camera has revealed a unique feature on the surface of Ceres, popularly referred to as the "pyramid." It is a roughly conical and flat-topped feature with an elevation of ~5 km and base diameter of ~20 km. The side slopes are roughly consistent with an angle of repose one expects of particulate material on Earth (which may change with gravity). The pyramid is also notable for its striations down its side over half of its circumference. These striations sharply terminate at the base of the cone without a distinctive talus deposit, including an adjacent crater. Recently released images of Norgay Montes and a second mountain chain in Tombaugh Regio on Pluto by the New Horizons mission reveal mountains with strikingly similar morphologies with the Ceres pyramid. They are of similar size to within a factor of a few. We investigate the hypothesis that there may be a common mechanism giving rise to these features on the two dwarf planets. Given their significantly different heliocentric distances, the remarkable ongoing widespread processing of the surface of Pluto and increasing evidence of relatively recent activity in some areas of Ceres, interior processes such as plume activity or tectonics may be responsible. A comparative study of uplift morphology on the two dwarf planets may also lend insights into heat production and retention on such bodies throughout the solar system.

**Author(s): Mark V. Sykes8**, Michael Bland10, Debra L. Buczkowski4, William Feldman8, Martin Hoffmann6, Kynan Hughson9, Ralf Jaumann1, Scott King11, Lucille LeCorre8, Jian-Yang Li8, Scott Mest8, Andreas Natheus6, David O'Brien8, Thomas Platz6, Thomas Prettyman8, Carol Raymond3, Vishnu Reddy8, Ottaviano Reusch7, Christopher T. Russell9, Paul Schenk5, Hanna Sizemore8, Britney Schmidt2, Bryan Travis8
**Institution(s):** *1. Deutsches Zentrum für Luft- und Raumfahrt, 2. Georgia Institute of Technology, 3. Jet Propulsion Laboratory, Cal Tech, 4. JHU/APL, 5. Lunar and Planetary Institute, 6. Max Planck Institute for Solar System Research, 7. NASA GSFC, 8. Planetary Science Institute, 9. UCLA, 10. USGS, 11. Virginia Tech*

### 212.07 – The fate of Ceres' original crust

The bulk density of Ceres implies that water ice comprises a substantial fraction of Ceres' interior. However, water ice is not stable at Ceres orbital distance and if exposed would have a loss rate of 1 km $Myr^{-1}$ or more. The near-hydrostatic shape of Ceres, and relatively low melting point of ice suggests that the interior is at least partly differentiated. Because Ceres' surface remains exposed to space, it radiates very effectively, and models predicting differentiation retain an undifferentiated crust. This would be denser than the ice shell beneath it resulting in an unstable stratification. This has led to expectations that the crust would founder and the surface of Ceres might be very smooth and relaxed. But could the crust have remained to the present day? Here, we model global-scale overturn on Ceres using both analytical two-layer linear stability analyses, and numerical models to predict the most unstable wavelength, and growth timescales for Rayleigh-Taylor instabilities. We find that for a 10 km-thick crust above a 75 km-thick ice layer, instabilities grow fastest at spherical harmonic degree $l$=4. The growth timescale is a function of the viscosity of the upper layer. This timescale is less than the age of the solar system unless the effective viscosity of the crust is > $10^{24}$ Pa s. We conclude that the crust of Ceres could remain at the surface if it either has some finite elastic strength over a ~800 km length scale, or is an unconsolidated regolith with a large, (> 50%) macro-porosity, such that the regolith is buoyant relative to water ice.

Neither end-member for the crustal strength precludes convective activity in the underlying ice layer. However we note that a thick, porous regolith is a fantastic insulator and may promote heating of the interior and potential foundering of the regolith if the top of the ice becomes too warm. This possibility can be evaluated by models of thermal evolution (e.g., Castillo-Rogez et al., 2010). An episode of global overturn may have been preserved as spatially correlated long-wavelength ($l$=3-5) variations in albedo, composition, and topography, which could be measured by Dawn.

**Author(s): James H. Roberts**[1], Andrew S Rivkin[1]
**Institution(s):** *1. Johns Hopkins University Applied Physics Laboratory*

### 212.08 – Post-Impact Cryovolcanism and the Bright Spots on Ceres

The bright spots on Ceres recently found by NASA's Dawn mission have defied easy explanation. The spots are young, because the 90 km diameter crater in which they are found generally lacks superposed craters, but the composition is equivocal. The very high albedo contrasting on Ceres' dark surface suggests ice, but the spots could be salt deposits. In either case, formation via water volcanism is plausible, either as ice or a salty sublimate. These observations pose the problem: How can there be recent cryovolcanic processes on a relatively low mass and density body that thus has a small complement of long lived radiogenic isotopes (the only plausible heat source)? Here, we suggest the spots are a consequence of the impact process. Ceres' low bulk density indicates abundant water ice, yet spectra indicate a non-volatile surface. Various interior models predict full or partial differentiation, which means that the near surface is structured as a largely icy layer covered by a non-volatile layer of unknown thickness. For a sufficiently thick layer (> 5-10 km), the formation of a 90 km crater will not penetrate this layer; however, the flow field associated with transient crater collapse may extend into the underlying icy material to give final crater morphological characteristics consistent with an icy surface. Deposition of impact heat would primarily be in this non-volatile layer, which would then diffuse away, including some downwards. We have performed finite element simulations of this diffusion, finding that for a non-volatile layer ~10 km thick, this downward diffusion can lead to supra-melting temperatures in the underlying icy material from 0.1 to 10 Myr after the impact, leading to the deposits. This phenomenon might explain why bright spots are not abundant: the crater needs to be the right size relative to layer thickness, the impact would likely need to occur at a high strike angle (for the deepest deposition of impact heat), and any resultant deposits could be ephemeral, consistent with the crater's apparent very young age. Additionally, no special conditions are needed for the evolution of Ceres; instead, these bright spots result from the most common geological process in the solar system: impact.

**Author(s): Andrew J. Dombard**[2], Saman Karimi[2], Paul M. Schenk[1]
**Institution(s):** *1. Lunar and Planetary Institute, 2. Univ. of Illinois at Chicago*

### 212.09 – Dawn Mission's Search for satellites at Ceres: Upper limits on size of orbital objects

Hundreds of asteroids have small secondary satellites or are double, or even multiple body systems; yet dwarf planet Ceres doesn't and isn't. Ground-based and space-based telescopic searches have placed upper limits on the size of any secondary bodies gravitationally bound to Ceres of 1-2 km (Gehrels et al 1987, Bieryla et al. 2011). The Dawn project's satellite working group designed and conducted a search during approach to Ceres and during high orbit concentrating its search close to Ceres' limb where previous searches could not reach. Over 2000 images for both science and optical navigation were searched. In addition, a dedicated satellite search was conducted during two commanded off-nadir pointings. The acquired images extend 5.5° x 5.5° on either side of Ceres, at a range of ~ 145,000 km and solar phase angle at Ceres of 18°. No moving objects associated with Ceres were detected. The search extended down to Ceres' limb (previous searches went to 500 km above the limb) and extended the upper limit for the non-detection to 30 +/- 6 and 45 +/-9 meter radius for effective exposure times of 114s and 19s respectively. An additional small search was conducted using the spacecraft's star tracker from which no objects were found. The Dawn mission's search reduced the previous detection limit from Hubble Space Telescope images by two orders of magnitude. Why some asteroids have satellites and others don't is a matter for dynamical speculation.

**Author(s): Lucy-Ann A. McFadden3**, David R. Skillman3, Nargess Memarsadeghi3, Uri Carsenty[1], Stefan E. Schroeder[1], Jian-Yang Y. Li4, Marc D. Rayman[2]
**Institution(s):** *1. DLR, 2. JPL, 3. NASA/GSFC, 4. PSI*

### 212.10 – Physical Properties of Ceres from the Dawn Mission

The physical parameters of Ceres are determined from processing the images and radio tracking data acquired during the Approach and Survey phases of the Dawn mission. The images with spatial resolution ranging from 8 km to 400 meters were processed using a stereophotoclinometry method. The radiometric tracking data were processed through precision orbit determination together with landmarks derived from the stereophotoclinometry shape reconstruction. Combining the mass and volume values gives the bulk density of 2161 kg/m3, which implies a mixture of silicates with lighter materials. Analyzing the second degree gravity field shows that the rotation of Ceres is very nearly about a principal axis, the degree 2 gravity field is consistent with hydrostatic equilibrium, and the magnitude of J2, combined with the hydrostatic assumption implies some degree of central condensation.

**Author(s): Ryan Park**[1], Alexander Konopliv[1], Bruce Bills[1], Andrew Vaughan[1], Carol Raymond[1], Chris Russell[2]
**Institution(s):** *1. Jet Propulsion Laboratory, 2. UCLA*

### 212.11 – Ceres Evolution: From Thermodynamic Modeling and Telescope to Dawn Orbital Observations

Thermodynamic modeling indicated that Ceres has experienced planetary processes, including extensive melting of its ~25% water and differentiation, (McCord and Sotin, JGR, 2005; Castillo and McCord, Icarus, 2009). Early telescopic studies showed Ceres' surface to be spectrally similar to carboneous-chondrite-like material, i.e., aqueously altered silicates darkened by carbon, with a water-OH-related absorption near 3.06 µm. Later observations improved the spectra and suggested more specific interpretations: Structural water in clay minerals, phyllosilicates, perhaps ammoniated, iron-rich clays, carbonates, brucite, all implying extensive aqueous alteration, perhaps in the presence of $CO_2$. Telescopic observations and thermodynamic models predicted Dawn would find a very different body compared to Vesta (e.g. McCord et al., SSR, 2011), as current Dawn observations are confirming. Ceres' original water ice should have melted early in its evolution, with the resulting differentiation and mineralization strongly affecting Ceres' composition, size and shape over time. The ocean should have become very salty and perhaps may still be liquid in places. The surface composition from telescopes seems to reflect this complex history. The mineralization with repeated mixing of the crust with the early liquid interior and with in-fall from space would create a complex surface that will present an interpretation challenge for Dawn. The Dawn spacecraft is currently collecting observations of Ceres' landforms, elemental and mineralogical/molecular composition and gravity field from orbit. Early results suggest a heavily cratered but distorted and lumpy body with features and composition consistent with internal activity, perhaps recent or current, associated with water and perhaps other volatiles. We will present and interpret the latest Dawn Ceres findings and how they affect our earlier understanding of Ceres evolution from modeling and telescope observations.

**Author(s): Thomas B. McCord4**, Jean Philippe Combe4, Julie C. Castillo-Rogez3, Carol A. Raymond3, Maria Cristina De Sanctis[1], Ralf Jaumann[2], Eleonora Ammannito5, Christopher Russell5
**Institution(s):** *1. 1 Istituto di Astrofisica e Planetologia Spaziali – INAF, 2. DLR, Institute of Planetary Research, 3. Jet Propulsion Laboratory, 4. The Bear Fight Institute, 5. University of California at Los Angeles*

### 212.12 – Arruntia Crater: A Rare Window into Vesta's Northern Hemisphere

One of the intriguing results of the Dawn mission to Vesta was the discovery that the only deposits containing significant olivine, a key mineralogic indicator of primitive materials, occur in two shallow craters in the northern hemisphere. Numerous investigations into these exposures using either the Framing Camera (FC) or the VIR spectrometer typically find similarities between the olivine outcropping in Bellicia's wall and in the Arruntia ejecta. Our own investigations – using a hybrid VIR-FC approach –suggest an important distinction between the exposures at the two craters. Specifically, we find that the proximal Arruntia ejecta are dominated not by an olivine-rich component (although isolated examples occur), but instead by a more evolved, eucritic component. These interspersed eucritic materials are similar to olivine-rich materials in FC data because both components pull the 1 um band to longer wavelengths. Ultimately, however, they are distinguished by the position and strength of the 2 um band, which is not covered by FC wavelengths. The Arruntia ejecta also appear olivine-like in some parameterizations of VIR spectra for the area, but closer examination of the full spectra at a fine spatial scale clearly suggests the presence of two different materials. Interestingly, the approach used here also reveals a separate diogenitic component in the distal Arruntia ejecta as well as in isolated locations within Arruntia's wall. Initial evaluation of stratigraphic relationships in the Arruntia ejecta suggest a pre-impact sequence of eucrite –> olivine-rich -> diogenite grading from depth to the shallowest subsurface (although the small size of Arruntia means that this entire assemblage was excavated from no more than a few of kilometers below the surface). These results illustrate two main points: first, that pyroxene-bearing materials rich in olivine are difficult to distinguish from evolved pyroxenes in the absence of full resolution spectroscopy at a fine spatial scale. Second, we find that Arruntia crater is likely a unique location on Vesta where pervasive mechanical gardening has not yet masked the stratigraphic relationships between endmember diogenitic and eucritic components nor olivine-enhancements.

**Author(s): Jessica Sunshine[1]**, Leah Cheek[1]
**Institution(s):** *1. University of Maryland*

### 212.13 – DAWN observations of Vesta versus lunar-type space weathering

The major reason for spectral changes in lunar-type space weathering is production of nanophase iron ($npFe^0$) in the lunar regolith. The spectral changes include attenuation of silicate absorption bands, darkening, and slope change (reddening). Spectral observations of the asteroid Vesta by DAWN mission revealed a different pattern. The darkening and the absorption band attenuation occur in similar way as on the Moon. The reddening, however, is not apparent. Thus, is space weathering on Vesta different from that we see on the Moon?
In order to study effects of $npFe^0$ on thereflectance spectra, pyroxene (En 90) and howardite (NWA 1929) powder samples were subjected to the space weathering experiments. Both enstatite and howardite show progressive changes in their spectra as a function of the increasing $npFe^0$ amount. An interesting feature is observed in the comparison of the slope over the 1 and 2 µm bands in both pyroxene and howardite. While the slope over 2 µm band show progressive reddening with increasing $npFe^0$ amount (similarly to olivine), the situation is reversed in the 1 µm band region. The relative reduction in the spectral slope is observed in this region.
This is due to the fact that the decrease in reflectance when adding $npFe^0$ is a nonlinear process where higher reflectance values will decrease more than lower values. If the original slope is positive, as the slope over the 1 µm band in pyroxene and howardite, the slope will flatten with increasing $npFe^0$ (relative bluing).
This finding can potentially explain some of the space weathering observations for Vesta. The majority of the DAWN observations were done in the 1 µm region where the lack of reddening is observed, similar to our pyroxene and howardite results. Thus, the lack of reddening over the 1 µm region as observed on Vesta does not contradict the space weathering mechanism driven by the presence of $npFe^0$. In order to confirm this more NIR data from Vesta are needed over the 2 µm region where our experiments predict progressive reddening.

**Author(s): Tomas Kohout[2]**, Ondrej Malina3, Antti Penttila[2], Anni Kroger[2], Daniel Britt[1], Jan Fillip3, Karri Muinonen[2], Radek Zboril3
**Institution(s):** *1. Department of Physics, University of Central Florida, 2. Department of Physics, University of Helsinki, 3. Regional Centre of Advanced Technologies and Materials, Departments of Physical Chemistry and Experimental Physics, Palacky University Olomouc*

## 213 – Asteroid Surfaces

### 213.01 – Investigating Hydroxyl at Asteroid 951 Gaspra

Recent investigations [*Granahan*, 2011; 2014] of Galileo Near Infrared Mapping Spectrometer (NIMS) observations of asteroid 951 Gaspra have detected an infrared absorption feature near 2.8 micrometers. These were detected in NIMS data acquired by the Galileo spacecraft on October 29, 1991 at wavelengths ranging from 0.7 – 5.2 micrometers [*Carlson et al.*, 1992]. This abstract presents a summary of the investigation to identify the material creating the 2.8 micrometer spectral absorption feature. The current best match for the observed 951 Gaspra feature is the phyllosilicate bound hydroxyl signature present in a thermally desiccated QUE 99038 carbonaceous chondrite as measured by *Takir et al.* [2013].
The 951 Gaspra absorption feature has been compared to a variety of hydroxyl bearing signatures. Many phyllosilicates, hydroxyl bearing minerals, have absorption minima at different positions (2.7 or 2.85 micrometers). It also differs from similar absorptions in a potential R chondrite analog, LAP 04840. The spectra LAP 04840 has a 2.7 micrometer feature due to biotite and a 2.9 micrometer feature due to adsorbed water [*Klima et al.*, 2007]. 2.8 micrometer absorption minima have been found for adsorbed hydroxyl on the Moon [*McCord et al.*, 2011] and various carbonaceous chondrites [*Calvin and King*, 1997; *Takir et al.*, 2013]. The best match, with a minimum Euclidean distance difference to the 951 Gaspra feature, is found in the spectrum of QUE 99038 [*Takir et al.*, 2013]. This spectrum is the product of an infrared measurement of a sample that had its adsorbed water baked off and removed in a vacuum chamber. The remaining hydroxyl in the sample belongs to a mixture of phyllosilicates dominated by the presence of cronstedtite.
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**Author(s): James C. Granahan[1]**
**Institution(s):** *1. Leidos*

### 213.02 – Potentially hazardous asteroid (214869) 2007 PA8: The missing link between H chondrites and the outer asteroid belt

We report near-infrared spectra (0.7-2.55 µm) of potentially hazardous asteroid (PHA) (214869) 2007 PA8 obtained with the NASA Infrared Telescope Facility during its close approach to Earth on November 2012. A detailed mineralogical analysis of this object was performed using the measured band parameters, along with laboratory spectral calibrations. We found that 2007 PA8 is a Q-type asteroid with an H chondrite-like composition. The olivine-pyroxene abundance ratio was estimated to be 47%. We determined that the olivine and pyroxene chemistries of this asteroid are $Fa_{18}(Fo_{82})$ and $Fs_{16}$, respectively. The low olivine abundance and the location of the band parameters, close to the H4 and H5 chondrites, suggest that this object originated in the upper middle layers of a larger body that experienced certain degree of thermal metamorphism. The orbit of 2007 PA8 places the source region of this asteroid in the outer part of the main belt. Due to its proximity to the J5:2 resonance, low orbital inclination, and compositional affinity, we determined that 2007 PA8 originated in the Koronis family.

**Author(s): Juan Andres Sanchez3**, Vishnu Reddy3, Melissa Dykhuis[2], Sean Lindsay[1], Lucille Le Corre3
**Institution(s):** *1. Atmospheric, Oceanic, and Planetary Physics, University of Oxford, 2. Lunar and Planetary Laboratory, University of Arizona, 3. Planetary Science Institute*

### 213.03 – The Shape of Near-Earth Asteroid 275677 (2000 RS11) From Inversion of Arecibo and Goldstone Radar Images

We observed near-Earth asteroid 2000 RS11 with the Arecibo and Goldstone planetary radars during a 0.035 au approach in March 2014, obtaining delay-Doppler images between March 13 and March 17. The finest-resolution images have range resolution of 7.5 m/pixel and show that RS11 is a contact binary with complex topography. We used the SHAPE software package (Magri et al., Icarus 186, 156–160; 2007) to create a physical model of RS11 and its spin state from these delay-Doppler images.
The rotation period of RS11 is well constrained from optical lightcurves, P = 4.444 ± 0.001 h (Warner et al., Minor Planet Bulletin 41, 160; 2014 and Benishek, Minor Planet Bulletin 41, 257; 2014). We found two possible pole directions and corresponding shape models, mirror images of one another, which provide equally good fits to the radar data. RS11's pole direction is either $(\lambda , \beta) = (155°, 30°) \pm 10°$ or $(335°, -30°) \pm 10°$ in J2000 ecliptic coordinates. The most likely pole directions of RS11 are not aligned with the heliocentric orbit normal and instead have an obliquity within 10° of 56° or 124°.
Our best-fit shape models are 1400-vertex polyhedra comprising two lobes in contact. The lengths of RS11's principal axes are 698 ± 71 m, 578 ± 59 m, and 758 ± 77 m. RS11 has a volume of 0.086 ± 0.026 km^3. The long axis of RS11's larger lobe is 751 ± 77 m and the long axis of the smaller lobe is 398 ± 41 m; the volume ratio between these lobes is roughly 2.7 ± 10%. Spectral data informs us that RS11 is an S-class object (Lazzarin et al., Icarus 169, 379; 2004).
RS11's shape is unusual compared with those of other contact binary NEAs imaged by radar. Its larger lobe is flattened. Additionally, while the neck between the smaller and larger lobes of most contact binaries is located near the larger lobe's longest principal axis (such as in the cases of 25143 Itokawa and 4179 Toutatis), RS11's neck is near its larger lobe's shortest principal axis. RS11 is the first asteroid of this type for which we have a shape model.

**Author(s): Kaley Brauer[2]**, Michael W. Busch5, Lance A.M. Benner3, Marina Brozovic3, Ellen S. Howell4, Michael C. Nolan4, Alessondra Springmann4, Jon D. Giorgini3, Patrick A. Taylor[1], Joseph S. Jao3
**Institution(s):** *1. Arecibo Observatory, 2. Brown University, 3. Jet Propulsion Laboratory, California Institute of Technology, 4. Lunar & Planetary Laboratory, University of Arizona, 5. SETI Institute*

### 213.04 – Thermophysical Model of S-complex NEAs: 1627 Ivar

We present updates to the thermophysical model of asteroid 1627 Ivar. Ivar is an Amor class near Earth asteroid (NEA) with a taxonomic type of Sqw [1] and a rotation rate of $4.795162 \pm 5.4 * 10^{-6}$ hours [2]. In 2013, our group observed Ivar in radar, in CCD lightcurves, and in the near-IR's reflected and thermal regimes (0.8 – 4.1 µm) using the Arecibo Observatory's 2380 MHz radar, the Palmer Divide Station's 0.35m telescope, and the SpeX instrument at the NASA IRTF respectively. Using these radar and lightcurve data, we generated a detailed shape model of Ivar using the software SHAPE [3,4]. Our shape model reveals more surface detail compared to earlier models [5] and we found Ivar to be an elongated asteroid with the maximum extended length along the three body-fixed coordinates being 12 x 11.76 x 6 km. For our thermophysical modeling, we have used SHERMAN [6,7] with input parameters such as the asteroid's IR emissivity, optical scattering law and thermal inertia, in order to complete thermal computations based on our shape model and the known spin state. We then create synthetic near-IR spectra that can be compared to our observed spectra, which cover a wide range of Ivar's rotational longitudes and viewing geometries. As has been noted [6,8], the use of an accurate shape model is often crucial for correctly interpreting multi-epoch thermal emission observations. We will present what SHERMAN has let us determine about the reflective, thermal, and surface properties for Ivar that best reproduce our spectra. From our derived best-fit thermal parameters, we will learn more about the regolith, surface properties, and heterogeneity of Ivar and how those properties compare to those of other S-complex asteroids. References: [1] DeMeo et al. 2009, Icarus 202, 160-180 [2] Crowell, J. et al. 2015, LPSC 46 [3] Magri C. et al. 2007, Icarus 186, 152-177 [4] Crowell, J. et al. 2014, AAS/DPS 46 [5] Kaasalainen, M. et al. 2004, Icarus 167, 178-196 [6] Crowell, J. et al. 2015, TherMoPS II [7] Howell, E. et al. 2012, AAS/DPS 44 [8] Howell, E. et al. 2015, TherMoPS II. This work is partially supported by NSF (AST-1109855), NASA (NNX13AQ46G), CLASS (NNA14AB05A), and USRA (06810-05).

**Author(s): Jenna L Crowell5**, Ellen S. Howell3, Christopher Magri[6], Yan R. Fernandez5, Sean E. Marshall[2], Brian D. Warner[1], Ronald J. Vervack4
**Institution(s):** *1. Center for Solar System Studies - Palmer Divide Station, 2. Cornell University, 3. LPL/University of Arizona , 4. The Johns Hopkins University Applied Physics Laboratory, 5. University of Central Florida, 6. University of Maine at Farmington*

### 213.05 – Using Simple Shapes to Constrain Asteroid Thermal Inertia

With the use of remote thermal infrared observations and a thermophysical model (TPM), the thermal inertia of an asteroid surface can be determined. The thermal inertia, in turn, can be used to infer physical properties of the surface, specifically to estimate the average regolith grain size. Since asteroids are often non-spherical techniques for incorporating modeled (non-spherical) shapes into calculating thermal inertia have been established. However, using a sphere as input for TPM is beneficial in reducing running time and shape models are not generally available for all (or most) objects that are observed in the thermal-IR. This is particularly true, as the pace of infrared observations has recently dramatically increased, notably due to the WISE mission, while the time to acquire sufficient light curves for accurate shape inversion remains relatively long. Here, we investigate the accuracy of using both a spherical and ellipsoidal TPM, with infrared observations obtained at pre- and post-opposition (hereafter multi-epoch) geometries to constrain the thermal inertias of a large number of asteroids.
We test whether using multi-epoch observations combined with a spherical and ellipsoidal shape TPM can constrain the thermal inertia of an object without *a priori* knowledge of its shape or spin state. The effectiveness of this technique is tested for 16 objects with shape models from DAMIT and WISE multi-epoch observations. For each object, the shape model is used as input for the TPM to generate synthetic fluxes for different values of thermal inertia. The input spherical and ellipsoidal shapes are then stepped through different spin vectors as the TPM is used to generate best-fit thermal inertia and diameter to the synthetically generated fluxes, allowing for a direct test of the approach's effectiveness. We will discuss whether the precision of the thermal inertia constraints from the spherical TPM analysis of multi- epoch observations is comparable to works that use non-spherical shapes. The findings presented at the conference will be discussed in relation to works that also use different shape models (i.e. sphere, lightcurve and radar-derived shapes) to perform TPM analyses on asteroid

thermal data.

**Author(s): Eric M. MacLennan[1]**, Joshua P. Emery[1]
**Institution(s):** *1. The University of Tennessee*

### 213.06 – Near-Infrared Spectroscopy of Trojan Asteroids: Assessing Compositional Bimodality at Small Sizes

The Trojan asteroids orbit the sun within Jupiter's gravitationally stable Lagrange points (L4 and L5). Their unique orbits make them prime targets for study by which to further our understanding of the evolution of the Solar System. The formation scenario that best fits their orbital properties comes from the Nice model, which predicts that the Trojan asteroids originally formed in the Kuiper Belt and were trapped in Jupiter's Lagrange regions during the period of giant-planet-migration-induced instability. Compositions of Trojans offer a test of this prediction. Although the featureless spectra observed previously in the near-infrared (NIR, 0.7–2.5 $\mu$m) preclude compositional determination, further analysis of the spectral slopes for these data revealed two distinct spectral groups. The bimodality of Trojans is defined by the degree of spectral reddening, in which two-thirds of Trojans exhibit redder spectra with the remaining one-third exhibiting less-red spectra. Previous NIR observations of the Trojan asteroids to assess compositional groups focused on the largest objects. Those observations included all Trojans with diameter (>75 km, but an incomplete census at smaller sizes). This study aims to determine whether the bimodality observed in large Trojans is also present for small Trojans (<75 km). We have observed 17 small Trojans residing within Jupiter's L5 Lagrange point (ranging in diameter from ~ 39 km to ~ 75 km) using the SpeX spectrograph at NASA's Infrared Telescope Facility. We have reduced these data and extracted their corresponding spectra. We will analyze the spectral slopes of these objects in the context of previous results on Trojan spectral groups. Such analysis will help further our understanding of the origins of Trojan asteroids, from where they may have originated, and possibly provide a unique perspective into the evolution of the Solar System.

**Author(s): Nicholas C. Stamper[1]**, Joshua P. Emery[1], Michael P. Lucas[1], Richard J. Cartwright[1]
**Institution(s):** *1. University of Tennessee*

### 213.07 – Explaining Space-Weathering Effects on UV-Vis-NIR Spectra with Light-Scattering Methods

Space-weathering (SW) introduces changes to the asteroid reflectance spectra. In silicate minerals, SW is known to darken the spectra and reduce the silicate absorption band depths. In olivine, the neutral slope in Vis and NIR wavelengths is becoming positive [1]. In pyroxene, the positive slope over the 1 µm absorption band is decreasing, and the negative slope over the 2 µm band is increasing towards positive values with increasing SW [2].
The SW process generates small nanophase iron ($npFe^0$) inclusions in the surface layers of mineral grains. The inclusions are some tens of nm in size. This mechanism has been linked to the Moon and to a certain extent also to the silicate-rich S-complex asteroids.
We offer two simple explanations from light-scattering theory to explain the SW effects on the spectral slope. First, the $npFe^0$ will introduce a posititive general slope (reddening) to the spectra. The $npFe^0$ inclusions (~10 nm) are in the Rayleigh domain with the wavelength $\lambda$ in the UV-Vis-NIR range. Their absorption cross-section follows approximately the $1/\lambda$-relation from the Rayleigh theory. Absorption is more efficient in the UV than in the NIR wavelengths, therefore the spectra are reddening.
Second, the effect of $npFe^0$ absorption is more efficient for originally brighter reflectance values. Explanation combines the effective medium theory and the exponential attenuation in the medium. When adding a small amount of highly absorbing $npFe^0$, the effective absorption coefficient $k$ will increase approximately the same $\Delta k$ for the typical values of silicates. This change will increase more effectively the exponential attenuation if the original $k$ was very small, and thus the reflectance high. Therefore, both positive and negative spectral slopes will approach zero with SW.
We conclude that the SW will introduce a general reddening, and neutralize local slopes. This is verified using the SIRIS code [3], which combines geometric optics with small internal diffuse scatterers in the radiative transfer domain.

[1] Kohout T. et al. (2014), *Icarus* 237(15), 75–83.
[2] Kohout T. et al. (2015), *Workshop on Space Weathering of Airless Bodies*, Abstract.
[3] Muinonen K. et al. (2009), *JQSRT* 110, 1628–1639.

**Author(s): Antti Penttilä[1]**, Timo Väisänen[1], Julia Martikainen[1], Tomas Kohout[1], Karri Muinonen[1]
**Institution(s):** *1. University of Helsinki*

### 213.08 – Comparing the Data-reduction Methods for Photometric Modeling

Photometric models describe the light scattering properties of the asteroid's surface, providing clues for the physical properties of the surface, and photometric correction for comparisons between different area on asteroids and laboratory measurements. Different techniques have been widely used to reduce the photometric data for modeling purposes, including different sampling methods, such as average of each image, or keep only four-corners or center area of each image. The purpose of this work is to compare these techniques, analyzing their different effect on photometric modeling and photometric corrections to spectrophotometric data. Our goal is to identify which data-reduction method is the best approach to retrieve the true photometric properties of planetary surface and generate the most credible photometric corrections. Using a set of image data from the Near Earth Asteroid Rendezvous (NEAR) Spacecraft's Multi-Spectral Imager (MSI), we find that the different approaches produce similar results, but they tend to perform differently when the data set is with different quality.

**Author(s): Xiaoduan Zou[2]**, Jian-Yang Li[2], Beth Ellen Clark[1]
**Institution(s):** *1. Ithaca College, 2. Planetary Science Institute*

### 213.09 – Shape and topography corrections for planetary nuclear spectroscopy

The elemental composition of planetary surfaces can be determined using gamma ray and neutron spectroscopy. Most planetary bodies for which nuclear spectroscopy data have been acquired are round, and simple, analytic corrections for measurement geometry can be applied; however, recent measurements of the irregular asteroid 4 Vesta by Dawn required more detailed corrections using a shape model (Prettyman et al., Science 2012). In addition, subtle artifacts of topography have been observed in low altitude measurements of lunar craters, with potential implications for polar hydrogen content (Eke et al., JGR 2015). To explore shape and topography effects, we have updated the general-purpose Monte Carlo radiation transport code MCNPX to include a polygonal shape model (Prettyman and Hendricks, LPSC 2015). The shape model is fully integrated with the code's 3D combinatorial geometry modules. A voxel-based acceleration algorithm enables fast ray-intersection calculations needed for Monte Carlo. As modified, MCNPX can model neutron and gamma ray transport within natural surfaces using global and/or regional shape/topography data (e.g. from photogrammetry and laser altimetry). We are using MCNPX to explore the effect of small-scale roughness, regional-, and global-topography for asteroids, comets and close-up measurements of high-relief features on larger bodies, such as the lunar surface. MCNPX can characterize basic effects on measurements by an orbiting spectrometer such as 1) the angular distribution of emitted particles, 2) shielding of galactic cosmic rays by surrounding terrain and 3) re-entrant scattering. In some cases, re-entrant scattering can be ignored, leading to a fast ray-tracing model that treats effects 1 and 2. The algorithm is applied to forward modeling and spatial deconvolution of epithermal neutron data acquired at Vesta. Analyses of shape/topography effects and correction strategies are presented for Vesta, selected small bodies and cratered planetary surfaces.

**Author(s): Thomas H. Prettyman[1]**, John S. Hendricks[2]
**Institution(s):** *1. Planetary Science Institute, 2. Techsource, Inc.*

**213.10 – Spectral bluing on 101955 Bennu and implications for dynamics of sub micron regolith grains on asteroids**

C and B class asteroids (including 101955 Bennu, the destination of the OSIRIS REx mission) display spectral bluing in the visible (Lantz et al. 2013). This spectral bluing effect has been found to be temporally variable on Bennu (Binzel et al. 2015). Binzel et al. suggested this is due to a fining of the ~45 micron grain size fraction, which causes spectral reddening. This finer grain size of the ~45 micron fraction may be associated with regolith migration during formation of Bennu's equatorial ridge.
In Brown (2014) the effect of grain size and optical index on the albedo of small conservative and absorbing particles as a function of wavelength was examined. The conditions necessary for maximization of spectral bluing effects in real-world situations were identified.
The spectral bluing to be discussed in this presentation was present in the Lantz et al. spectra, but not the Binzel et al. spectra, suggesting that in addition to finer grain ~45 micron material, a decrease in the sub micron grain sized fraction has taken place as Bennu's sub-Earth latitude changed between these observations. Observations of this effect may provide the strongest test yet for cohesive regolith models (e.g. Rositis et al. 2014).
In this presentation, I will discuss: 1.) the evidence for spectral bluing on 101955 Bennu (in particular) and other bodies in our solar system and 2.) the implications of how the OVIRS instrument on OSIRIS-REx may be used to determine the spatial variability of this spectral feature on Bennu and 3.) the potential for OVIRS to augment our understanding of the dynamics of sub micron material on asteroids.
Refs:
Binzel, R. P. et al. "Spectral slope variations for OSIRIS-REx target Asteroid (101955) Bennu: Possible evidence for a fine-grained regolith equatorial ridge" Icarus 256 (2015), 22-29
Brown, Adrian J. “Spectral Bluing Induced by Small Particles under the Mie and Rayleigh Regimes.” Icarus 239 (2014): 85–95.
Lantz, C., et al. “Evidence for the Effects of Space Weathering Spectral Signatures on Low Albedo Asteroids.” A&A 554 (2013): 138.
Rositis, B. et al. "Cohesive forces prevent the rotational breakup of rubble-pile asteroid (29075) 1950 DA" Nature (2014): 174-176

**Author(s): Adrian J Brown[1]**
**Institution(s):** *1. SETI Institute*

**213.11 – SHERMAN: A Shape-based Thermophysical Model for Near-Earth Asteroids**

We have developed a thermophysical model, SHERMAN, which can produce temperature distributions and thermal fluxes for airless bodies. Although intended for near-Earth asteroids (NEAs), it has applications to the Moon and may be adapted for other situations. SHERMAN is based on the asteroid shape modeling code, developed by Hudson (1993) and enhanced by Magri et al., (2007, 2011). The input model asteroid can have an arbitrary shape described as a polyhedral solid with triangular facets. The user specifies a spin state, which can include non-principal axis rotation. The asteroid orbit and positions of the Sun and Earth are input so that the proper heating and viewing geometry of the object are used. The user specifies the optical scattering law, IR emissivity, thermal inertia, specific heat, density and conductivity, all of which are permitted to vary across the surface if desired. We have applied this model to relative reflectance observations of NEAs with a wide range of compositions, sizes and shapes, in order to determine how much these properties can affect the thermal emission. We have selected objects that are also observed with radar, so that the shape and spin state is known, at least to some extent. We find that irregular shapes can significantly affect the surface temperature distribution. Observations at several different viewing geometries can rarely be fit by a single set of thermal parameters, unless the detailed shape, spin and surface properties are included. We present results using this model, and discuss future applications to better understand the nature of asteroid surfaces.

**Author(s): Ellen S. Howell[4]**, Christopher Magri[6], Ronald J. Vervack[3], Yanga R Fernandez[5], Michael C Nolan[4], Patrick A. Taylor[1], Sean E Marshall[2], Jenna L. Crowell[5]
**Institution(s):** *1. Arecibo Observatory/USRA, 2. Cornell University, 3. JHU/APL, 4. LPL/U. Arizona, 5. U. Central Florida, 6. U. Maine at Farmington*

**213.12 – Spectrophotometric Properties of Gaspra's Surface**

Using the shape-model derived for Gaspra [1] we calculate the local incidence, emission, and phase angles on a pixel-by-pixel basis for the color image sets (164 m/px spatial resolution) acquired by the Galileo Solid State Imager (SSI) [2]. Using these geometric values, we derive a disk-resolved photometric correction for application to the to the spectral data set for more accurate regional examination of mineralogy and weathering across the surface. We use regional variations in color ratios of Gaspra's surface to examine the degree of space weathering incurred upon the surface, and find subtle variations across its surface. Using mixing modeling methods that account for submicroscopic components, we examine evidence for space weathering variations correlated to composition and grain size. We note evidence of a young surface, with only moderate modification by space weathering processes. SSI radiometrically-calibrated data combined with shape-model derived incidence, emission, and phase angle backplanes have been archived in the Planetary Data System for broader use by the community [3, 4].
[1] P. Thomas et al. 1994, Icarus 107, 23 – 36. [2] M. Belton et al. 1992, Science 257, 1647 – 1652. [3] D. Domingue 2015, Galileo SSI/Gaspra Radiometrically Calibrated Images V1.0. NASA PDS. [4] D. Domingue 2015, Galileo SSI/Gaspra Color and Geometry Image Cubes V1.0. NASA PDS, submitted.

**Author(s): Deborah L. Domingue[2]**, Faith Vilas[2], Karen Stockstill-Cahill[2], Joshua Cahill[1], Amanda Hendrix[2]
**Institution(s):** *1. Johns Hopkins University/Applied Physics Laboratory, 2. Planetary Science Institute*

**213.13 – Methodology of Space Weathering Simulation and Its Application on Olivine and Pyroxene Samples**

Here, we reported a two-step thermal treatment method [1] for the space weathering simulation and the differences in the formation of metallic iron nanoparticles ($npFe^0$) on the surface of olivine and pyroxene samples are discussed.
In general, the main goal is in controlled size of $npFe^0$ formed on the surface of olivine and pyroxene and in quantification of the related spectral changes. The transmission electron microscopy (TEM) after double-heating method revealed two significant features. First, different sizes and concentration of $npFe^0$ are observed, and secondly, due to more resistance of pyroxene (e.g. [2]), higher temperatures are needed to produce the same amount of $npFe^0$ as in the olivine case. [1]
Results from TEM are fully consistent with reflectance spectra, which show progressive changes as a function of the increasing $npFe^0$ amount. The reason for the observed differences in reflectance spectra can be found in the crystal structure and local environment at each crystallographic position of both samples. It is very similar as in the case of laser heating experiments (e.g. [2]), where the surface of orthopyroxene is significantly more resistant to reduction than olivine due to mobility of oxygen and cation diffusions from the bulk to surface of the samples.
References:
[1] Kohout T. et al. (2014) *Icarus*, 237, 75-83
[2] Quadery A. et al (2015) *JGR-Planets* 120, 1-19.

**Author(s): Ondrej Malina[2]**, Tomas Kohout[3], Jiri Tucek[2], Jan Filip[2], Daniel Britt[1], Radek Zboril[2]
**Institution(s):** *1. Department of Physics, University of Central Florida, 2. Palacky University, 3. University of Helsinky, Department of Physics*

**213.14 – Visible Wavelength Reflectance Spectra and Taxonomies of Near-Earth Objects from Apache Point Observatory**

Near-Earth Objects (NEOs) are interesting to scientists and the

general public for diverse reasons: their impacts pose a threat to life and property; they present important albeit biased records of the formation and evolution of the Solar System; and their materials may provide *in situ* resources for future space exploration and habitation.
In January 2015 we began a program of NEO astrometric follow-up and physical characterization using a 17% share of time on the Astrophysical Research Consortium (ARC) 3.5-meter telescope at Apache Point Observatory (APO). Our 500 hours of annual observing time are split into frequent, short astrometric runs (see poster by K. A. Nault *et. al*), and half-night runs devoted to physical characterization (see poster by M. J. Brucker *et. al* for preliminary rotational lightcurve results). NEO surface compositions are investigated with 0.36-1.0 μm reflectance spectroscopy using the Dual Imaging Spectrograph (DIS) instrument. As of August 25, 2015, including testing runs during fourth quarter 2014, we have obtained reflectance spectra of 68 unique NEOs, ranging in diameter from approximately 5m to 8km.
In addition to investigating the compositions of individual NEOs to inform impact hazard and space resource evaluations, we may examine the distribution of taxonomic types and potential trends with other physical and orbital properties. For example, the Yarkovsky effect, which is dependent on asteroid shape, mass, rotation, and thermal characteristics, is believed to dominate other dynamical effects in driving the delivery of small NEOs from the main asteroid belt. Studies of the taxonomic distribution of a large sample of NEOs of a wide range of sizes will test this hypothesis. We present a preliminary analysis of the reflectance spectra obtained in our survey to date, including taxonomic classifications and potential trends with size.
Acknowledgements: Based on observations obtained with the Apache Point Observatory 3.5-meter telescope, which is owned and operated by the Astrophysical Research Consortium. We gratefully acknowledge support from NASA NEOO award NNX14AL17G, and thank the University of Chicago Department of Astronomy and Astrophysics for observing time in 2014.

**Author(s): Mark Hammergren[1]**, Melissa J. Brucker[1], Kristie A. Nault[1], Geza Gyuk[1], Michael R. Solontoi[2]
**Institution(s):** *1. Adler Planetarium, 2. Lynchburg College*

### 213.15 – A 3 mircon spectral survey of Jupiter trojans

The surface compositions of Jupiter trojans remain mysterious. While the red colors have often been taken to be indicative of the presence of organic materials, no distinct spectral features have been found in reflectance spectroscopy spanning 0.4 - 2.5 microns, while thermal emission spectroscopy has shown only the signature of fine-grained silicates. Many materials which may reside on the surfaces of Jupiter trojans have their strongest fundamental bands in the 3-4 micron region, making this spectral region a prime target for understanding composition of otherwise featureless objects. We have obtained 2-4 micron spectra of 16 large Jupiter trojans using the NIRSPEC instrument at the Keck Observatory. We find significant variability in the spectral behavior across this range. While some of the Jupiter trojan asteroids remain featureless, others have a deep absorption at 3 microns. The depth of this 3 micron absorption feature is strongly correlated with the optical color of the individual asteroid. We will discuss possible spectral identifications of this spectral feature, the implications of the color-absorption correlation, and conclusions to be drawn on the source of the Jupiter trojans.

**Author(s): Michael E. Brown[1]**
**Institution(s):** *1. Caltech*

### 213.16 – A Near-Infrared Spectral Survey of Hungaria Region Asteroids: Compositionally Diverse Neighbors of the Terrestrial Planets

The surface compositions of Hungaria region asteroids are poorly understood. These neighbors to the terrestrial planets are unique as they are found interior to the Main-belt and have resided in their current location since early in solar system history. Mars-crossing and near-Earth asteroids make closer approaches to the terrestrial planets, but they are dynamically short-lived (~10 Myr) escapees from the Main-belt. Original planetesimals within the terrestrial planet region were either accreted or scattered out early in solar system history, leaving the Hungarias as the closest remaining "survivors" of the asteroidal material from which the terrestrial planets accreted.
We have undertaken an observational campaign to record the near-infrared reflectance spectra of 42 (36 background; 6 family) Hungaria asteroids with absolute magnitudes $H_v$ <16 to characterize their surface mineralogy through spectral band parameter measurements. By comparing these telescopic data with spectral and geochemical data obtained in the laboratory from "free" asteroid samples that arrive to Earth as meteorites, we can establish connections between Hungaria asteroids and analogous meteorite groups.
We find evidence of three main meteorite-groups represented in the Hungaria region; 1) enstatite achondrites (i.e., aubrites), 2) ordinary chondrites (i.e., H, L, and LL), and 3) primitive achondrites (i.e., acapulcoites and lodranites). Five of the six Hungaria family members are spectrally consistent with the largest collisional fragment (434) Hungaria, which is widely considered to be related to fully-melted aubrite meteorites. Analyses of spectral band centers and band area ratios for 25 of 36 Hungaria background objects reveal evidence for two other meteorite groups. Published laboratory data for ordinary chondrites compared with our asteroid spectra point to the existence of unmelted L and LL chondrites in the region. Preliminary results from the laboratory analyses of our suite of 12 primitive achondrites indicate the existence of partially-melted primitive achondrites in the region as well. These asteroid-meteorite connections suggest that planetesimals in the Hungaria region have experienced varying degrees of petrologic evolution.

**Author(s): Michael P Lucas[1]**, Joshua P. Emery[1], Noemi Pinilla-Alonso[1], Sean S. Lindsay[2], Vania Lorenzi3
**Institution(s):** *1. Department of Earth & Planetary Sciences, University of Tennessee, 2. Department of Physics & Astronomy, University of Tennessee, 3. Fundación Galileo Galilei - Istituto Nazionale di Astrofisica*

### 213.17 – Error Analysis of Stereophotoclinometry in Support of the OSIRIS-REx Mission

Stereophotoclinometry has been used on numerous planetary bodies to derive the shape model, most recently 67P-Churyumov-Gerasimenko (Jorda, et al., 2014), the Earth (Palmer, et al., 2014) and Vesta (Gaskell, 2012). SPC is planned to create the ultra-high resolution topography for the upcoming mission OSIRIS-REx that will sample the asteroid Bennu, arriving in 2018. This shape model will be used both for scientific analysis as well as operational navigation, to include providing the topography that will ensure a safe collection of the surface.
We present the initial results of error analysis of SPC, with specific focus on how both systematic and non-systematic error propagate through SPC into the shape model. For this testing, we have created a notional global truth model at 5cm and a single region at 2.5mm ground sample distance. These truth models were used to create images using GSFC's software Freespace. Then these images were used by SPC to form a derived shape model with a ground sample distance of 5cm.
We will report on both the absolute and relative error that the derived shape model has compared to the original truth model as well as other empirical and theoretical measurement of errors within SPC.
Jorda, L. et al (2014) "The Shape of Comet 67P/Churyumov-Gerasimenko from Rosetta/Osiris Images", AGU Fall Meeting, #P41C-3943. Gaskell, R (2012) "SPC Shape and Topography of Vesta from DAWN Imaging Data", DSP Meeting #44, #209.03. Palmer, L. Sykes, M. V. Gaskll, R.W. (2014) "Mercator — Autonomous Navigation Using Panoramas", LPCS 45, #1777.

**Author(s): Eric Palmer[1]**, Robert W Gaskell[1], John R Weirich[1]
**Institution(s):** *1. Planetary Science Institute*

### 213.18 – From microscope to telescope: Using laboratory spectroscopic measurements to constrain

**the thermal evolution of silicate bodies in the solar system**

Spectral measurements of planets and asteroids have long been used to inventory the composition of their surfaces. If laboratory techniques can be extrapolated to the larger spatial scales of remote observations, infrared spectroscopic measurements offer the potential to delve even deeper into the thermal evolution of these bodies. However, the scattering of light and mixing from the microscopic through macroscopic scales greatly complicates the analysis of components present even when surfaces are viewed at comparably high spatial resolution (<10-100 m/pixel). For this project, we have prepared and measured a set of meteorites and terrestrial analog rocks to perform coordinated spectroscopic studies, from microscopic spectral measurements across individual grains through measurement of bulk mineral and rock samples in ultra-high vacuum (UHV), to investigate two questions: (1) can microscopic mineral textures related to cation ordering and exsolution be reliably distinguished from physical mixtures as occur in regoliths and (2) can internally bound water in minerals be distinguished from water that has adsorbed from the environment. In each case, we explore how well the laboratory techniques address these questions and, through spectral modeling, what the limitations and challenges are for extrapolating these measurements to remote observations.

**Author(s): Rachel L. Klima[1]**, Brianna C. Young[1], Andy S. Rivkin[1]
**Institution(s):** *1. Johns Hopkins University Applied Physics Laboratory*

### 213.19 – New insights into asteroid 3200 Phaethon's meteor complex

In this work, we study the meteor complex originating from asteroid 3200 Phaethon. Using a modeling of variety of meteoroid streams and following their dynamical evolution, we confirm the presence of two filaments crossing the Earth observed as Geminid and Daytime Sextantid meteor showers. We use numerical integrations of modeled particles performed for several past perihelion passages of the asteroid considering (i) only the gravity of planets and (2) gravity of planets and the Poynting-Robertson effect. We present the results of comparing our models (predicted showers) with observed showers. We also point out discrepancies, their possible solutions and/or new hypothesis concerning the examined meteor complex.

**Author(s): Marian Jakubik[1]**, Lubos Neslusan[1]
**Institution(s):** *1. Astronomical Institute of the Slovak Academy of Sciences*

### 213.20 – Scale-Dependent Measurements of Meteorite Strength and Fragmentation: Tamdakht (H5) and Allende (CV3)

Meteorites are pieces of natural space debris, which have survived ejection from their parent bodies and passage through the Earth's atmosphere. As such, they provide a unique opportunity to study the fundamental physical and mechanical properties of early Solar System materials. But to date, few direct studies of physical properties have been conducted on meteoritic materials, in contrast to extensive chemical and isotopic analyses. It is important to determine these properties as they are related to disruption and fragmentation of bolides and asteroids, and activities related to sample return and hazardous asteroid mitigation. Here we present results from an ongoing suite of scale-dependent studies of meteorite strength and fragmentation. The meteorites studied are Tamdakht (H5), an ordinary chondrite that exhibits a heterogeneous structure criss-crossed with shock veins and centimeter-sized regions of white and light grey, and the carbonaceous chondrite Allende (CV3), which suitable pieces are light grey with abundant chondrules and CAIs. Uniaxial compression tests are performed on meteorite cubes ranging from 0.5 to 4 centimeters using an Instron 5985 frame with a 250 kN load cell and compression fixtures with 145mm diameter radial platens. All tests are conducted at room temperature and in displacement control with a displacement rate of 0.25 mm per minute to ensure quasi-static conditions. A three-dimensional digital image correlation (DIC) system that enables noncontact measurement of displacement and strain fields is also used. Analysis of the strength and failure process of the two meteorite types is conducted and compared to terrestrial materials.

**Author(s): Desireé Cotto-Figueroa[1]**, Erik Asphaug[1], Laurence Garvie[1], Melissa Morris[2], Ashwin Rai[1], Aditi Chattopadhyay[1], Nikhilesh Chawla[1]
**Institution(s):** *1. Arizona State University, 2. State University of New York at Cortland*

### 213.21 – Compositional study of asteroids in the Erigone collisional family using visible spectroscopy at the 10.4m GTC

Asteroid families are formed by the fragments produced by the disruption of a common parent body (Bendjoya & Zappalà 2002). Primitive asteroids in the solar system are believed to have undergone less thermal processing than the S-complex asteroids. Thus, study of primitive asteroid families provides information about the solar system formation period. The Erigone collisional family, together with other three families (Polana, Clarissa and Sulamitis), are believed to be the origin of the two primitive Near-Earth asteroids that are the main targets of the NASA's OSIRIS-REx ((101955) Bennu) and JAXA's Hayabusa 2 ((162173) 1999 JU3) missions (Campins et al. 2010; Campins et al. 2013; Lauretta et al. 2010; Tsuda et al. 2013). These spacecrafts will visit the asteroids, and a sample of their surface material will be returned to Earth. Understanding of the families that are considered potential sources will enhance the scientific return of the missions. The main goal of the work presented here is to characterize the Erigone collisional family. Asteroid (163) Erigone has been classified as a primitive object (Bus 1999; Bus & Binzel 2002), and we expect the members of this family to be consistent with the spectral type of the parent body. We have obtained visible spectra (0.5-0.9 μm) for 101 members of the Erigone family, using the OSIRIS instrument at the 10.4m Gran Telescopio Canarias. We performed a taxonomical classification of these asteroids, finding that the number of primitive objects in our sample is in agreement with the hypothesis of a common parent body. In addition, we have found a significant fraction of asteroids in our sample that present evidences of aqueous alteration. Study of aqueous alterations is important, as it can give information on the heating processes of the early Solar System, and for the associated astrobiological implications (it has been suggested that the Earth's present water supply was brought here by asteroids, instead of comets, in opposition to previous explanations (Morbidelli et al. 2000).

**Author(s): David Morate[2]**, Julia de León[2], Mário De Prá[4], Javier Licandro[2], Antonio Cabrera-Lavers[1], Humberto Campins[5], Noemí Pinilla-Alonso[6], Víctor Alí-Lagoa[3]
**Institution(s):** *1. GTC Project Office, 2. Instituto de Astrofisica de Canarias, 3. Lagrange Boulevard de l'Observatoire, 4. Observatório Nacional, 5. University of Central Florida, 6. University of Tennessee*

## 214 – Asteroid Dynamics

### 214.01 – On the dynamical dispersal of primordial asteroid families

Many asteroid families are identified and well characterized all over the main belt asteroid. Interestingly, however, none of them are older than ~4 Gyr. Many mechanisms have been proposed to disperse such old primordial asteroid families that presumably have existed, but none have really worked. Here we present a plausible mechanism for dispersing primordial asteroid families that is based on the 5-planet instability model known as jumping Jupiter. Using two different evolutions for the jumping-Jupiter model, we have numerically integrated orbits of eight primordial families. Our results show that the most important effect on the asteroid families' eccentricity and inclination dispersal is that of the secular resonances, in some cases associated with the mean motion resonances. As for the semimajoraxes spreading we find that the principal effect is that of close encounters with the fifth giant planet whose orbit briefly overlaps with (part of) the main belt. Therefore, the existence of a fifth giant planet with the mass comparable with that of Uranus' or Neptune's could contribute in important ways to dispersal of the primordial asteroid families. To have that effect, the interloper planet should penetrate and considerably interact with the asteroids during the instability phase.

**Author(s): Pedro Ivo de Oliveira Brasil[1]**, Fernando Roig[1], David Nesvorný[2], Valerio Carruba[3], Safwan Aljbaae[3], Mariela Espinoza Hauman[3]
**Institution(s):** *1. Observatório Nacional, 2. SwRI, 3. UNESP*

### 214.02 – Modeling Asteroid Dynamics using AMUSE: First Test Cases

We are creating a dynamic model of the current asteroid population. The goal is to reproduce measured impact rates in the current Solar System, from which we'll derive delivery rates of water and organic material by tracing low-albedo C-class asteroids (using the measured albedo distribution from WISE catalog), the parent bodies of carbonaceous chondrite meteorites. Ultimately, we aim at studying the role of "exo-asteroids" in the delivery of water to exoplanets.
Our model is set up using the Astrophysical Multipurpose Software Environment (AMUSE; amusecode.org). AMUSE provides a common Python wrapper around numerous astrophysical codes including N-body gravity codes such as Mercury and Huayno.
We report first results towards a validation of our model: long-term integrations of the planets alone as well as studies of the depletion of the Kirkwood gaps in the asteroid belt. Further model developments will be discussed.

**Author(s): Kateryna Frantseva[2]**, Michael Mueller[1], Floris van der Tak[2], Frank P. Helmich[2]
**Institution(s):** *1. Kapteyn Astronomical Institute (University of Groningen), 2. Netherlands Institute for Space Research*

### 214.03 – Stability of the Slivan states

The past decade has seen an increase in the number of asteroids for which observations allowed resolving the rotation pole orientation. This data led to new studies of asteroids and their populations. One of the early examples was a discovery of Slivan states in the Koronis family (Slivan 2002). The group of prograde-rotating asteroids had spin axes nearly parallel in inertial space and similar rotation periods (later dubbed the Slivan states). Vokrouhlicky et al. (2003) proposed model based on the idea that the spin axis is confined in a resonance between its precession rate by solar torques and a particular mode of these asteroids' orbit precession in the inertial space (in this case the $s_6$ mode). The theoretical framework describing such situation is called Cassini dynamics.
Since the past decade the importance of the Cassini dynamics in description of asteroid rotation has significantly increased, we aim to present an efficient tool for its description.
We combined two symplectic integration tools into a single software. First, we use the widespread and well-tested swift integrator for orbital dynamics of the asteroid (Levison & Duncan 1994). Second, we included the spin propagator formulated by Breiter et al. (2005) into the swift architecture. This enables to simultaneously integrate orbital and rotational dynamics in a single run.
We show tests that reproduce Slivan states in the Koronis zone. We also analyse stability of the Slivan states in the inner main belt, specifically in the Flora family region. We find Massalia family to be a more suitable inner main-belt location of the classical Slivan states, because of a separation between the s and $s_6$ nodal frequencies. We also demonstrate that the Slivan states may associated with other than the $s_6$ frequency. Under well-tuned conditions, the Slivan states may also exists for the $s_7$ planetary frequency. For the outer main-belt body 184 Dejopeja, we find its pole location near a stable $s_7$-associated Slivan state. Because the forced inclination of the $s_7$ term is significantly smaller than that of the $s_6$ term, the obliquity range of the $s_7$ Cassini state is very small. Therefore the new, $s_7$-related Slivan states are perhaps of only an academic interest.

**Author(s): Jan Vrastil[1]**, David Vokrouhlicky[1]
**Institution(s):** *1. Charles University in Prague*

### 214.04 – The Orbit and Size of (87) Sylvia's Romulus from the 2015 Apparition

Using the US Air Force's Starfire Optical Range 3.5 meter telescope with adaptive optics and a laser guidestar, we obtained 68 images of asteroid (87) Sylvia and its satellite Romulus over 10 nights in March and May of 2015. Adding an additional 3 images from earlier observations on one night in November 2012, we are able to derive a circular (but not an eccentric) orbit for Romulus, leading to a density for Sylvia of 1.37±0.04 gm/cm3. Extending the time base to 14 years by combining our data with previous observations from Keck, HST, and the VLT reported in the literature, we can fit for a new circular orbit and improve the density estimate to 1.35±0.03 gm/cm3. By fitting a Fourier series to the measured magnitude difference between Sylvia (V=12.5) and Romulus, which ranged from 4.1 to 5.1 in the J-band (λ=1.2μm), and modeling both as triaxial ellipsoids, we are able to derive equatorial ellipsoid diameters for Romulus of 39x29, both ±1 km. (All errors here are formal fitting errors.) As far as we know, our 3.5 m telescope is the smallest ground-based telescope to ever image any asteroid's moon.

**Author(s): Jack D. Drummond[1]**, Odell Reynolds[1], Miles Buckman[1]
**Institution(s):** *1. Starfire Optical Range*

### 214.05 – The evolution of asteroids in the jumping-Jupiter migration model

In this work, we investigate the evolution of a primordial belt of asteroids, represented by a large number of massless test particles, under the gravitational effect of migrating Jovian planets in the framework of the jumping-Jupiter model. We perform several simulations considering test particles distributed in the Main Belt, as well as in the Hilda and Trojan groups. The simulations start with Jupiter and Saturn locked in the mutual 3:2 mean motion resonance plus 3 Neptune-mass planets in a compact orbital configuration. Mutual planetary interactions during migration led one of the Neptunes to be ejected in less than 10 Myr of evolution, causing Jupiter to jump by about 0.3 au in semi-major axis. This introduces a large scale instability in the studied populations of small bodies. After the migration phase, the simulations are extended over 4 Gyr, and we compare the final orbital structure of the simulated test particles to the current Main Belt of asteroids with absolute magnitude $H < 9.7$. The results indicate that, in order to reproduce the present Main Belt, the primordial belt should have had a distribution peaked at ~$10^o$ in inclination and at ~0.1 in eccentricity. We discuss the implications of this for the Grand Tack model. The results also indicate that neither primordial Hildas, nor Trojans, survive the instability, confirming the idea that such populations must have been implanted from other sources. In particular, we address the possibility of implantation of Hildas and Trojans from the Main Belt population, but find that this contribution should be minor.

**Author(s): Fernando Virgilio Roig[1]**, David Nesvorný[2]
**Institution(s):** *1. Observatorio Nacional, 2. Southwest Research Institute*

### 214.06 – Predicting close encounters between asteroids with the STB software

We have developed a method that can quickly and efficiently calculate close encounters between all known asteroids both in the past and the future. Only several hundred asteroids out of more than 690,000 have their masses currently known. The most accurate values are from direct measurements by in situ visits (e.g. Dawn at Ceres and Vesta (Russell et al. 2012, Science 336, 6082, pp. 684), Hayabusa at Itokawa (Abe et al. 2006, Science 312, 5778, pp. 1344-1349)) followed by measurements of binary systems and also from mutual orbit perturbations during close encounters between a handful of the largest MBAs.
We used software called "Space Time Box" (STB) invented by IBM capable of efficiently determine co-located entities in 3D space and

time. Orbits from the MPCORB.DAT database were placed into selected STB granularity with 1 day and 0.05 AU-wide bins. By determining and only tracking asteroids co-located within a selected minimal distance the computational requirements were significantly reduced. Selected instances of co-location were then provided as an input for a numerical integrator SWIFT with 8 planets as perturbers and were integrated until desired epoch with a 0.5 and 1 day timestep. We then used interpolation for the specified time window to check if the positions of asteroids intersect or are within a certain distance parameter.
Using the STB optimization we calculated close encounters between years 2014 and 2039. These events offer the opportunity to search in the survey archives for potential collisions and carefully select the events for mass determination based on their minimal approach distance, angle and mass ratio of participating objects. A follow-up astrometric campaign would ensure improvement of the mass determination precision. Predicted future events can also be directly observed in the real time with optical and IR telescopes in search for collisions or mass loss.
As an example we present one close encounter event observed with the University of Hawaii 2.2 m telescope on June 9th, 2015.

**Author(s): Eva Lilly (Schunova)3**, Jeff Jonas[2], Mudhakar Srivatsa[2], Raghu Ganti[2], Dakshi Agrawal[2], Larry Denneau3, Martin Kratky[1], Richard J Wainscoat3
**Institution(s):** *1. Comenius University Bratislava, 2. IBM, 3. Institute for Astronomy University of Hawaii*

### 214.07 – Thermally-driven destruction of asteroids at small perihelion distances

State-of-the-art models describing the orbits and absolute magnitudes of near-Earth objects (NEOs) predict that numerous NEOs should have been found on orbits with small perihelion distances, but few actual discoveries have been made. In addition, even though the NEO population in general is an even mix of low-albedo and high-albedo asteroids, the characterized NEOs near the Sun show a strong preference for high albedos. We have found, via a quantitative comparison of actual NEO detections and a new NEO model accounting for observational selection effects, that the deficit is produced by the super-catastrophic disruption of a substantial fraction of NEOs when they achieve perihelion distances of a few tens of solar radii. The destruction distance increases for small asteroids, and their temperatures during perihelion passages do not reach levels where evaporation could explain their disappearance. Although both bright and dark asteroids eventually disrupt, our work shows a preference for the elimination of low-albedo NEOs farther from the Sun, which explains the apparent excess of high-albedo NEOs and suggests that low-albedo asteroids break more easily as a result of thermal effects.

**Author(s): Mikael Granvik[6]**, Alessandro Morbidelli3, Robert Jedicke[1], Bryce Bolin3, William F. Bottke4, Ed Beshore5, David Vokrouhlicky[2], Marco Delbo3, Patrick Michel3
**Institution(s):** *1. Institute for Astronomy, University of Hawaii, 2. Institute of Astronomy, Charles University, 3. OCA, 4. Southwest Research Institute, 5. University of Arizona, 6. University of Helsinki*

### 214.08 – Monitoring NEO discoveries for imminent impactors

We are setting up an automated service that will regularly compute asteroid-Earth collision probabilities for objects on the Minor Planet Center's Near-Earth-Object Confirmation Page (NEOCP). Our goal is to identify objects similar to 2008 $TC_3$ and 2014 AA and provide enough warning time to allow for, e.g., detailed follow-up observations prior to a collision. Our system downloads all the new data on the NEOCP every 30 minutes and, for each object with new data, solves the orbital inverse problem which results in a sample of orbits that describes the typically highly-nonlinear orbital-element probability-density function (PDF). We then propagate the orbital-element PDF forward in time for 7 days and compute the collision probability as the weighted fraction of the sample orbits that impact the Earth. Our tests have shown that the system correctly predicts the collisions of 2008 $TC_3$ and 2014 AA based on the very first astrometry batches available (collision probabilities greater than 70%). Using the same configuration we find that the collision probabilities for objects typically on the NEOCP, based on 4 weeks of continuous operations, are always less than 1 in 10 million.

**Author(s): Otto Solin[1]**, Mikael Granvik[1], Karri Muinonen[1]
**Institution(s):** *1. University of Helsinki*

### 214.09 – Overview of the JPL Center for NEO Studies (CNEOS)

Concurrent with the reformulation of NASA's Near-Earth Object (NEO) program at NASA Headquarters, the Jet Propulsion Laboratory has formed the Center for NEO Studies (CNEOS), which will continue the technical work on NEOs that JPL has performed in the past, and expand on that work. The poster will provide a brief history of NEO activities at JPL, including the establishment of the original NEO Program Office at JPL in 1998 to provide a central node of critical expertise in the area of trajectory dynamics of Near-Earth Objects (NEOs). With the reformulation of the NEO program at NASA HQ, that office has become the Center for NEO Studies. The poster will review some of the Center's key activities, such as: the computation of high precision orbits for NEOs, tabulation of their close approaches, and calculation of impact probabilities by all known NEOs over the next century via the Sentry and Scout impact monitoring systems. The Center will continue to host the website for NASA's NEO Program, providing detailed information on the orbits and physical characteristics of all known NEOs. Other technical activities of the Center will also be outlined, including the Horizons on-line ephemeris service, the development of hypothetical impact scenarios and online kinetic-impactor deflection analysis tools, and the detection and mapping of keyholes.

**Author(s): Paul Chodas[1]**
**Institution(s):** *1. Jet Propulsion Laboratory*

### 214.10 – Gravitational Influence of a Large Captured Body on the Stability of Jupiter's Trojan Asteroids

The Trojan asteroids orbit the Sun about the L4 and L5 Lagrangian points of Jupiter. These objects have a wide range of eccentricities and inclinations, and are thought to be captured planetesimals. Since the origin of the Trojan asteroids is expected to provide clues to the dynamical evolution of the planets and small bodies in the Solar System, various models have been proposed, e.g., capture due to gas drag from the solar nebula, capture during Jupiter's mass growth, or capture during smooth migration of Jupiter. However, such models failed to reproduce some important characteristics of the present Trojan asteroids, such as the total mass of the Trojans, the distribution of orbital elements, or the distribution of the libration amplitudes. On the other hand, recent models for the formation of the Solar System suggest that the giant planets likely experienced significant radial migration and orbital instability after their formation. Studies of capture of Trojan asteroids based on such models of giant planet migration show that icy planetesimals originally in the outer Solar System can be captured into Jupiter's Trojan regions, and the present total mass as well as the observed orbital characteristics of the Trojan asteroids can be explained in such models. However, in such studies of capture of the Trojan asteroids, asteroids were treated as test particles, thus gravitational interactions between planetesimals are not taken into account. Although effects of gravitational interactions between sufficiently small asteroids may reasonably be neglected, there may have been significantly large objects in the original swam of Trojan asteroids immediately after their capture. In the present study, we assume that a large body was captured into Jupiter's Trojan region, and examine its dynamical influence on other Trojan asteroids using orbital integration. From the results of our calculations, we will discuss constraints on the mass of bodies existed in the Trojan swarm in the past.

**Author(s): Keiji Ohtsuki[1]**, Hiroaki Okayama[1]
**Institution(s):** *1. Kobe University*

# 215 – Mercury and the Moon

## 215.01 – Observations of the minor species Al, Fe and $Ca^+$ in Mercury's exosphere

We report here on the first observational evidence of Al and Fe in the exosphere of Mercury, based on measurements of 4-5-σ resolved emission lines of these metals with Keck-1/HIRES. AlI emission was observed on two separate runs, in 2008 and 2013, with tangent column densities of 2.4 and 3 x $10^7$ Al atoms $cm^{-2}$ at altitudes of 1300 and 1850 km (1.1 and 1.5 $R_M$), respectively. FeI emission has been observed once, yielding a tangent column of 6.2 x $10^8$ $cm^{-2}$ at an altitude of 950 km (1.4 $R_M$) in 2009. We also present observations of 3.5-σ $Ca^+$ emission features near Mercury's equatorial anti-solar limb in 2011, from which a stringent tangent column abundance of 4.0 x $10^6$ $cm^{-2}$ is derived for the Ca ion.
A simple model for zenith column abundances of the neutral species yields 2.0 x $10^7$ Al $cm^{-2}$, and 8.2 x $10^8$ Fe $cm^{-2}$. The observations appear to be consistent with production of these species by impact vaporization, with a large fraction of the Al ejecta in molecular form, and that for Fe in mixed atomic and molecular forms. The scale height of the Al gas is consistent with a kinetic temperature of 4800-8200 K while that of Fe is 5000-13000 K. The apparent high temperature and low density of the Al gas would suggest that it may be produced by dissociation of molecules. A large fraction of both Al and Fe appear to condense in a vapor cloud at low altitudes.

**Author(s): Rosemary M. Killen[2]**, Thomas A Bida[1]
**Institution(s):** *1. Lowell Observatory, 2. NASA Goddard Space Flight Center*

## 215.02 – Dissociation of Ca-bearing Molecules as a Source of Mercury's Ca Exosphere

Observations of Mercury's calcium exosphere by MESSENGER have revealed three key features: (1) The Ca is extremely energetic, with a temperature ~70,000 K if the source is thermal, (2) the source region is located in the dawn hemisphere, and (3) there is a strong annual variation in the Ca source rate (Burger et al. 2014). Killen and Hahn (2015) have shown that the source rate is consistent with impact vaporization by interplanetary dust and the intersection of Mercury with a cometary dust stream (likely associated with Comet Encke, Christou et al., submitted).
Killen et al. (2005) suggested that energetic calcium could be produced by the dissociation of Ca-bearing molecules produced in impact vaporization plumes. We test this hypothesis with a Monte Carlo model that follows the evolution of atomic and molecular calcium produced in impact plumes. Ca-bearing molecules such as CaO, CaOH, and $Ca(OH)_2$ are more likely to be are produced in vapor plumes than atomic Ca (Berezhnoy and Klumov 2008); these molecules quickly break apart either through vibrational dissociation or photodissociation. The excess energy associated with dissociation gives the atomic Ca an extra energy boost above the temperature of the impact plumes (~5000 K). We determine impact vaporization rates and excess energies required by the dissociation process to reproduce the scale height and spatial morphology of the Ca exosphere as observed by the MESSENGER Ultraviolet and Visible Spectrometer (UVVS).
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Mercury's calcium exosphere, Icarus, 250, 230-237, 2015, doi:10.1016/j.icarus.2014.11.035.

**Author(s): Matthew H. Burger[2]**, Rosemary M Killen[1]
**Institution(s):** *1. GSFC, 2. Morgan State University*

## 215.03 – Comparing Different Exospheric Species at Mercury to Constrain Source, Loss, and Transport Processes

Mercury's exosphere is maintained by processes that eject atoms or molecules from the surface of the planet. The atoms are initially a part of the regolith or are possibly delivered to the planet via meteorites. In either case spatial and temporal variations in source processes, dynamical transport processes such as radiation pressure and ion recycling, and the surface chemistry associated with exospheric atoms impacting the regolith affect the distribution of species in the exosphere. Each of these processes acts differently depending on the particular atom due in part to the atomic mass, surface sticking coefficient, and thermal accommodation coefficient of the atom. A comparison between the differences and similarities in the spatial distribution and temporal variations of more than one atomic species helps to unravel the physical processes driving the exosphere and ultimately helps to understand surface-exosphere interactions. The Mercury Atmospheric and Surface Composition Spectrometer (MASCS) on the MESSENGER spacecraft obtained profiles of Mercury's exosphere during three Mercury flybys and during the orbital phase of the mission from March, 2011 through April, 2015. Specifically, MASCS, a scanning-grating monochromator, observed resonantly scattered emissions at discrete wavelengths from atoms in the exosphere. A strategy was employed where several exospheric species were observed sequentially with integration times short enough that the observations for a particular set of exospheric atoms were almost simultaneous. These measurements are useful for comparing the distributions of different atoms since the geometry associated with the observation of each species is approximately the same. I will present results from an analysis of MASCS data comparing the differences and similarities of the spatial distributions and temporal variations of different exospheric species.

**Author(s): Eric Todd Bradley[1]**
**Institution(s):** *1. Univ. of Central Florida*

## 215.05 – Characterizing Water and Hydroxyl on Airless Bodies from Vacuum UV and IR Measurements

Water exists in the surfaces of airless bodies as ice and potentially as adsorbed species [1], either as molecular water or dissociated into hydroxyl when bulk water (ice) is not stable [2]. All physical states of water have a strong spectral signatures in the infrared from 2.7 to 3-um because of a fundamental OH-cation or H-O-H stretch vibration. But the IR is not always definitive of physical state. Although a band at 3.07 um is associated with water ice, an almost identical band exists in some hydrated minerals. Brucite, an alteration product of olivine, possesses this band [6] as does goethite, another alteration mineral of basalts [7]. In fact, the 3.05-um band on Ceres, which was initially attributed to water ice, has more recently been attributed to brucite [6]. Spectral observations in the UV can potentially resolve this degeneracy. In the UV, water ice possesses a very strong band near 180 nm [8], but adsorbed molecular water does not induce a band. Because of this, a combination of UV measurements at wavelengths from ~ 150 nm to ~200 nm and IR measurements near 3 um can discriminate ice from adsorbed water. The UV region, however, is also sensitive to silicate composition, with iron bearing minerals having a strong OMCT absorption feature near 300 nm and again shortward of 200 nm, that can potentially be a source of confusion between the identification of iron-poor minerals and water ice. In conclusion, the IR can sense all three forms of water (ice, adsorbed molecular water, and hydroxyl) and the UV, being sensitive to ice, may potentially be used either alone or with the IR to identify water ice separately from other phases of hydration.
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**Author(s): Charles A. Hibbitts[1]**
**Institution(s):** *1. JHU-APL*

### 215.06 – Revised Age Constraints on Absolute Age Limits for Mercury's Kuiperian and Mansurian Systems

On the basis of morphologically distinct basin and crater deposits, Mercury's surface units have been subdivided into five time-stratigraphic systems (youngest to oldest): Kuiperian, Mansurian, Calorian, Tolstojan, and pre-Tolstojan. Approximate age limits were initially suggested for these systems on the basis of the lunar-derived impact-flux history. High-resolution and multi-band image data obtained by the MErcury Surface, Space ENviroment, GEochemistry, and Ranging (MESSENGER) spacecraft were used to catalogue fresh impact craters interpreted to have formed during the Mansurian and Kuiperian systems. Mansurian and Kuiperian craters are characterized as morphologically fresh with crisp morphologies, well-preserved rims, few or no superposed craters, continuous ejecta with radial lineaments, and well-defined secondary craters; Kuiperian craters have bright ray systems while Mansurian craters maintain fresh morphologies but no longer have discernable ray systems.
The density of fresh craters in these datasets, along with the recent production and chronology function of Marchi et al. [2009], are used to estimate new limits for the boundaries of the two most recent of Mercury's systems. Given the effects of strength and other parameters (such as density), we estimate a model age for the population of craters that have formed since the onset of the Mansurian of ~1.9 ±0.3 Gyr. Likewise we estimate a model age for the population of craters that have formed since the onset of the Kuiperian of ~300 ±40 Myr. A particularly good fit for the Mansurian crater size frequency distribution (SFD) was found for the NEO-derived crater distribution. The same is true for the Kuiperian SFD, although the fit is not as robust as for the Mansurian SFD.

**Author(s): Maria E. Banks[6]**, Xiao Zhiyong[7], Sarah E. Braden[1], Simone S. Marchi[4], Nadine G. Barlow[5], Clark R. Chapman[2], Caleb I Fassett[3]
**Institution(s):** *1. Arizona State University, 2. Department of Space Studies, Southwest Research Institute, 3. Dept. of Astronomy, Mount Holyoke College, 4. NASA Lunar Science Institute, Southwest Research Institute, 5. Northern Arizona University, 6. Planetary Science Institute, 7. School of Earth Sciences, China University of Geosciences (Wuhan)*

### 215.07 – The Lunar Reconnaissance Orbiter - Six Years of Science and Exploration at the Moon

The LRO mission, currently in an extended mission phase, is producing a remotely sensed dataset that is unrivaled in planetary science. With an ever-increasing baseline of measurements the LRO data has revealed the Moon's surface and environment to be dynamic, with new craters and distal ejecta, variations in volatiles at and near the surface, a variable exosphere, and a surface that responds to variations in the flux of radiation from the Sun. Taken together the LRO dataset has significant value in forming how we understand airless bodies work in the Solar System and how planets evolve. We will discuss recent observations from the mission including, geologically recent volcanism, contemparay impacts, and polar volatiles.
We will also discuss the mission's support of future exploration of the Moon. As initially conceived, one of the primary objectives for the Lunar Reconnaissance Orbiter (LRO) was to identify safe landing sites for future human and robotic exploration, and LRO mission remains capable of targeted high resolution observations to support the planning of future robotic missions to the Moon. The LRO team seeks to engage with mission planners to discuss LRO's enabaling capabilities.

**Author(s): John W. Keller[1]**, Noah E. Petro[1], Timothy P. McClanahan[1], Richard R. Vondrak[1]
**Institution(s):** *1. NASA/Goddard Space Flight Center*

### 215.08 – Secondary electron emission from lunar soil by solar wind type ion impact: Laboratory measurements

**Introduction:** The lunar surface potential is determined by time-varying fluxes of electrons and ions from the solar wind, photoelectrons ejected by UV photons, cosmic rays, and micrometeorite impacts. Solar wind ions have a dual role in the charging process, adding positive charge to the lunar regolith upon impact and ejecting negative secondary electrons (SE). Electron emission occurs when the energy from the impacting ion is transferred to the solid, ionizing and damaging the material; electrons with kinetic energy greater than the ionization potential (band gap + electron affinity) are ejected from the solid[1].
**Experiment:** We investigate the energy distribution of secondary electrons ejected from Apollo soils of varying maturity and lunar analogs by 4 keV $He^{+}$. Soils are placed into a shallow Al cup and compressed. *In-situ* low-energy oxygen plasma is used to clean atmospheric contaminants from the soil before analysis[2]. X-ray photoelectron spectroscopy ascertains that the sample surface is clean. Experiments are conducted in a PHI 560 system ($<10^{-9}$ Torr), equipped with a double-pass, cylindrical-mirror electron energy analyzer (CMA) and μ-metal shield. The spectrometer is used to measure SE distributions, as well as for *in situ* surface characterization. A small negative bias (~5V) with respect to the grounded entrance grid of the CMA may be placed on the sample holder in order to expose the low energy cutoff.To measure SE energy distributions, primary ions rastered over a ~6 x 6 $mm^2$ area are incident on the sample at ~40° relative to the surface normal, while SE emitted with an angle of 42.3°± 3.5° in a cone are analyzed.
**Results:** The energy distribution of SE ejected from 4 keV He ion irradiation of albite with no bias applied shows positive charging of the surface. The general shape and distribution peak (~4 eV) are consistent with spectra for low energy ions on insulating material[1].
**Acknowledgements:** We thank the NASA LASER program for support.
**References:** [1]P. Riccardi, R. Baragiola et al. (2004); Surf. Science 57, L305-L310. [2]C.A. Dukes & R.A. Baragiola (2010) Surface Interface Anal. 42, 40-44.

**Author(s): Catherine Dukes[1]**, Caixia Bu[1], Raul A. Baragiola[1]
**Institution(s):** *1. Univ. Of Virginia*

### 215.09 – Comparison of Computational Techniques for Estimating Solar Wind Ion Sputtering Yields on Silicates

Bodies in space containing silicates and oxides continuously experience ion collisions that result in surface sputtering. Knowledge of sputter yields allows for the estimation of destruction rates of small grains in protoplanetary clouds and predictions of exosphere densities around small bodies to be carried out. However, sputter yields for astrophysical type materials are poorly constrained and there has been little work to compare computational models to experimental results. Theoretical models using sputtering yields commonly use the software SRIM to simulate ion implantation into solids. However, the program has been shown to give results that are in poor agreement with experimental data for low energy (<10 keV) incident ions typical of the solar wind.
Here we compare predicted sputtering yields from SRIM and a program based on the TRIM.Sp algorithm called SDTrimSP. Both programs were designed to simulate atomic collisions in amorphous targets with predefined stoichiometric compositions and atomic binding energies. During the simulation, a one dimensional target is exposed to an incident beam of particles with a composition and energy determined by the user. The binary collision approximation is used to handle the collisions and the energy loss of the incident particle and energy gain of the recoil is then calculated. This process is repeated for resulting collisions until all particle energies fall below a preset value or have left the target. However, SDTrimSP can account for changing surface composition with increasing irradiation fluence and also provides the option to use several different surface binding energy models. Simulations of H and He irradiation of simple oxides were run

using both programs at energies in the 0.1-10 keV range and compared to published experimental data. SDTrimSP was seen to display a better agreement with this data than SRIM, making it a more reliable method of estimating sputtering yields. The model was then expanded to simulate more complex meteorite compositions in order to determine the timescale at which equilibrium is achieved.

**Author(s): Adam Hutcherson[1]**, Micah Schaible[1], Robert Johnson[1]
**Institution(s):** *1. University of Virginia*

## 216 – Beyond the Moon: The Lunar Community Branches Out

### 216.01 – NASA's Solar System Exploration Research Virtual Institute (SSERVI)

NASA's Solar System Exploration Research Virtual Institute (SSERVI) represents a close collaboration between science, technology and exploration, and was created to enable a deeper understanding of the Moon and other airless bodies. SSERVI is supported jointly by NASA's Science Mission Directorate and Human Exploration and Operations Mission Directorate. The institute currently focuses on the scientific aspects of exploration as they pertain to the Moon, Near Earth Asteroids (NEAs) and the moons of Mars, but the institute goals may expand, depending on NASA's needs, in the future. The 9 initial teams, selected in late 2013 and funded from 2014-2019, have expertise across the broad spectrum of lunar, NEA, and Martian moon sciences. Their research includes various aspects of the surface, interior, exosphere, near-space environments, and dynamics of these bodies.
NASA anticipates a small number of additional teams to be selected within the next two years, with a Cooperative Agreement Notice (CAN) likely to be released in 2016. Calls for proposals are issued every 2-3 years to allow overlap between generations of institute teams, but the intent for each team is to provide a stable base of funding for a five year period. SSERVI's mission includes acting as a bridge between several groups, joining together researchers from: 1) scientific and exploration communities, 2) multiple disciplines across a wide range of planetary sciences, and 3) domestic and international communities and partnerships.
The SSERVI central office is located at NASA Ames Research Center in Mountain View, CA. The administrative staff at the central office forms the organizational hub for the domestic and international teams and enables the virtual collaborative environment. Interactions with geographically dispersed teams across the U.S., and global partners, occur easily and frequently in a collaborative virtual environment. This poster will provide an overview of the 9 current US teams and international partners, as well as information about outreach efforts and future opportunities to participate in SSERVI.

**Author(s): Yvonne J. Pendleton[1]**
**Institution(s):** *1. NASA Ames Research Center*

### 216.02 – Extending the Lunar Mapping and Modeling Portal – New Capabilities and New Worlds

NASA's Lunar Mapping and Modeling Portal (LMMP) provides a web-based Portal and a suite of interactive visualization and analysis tools to enable mission planners, lunar scientists, and engineers to access mapped lunar data products from past and current lunar missions (http://lmmp.nasa.gov). During the past year, the capabilities and data served by LMMP have been significantly expanded. New interfaces are providing improved ways to access and visualize data. Many of the recent enhancements to LMMP have been specifically in response to the requirements of NASA's proposed Resource Prospector lunar rover, and as such, provide an excellent example of the application of LMMP to mission planning.
At the request of NASA's Science Mission Directorate, LMMP's technology and capabilities are now being extended to additional planetary bodies. New portals for Vesta and Mars are the first of these new products to be released.
On March 31, 2015, the LMMP team released Vesta Trek (http://vestatrek.jpl.nasa.gov), a web-based application applying LMMP technology to visualize the asteroid Vesta. Data gathered from multiple instruments aboard Dawn have been compiled into Vesta Trek's user-friendly set of tools, enabling users to study the asteroid's features.
Released on July 1, 2015, Mars Trek replicates the functionality of Vesta Trek for the surface of Mars. While the entire surface of Mars is covered, higher levels of resolution and greater numbers of data products are provided for special areas of interest. Early releases focus on past, current, and future robotic sites of operation. Future releases will add many new data products and analysis tools as Mars Trek has been selected for use in site selection for the Mars 2020 rover and in identifying potential human landing sites on Mars.
Other destinations will follow soon. The Solar Sytem Exploration Research Virtual Institute, which manages the project, invites the user community to provide suggestions and requests as the development team continues to expand the capabilities of these portals.
This presentation will provide an overview of all three portals, demonstrate their uses and capabilities, highlight new features, and preview coming enhancements.

**Author(s): Brian Day[1]**, Emily Law[2]
**Institution(s):** *1. NASA AMES Research Center, 2. NASA Jet propulsion Laboratory*

## 217 – Venus

### 217.01 – Ionospheric Modulation of Venus Express Lightning Detection Rates

Venus Express completed its nearly 9 year campaign at Earth's sister planet in late 2014. During this period the onboard fluxgate magnetometer collected data up to 64 Hz in frequency while near periapsis. This is the expected frequency range for lightning-generated whistler-mode waves at Venus, between the local electron and ion gyrofrequencies. These waves are right-hand circularly polarized and are guided by the local magnetic field. When the Venusian ionopause is low enough in altitude to reside in the collisional region, the interplanetary magnetic field can get carried down with the ions and magnetize the lower ionosphere. As the field travels towards the terminator it gains a radial component, enabling whistlers to reach higher altitudes and be detected by the spacecraft.
The mission covered almost an entire solar cycle and frequently observed a magnetized ionosphere during the solar minimum phase when the ionosphere was weak due to reduced incident EUV. Detection was most common at 250 km altitude where the waves travel more slowly due to reduced ionospheric density. In response they increase in amplitude in order to conserve magnetic energy flux. Here, we examine the changes in the ionospheric properties associated with the evolution of the solar cycle and the rate of detection of these lightning-generated signals.

**Author(s): Richard A. Hart[2]**, Christopher T. Russell[2], Tielong Zhang[1]
**Institution(s):** *1. Austrian Academy of Science, 2. University of California, Los Angeles*

### 217.02 – Chemistry in the Venus clouds: Sulfuric acid reactions and freezing behavior of aqueous liquid droplets

Venus has a thick cloud deck at 40-70 km altitude consisting of liquid droplets and solid particles surrounded by atmospheric gases. The liquid droplets are highly concentrated aqueous solutions of sulfuric acid ranging in concentration from 70-99 wt%. Weight percent drops off with altitude (Imamura and Hashimoto 2001). There will be uptake of atmospheric gases into the droplet solutions and the ratios of gas-phase to liquid-phase species will depend on the Henry's Law constant for those solutions. Reactions of sulfuric acid with these gases will form products with differing solubilities. For example, uptake of HCl by $H_2SO_4/H_2O$ droplets yields chlorosulfonic acid, $ClSO_3H$ (Robinson et al 1998) in solution. This may eventually decompose to thionyl- or sulfuryl chlorides, which have UV absorbances. HF will also uptake, creating fluorosulfonic acid, $FSO_3H$, which has a greater solubility than the chloro- acid. As uptake continues, there will be many dissolved species in the cloudwaters. Baines and Delitsky (2013) showed that uptake will have a maximum at ~62 km and this is very close to the reported altitude for the mystery UV absorber in the Venus atmosphere. In addition, at very strong concentrations in lower altitude clouds, sulfuric acid will form hydrates such as $H_2SO_4.H_2O$ and $H_2SO_4.4H_2O$ which will have very different freezing behavior than sulfuric acid, with much higher freezing temperatures (Carslaw et al, 1997). Using temperature data from Venus Express from Tellmann et al (2009), and changes in $H_2SO_4$ concentrations as a function of altitude (James et al 1997), we calculate that freezing out of sulfuric acid hydrates can be significant down to as low as 56 km altitude. As a result, balloons, aircraft or other probes in the Venus atmosphere may be limited to flying below certain altitudes. Any craft flying at altitudes above ~55 km may suffer icing on the wings, propellers, balloons and instruments which could cause possible detrimental effects (thermal changes, reduced buoyancy, effects on control surfaces, plugging of sample inlets, etc.). Therefore, de-icing equipment should be considered when designing aircraft expected to fly at high altitudes in the Venus clouds.

**Author(s): M. L. Delitsky[1]**, K. H. Baines[2]
**Institution(s):** *1. California Specialty Engineering, 2. University of Wisconsin*

### 217.03 – Venus Atmospheric Maneuverable Platform Science Mission

Over the past several years, we have explored a possible new approach to Venus upper atmosphere exploration by applying recent Northrop (non-NASA) development programs and have come up with a new class of exploration vehicle: an atmospheric rover. We will discuss a possible suite of instruments and measurements to study the current climate through detailed characterization of cloud level atmosphere and to understand the processes that control climate on Earth-like planets.
Our Venus atmospheric rover concept, the Venus Atmospheric Maneuverable Platform (VAMP), is a hypersonic entry vehicle with an ultra-low ballistic coefficient that transitions to a semi-buoyant air vehicle (AV) after entering the Venus atmosphere. Prior to entry, the AV fully deploys to enable lifting entry and eliminates the need for an aeroshell. The mass savings realized by eliminating the aeroshell allows VAMP to accommodate significantly more instruments compared to previous Venus in situ exploration missions. VAMP targets the global Venus atmosphere between 50–65 km altitudes and would be an ideal, stable platform for atmospheric and surface interaction measurements. We will present a straw man concept of VAMP, including its science instrument accommodation capability and platform's physical characteristics (mass, power, wingspan, etc). We will discuss the various instrument options.
VAMP's subsonic flight regime starts at ~94 km and after <1 hour, the AV will reach its cruise altitude of ~65 km. During this phase of flight, the VAMP sensor suite will acquire a pre-defined set of upper atmosphere measurements. The nominal VAMP lifetime at cruise altitude is several months to a year, providing numerous circumnavigation cycles of Venus at mid-latitude. The stability of the AV and its extended residence time provide the very long integration times required for isotopic mass analysis. VAMP communicates with the orbiter, which provides data relay and possibly additional science measurements complementing the in situ measurements from the AV. We will specifically focus upon key factors impacting the design and performance of VAMP science.

**Author(s): Ronald S. Polidan[2]**, Gregory Lee[2], Floyd Ross[2], Daniel Sokol[2], Linden Bolisay[1]
**Institution(s):** *1. L-Garde, 2. Northrop Grumman Aerospace Systems*

### 217.04 – Some questions about the Venus atmosphere from past measurements

The many missions undertaken in the past half a century to explore Venus with fly-by spacecraft, orbiters, descending probes, landers and floating balloons, have provided us with a wealth of data. These data have been supplemented by many ground based observations at reflected solar wavelengths, short and long wave infrared to radio waves. Inter-comparison of the results from such measurements provide a good general idea of the global atmosphere. However, re-visiting these observations also raises some questions about the atmosphere that have not received much attention lately but deserve to be explored and considered for future measurements. These questions are about the precise atmospheric composition in the deep atmosphere, the atmospheric state in the lower atmosphere, the static stability of the lower atmosphere, the clouds and hazes, the nature of the ultraviolet absorber and wind speed and direction near the surface from equator to the pole. The answers to these questions are important for a better understanding of Venus, its weather and climate. The measurements required to answer these questions require careful and sustained observations within the atmosphere and from surface based stations. Some of these measurements should and can be made by large missions such as Venera-D (Russia), Venus Climate Mission (Visions and Voyages – Planetary Science Decadal Survey 2013-2022 or the Venus Flagship Design Reference Mission (NASA) which have been studied in recent years, but some have not been addressed in such studies. For example, the fact that the two primary constituents of the Venus atmosphere – Carbon Dioxide and Nitrogen are supercritical has not been considered so far. It is only recently that properties of binary supercritical fluids are being studied theoretically and laboratory validation is needed. With the end of monitoring of Venus by Venus Express orbiter in November 2014 after nearly a decade of observations and the imminent insertion of JAXA's Akatsuki spacecraft into orbit around Venus, it is a good moment to consider the unanswered or unexplored questions about Venus.

**Author(s): Sanjay Limaye[1]**
**Institution(s):** *1. University of Wisconsin*

### 217.05 – Long-term variations of carbon monoxide and trace species in the Venus troposphere from Venus Express/VIRTIS between 2006-2009

The understanding of spatial and temporal variations in tropospheric abundances of trace gases such as carbon monoxide is key to understanding the deep atmosphere of Venus. These gases are entrained in the global circulation, as well as being key ingredients to creating the sulfuric acid clouds. Long-term temporal variations of these species across Venus's disc would be provide key insights into the large-scale circulation and cloud forming processes in the troposphere.
The Venus Express spacecraft orbited Venus from April 2006 to December 2014. The VIRTIS instrument is a near-infrared imaging spectrometer that covers 0.3 to 5.0 μm. Nightside thermal emissions at 2.32 μm is sensitive to CO at 35 km. We present long term abundances of CO and other trace abundances as observed by VIRTIS from April 2006 through October 2008, when the MIR channel ceased operations. We compare the methods of *Tsang et al. (2009)* and *Barstow et al. (2012)* of deriving CO from band ratios. We will also provide long-term variations of cloud particle sizes. This work is done in conjunction with a study of long-term variations of 1.73 μm thermal emission brightnesses, a proxy of cloud optical depth in the lower atmosphere, with the same data (McGouldrick and Tsang 2015). This work is supported by NASA's Planetary Mission Data Analysis Program, grant number NNX14AP94G.

**Author(s): Constantine Tsang[1]**, Kevin McGouldrick[2]
**Institution(s):** *1. Southwest Research Institute, 2. University of Colorado*

### 217.06 – Ground-Based Venusian Thermal Structure and Dynamics Observations in August 2010

We measured equatorial winds above the cloud tops of Venus and in the lower thermosphere over 19-23 Aug 2010 (UT), a component of a Venus measurement program that extends over ~30+ years using ground-based Infrared Heterodyne Spectroscopy (IRHS). IRHS obtains sub-Doppler resolution on molecular transitions of atmospheric species. We used the Heterodyne Instrument for Planetary Winds and Composition (HIPWAC, NASA Goddard Space Flight Center) at the NASA Infrared Telescope Facility to acquire high-resolution spectra on pressure-broadened $CO_2$ absorption features,probing the lower mesosphere (70 km altitude) with non-LTE core emission that probes the lower thermosphere (110 km). The two features probe the transition from zonal wind flow near the cloud tops to subsolar-to-antisolar flow in the thermosphere. Fully resolved carbon dioxide transitions were measured near the 952.8808 $cm^{-1}$ (10.494 μm) rest frequency at resolving power $\lambda/\Delta\lambda = 2.5\times10^7$ on the equator on positions distributed about the central meridian and across the terminator at ~15° intervals in longitude. The non-LTE emission is solar-pumped and appears only on the daylight side, probing subsolar-to-antisolar wind velocity flowing radially from the subsolar point through the terminator, which was near the central meridian in these observations, with maximum tangential velocity but zero line-of-sight projection at the terminator and zero tangential velocity but maximum projection at the limb. The maximum measurable Doppler shift thus appears within the disc, between central meridian and limb. The velocity of the zonal flow is approximately uniform, with constant tangential velocity and maximum line-of-sight projection at the limb, and can be measured by the frequency of the absorption line on both the daylight and dark side. Variations in Doppler shift between the observable features and the differing angular dependence of the contributing wind phenomena thus provide independent mechanisms to distinguish dynamical processes at the altitude of each observed spectral feature. Winds up to >100 m/s were determined in previous investigations with uncertainties of order 10 m/s or less. This work was supported by the NASA Planetary Astronomy Program.

**Author(s): Tilak Hewagama5**, Theodor Kostiuk3, Timothy Livengood5, Tobias Stangier[6], Kelly Fast[2], John Annen4, Manuela Sornig[1], Pia Krause[6]
**Institution(s):** *1. DLR and Univ. of Cologne, 2. NASA, 3. NASA/Goddard Space Flight Center, 4. NASA/Goddard Space Flight Center (Retired), 5. Univ. of Maryland, 6. University of Cologne*

## 217.07 – The Role of Rheological Weakening in the Formation of Narrow Rifts on Venus

The rift zones on Venus are remarkably similar to those seen on Earth, despite Venus' current lack of plate tectonics. The Devana Chasma rift on Beta Regio accommodates extension in a narrow zone and is associated with volcanism. As a result, it has often been compared to the East African Rift (Burov and Gerya, 2014; Foster and Nimmo, 1996). It has been suggested that plate boundaries develop on Earth because an interconnected network of localized shear zones (areas of concentrated weakening) can form through the lithosphere (Regenauer-Lieb and Yuen, 2001). If Venusian rifts, such as Devana Chasma, are similar to terrestrial plate boundaries, then it is possible that shear zones should form in those locations.
Montesi (2013) showed that water-bearing minerals, such as micas, which are probably not present on Venus, largely dominate weakening in the Earth's crust. On Venus, melts are likely to play the role of the weak phase that allows for localization, due to its low viscosity relative to host rocks. Weakening due to grain size reduction is also possible if a dislocation-accommodated grain boundary sliding mechanism is active on Venus (Montesi, 2013). Rift stability for Venus-like conditions has been analyzed using the model of Buck (1991). This model links the evolution of lithospheric strength with the style of rifting (wide, narrow, or metamorphic core complex). The crust and mantle are assumed to be dry diabase and dry olivine, respectively (diabase rheological parameters are from Mackwell et. al. (1998), olivine rheological parameters are from Hirth and Kohlstedt (2003)). The crustal thickness and surface heat flux are varied based on estimated values from the literature (Nimmo and McKenzie, 1998; Buck, 2002). Without the inclusion of a weakening mechanism the large majority of model runs predict wide rifts developing. Adding a simplistic exponential decay to the lithospheric yield strength allows for more narrow rift formation to occur. Including explicit weakening processes, which may be associated with grain size reduction or development of a foliation, appears necessary to explain the presence of narrow rifts on Venus.

**Author(s): Alexis Martone[1]**, Laurent Montesi[1]
**Institution(s):** *1. University of Maryland, College Park*

## 217.08 – Reflection and Emission Spectra of Fe-Oxides Under Venus-Like Conditions

The Solar System's last solid planet for which we have no mineralogy data is Venus. Soviet landers acquired images and elemental abundances at six locations on the surface of Venus. γ-ray and XRF spectroscopy performed by the landers showed that the plains are made of mafic basalts. Very large concentrations of K at the Venera 8 and 13 landing sites indicated the presence of alkaline basalts.
Near-IR and thermal IR remote sensing of Mars, both from orbit and at the surface, have revealed the layered mineralogical complexity of that planet. Dominated by basalts and a wide-variety of fluid-altered phases, the mineralogy of Mars tells a complex story of wet and dry epochs in a history of dramatic climate change. At the surface of Venus, optical pathlengths are small and there is little scattering due to hazes. The environment around a lander or rover on Venus can be mapped from 0.4 to 3 μm just as well as it has been on Mars. Laboratory spectra show that the ferric edge at 0.55 μm that makes Mars red shifts to 1 μm at Venus surface temperatures (Pieters et al., 1986). This spectral feature is caused by strong charge transfer transitions in the UV between overlapping orbitals of iron and oxygen, and crystal-field electronic transition bands of ferric Fe (Pieters and Englert, 1993). Pressure and temperature will alter and broaden crystal-field electronic transition bands. Johnson and Fegley (2000) showed that a halogenated/hydrated amphibole (tremolite) is metastable on Venus; thus, metamorphic remnants of an ancient hydrosphere could still exist. In future work the reflectance and emission spectra of this phase will also be studied at high temperatures.
We will present reflection and emission spectra of several Fe-oxides up to 450°C and 100 bars. These environmental conditions are programmable in a small, off-the-shelf 1 cc chamber that sits in the optical path of a Nicolet FTIR spectrometer. Our work will show that ambient pressure and temperature have significant effects on Fe-oxide spectra, and that both must be understood to use near-IR spectroscopy to diagnose the mineralogy near a Venus lander.

**Author(s): Mark A. Bullock[1]**, Con C.C. Tsang[1], Dan D. Durda[1], Jeffrey S. Kargel[2]
**Institution(s):** *1. Southwest Research Inst., 2. University of Arizona*

## 217.09 – An Induced Venusian Magnetosphere Model for Investigating Venus's Interior

The deep layers of Venus are usually considered to be similar to those of the Earth, but the parameters of these layers, including the size of the Venusian core, remain unknown. If Venus has a metallic core, the magnetic field that enters the planet cannot diffuse into the core within the time scales when the external magnetic field can remain steady. The bending of magnetic field lines by the core could be measured at low altitudes, providing information to infer the core size. This method of magnetic sounding has successfully estimated the size of the lunar core, helped by the fact that the Earth's magnetotail can provide a uniform background magnetic field for the Moon. At Venus, the magnetic field is much more complicated, as the solar wind interaction with the planet develops an induced magnetosphere. Estimating the magnetic induction by the core in this non-uniform, non-axisymmetric magnetic field environment also requires numerical computation.
This study develops an induced Venusian magnetosphere model that is suitable for understanding Venus's interior. Different from the global plasma models, this model includes the planetary

interior in the model domain. A tradeoff is the use of magnetostatic equations, which enables faster computation in return. This approach is similar to that adopted by popular empirical models for the terrestrial magnetosphere. Improved from our previous 2-D model, the new 3-D model consists of a conducting core, the Venus counterpart of the Chapman-Ferraro current, and the tail current sheet. In a separate scenario, a global dipole moment is also considered. The finite element method is used to compute the magnetic field vectors within the induced Venusian magnetopause. We will present model results as well as their comparisons with the magnetic field measurements by PVO and by the more recent VEX mission.

**Author(s): Peter J. Chi[1]**, Christopher T. Russell[1], Michaela N. Villarreal[1], Janet G. Luhmann[3], T. L. Zhang[2]
**Institution(s):** *1. Department of Earth Planetary and Space Sciences, UCLA, 2. Space Research Institute, Austrian Academy of Sciences, 3. Space Sciences Laboratory, University of California Berkeley*

## 218 – Planetary Rings

### 218.01 – Investigations of Saturn’s Main Rings over Broad Range of Wavelengths

An abundance of information about the characteristics of Saturn’s ring particles and their regolith can be obtained by comparing the changes in their brightness, color and temperature with changing viewing geometry over a wide range of wavelengths from ultraviolet through the thermal infrared. Data from Cassini’s Composite Infrared Spectrometer (CIRS), Visual and Infrared Mapping Spectrometer (VIMS), Imaging Science Subsystem (ISS) and Ultraviolet Imaging Spectrograph (UVIS) are jointly studied using data from the lit and unlit main rings at multiple geometries and solar elevations over 11 years of the Cassini mission. Using multi-wavelength data sets allows us to test different thermal models by combining the effects of particle albedo, regolith grain size and surface roughness with thermal emissivity and inertia, particle spin rate and spin axis orientation.
CIRS temperatures, ISS colors and UVIS brightness appear to vary noticeably with phase angle, but are not a strong function of spacecraft elevation angle. Color, temperature and brightness dependence on solar elevation angle are also observed. VIMS observations show that the infrared ice absorption band depths change with the solar phase angle, in particular between 0-20° and at high phase. This trend indicates that single scattering approximation is correct only at low phases (<20°) while at high phase multiple scattering must be taken into account.
These results imply that the individual properties of the ring particles may play a larger role than the collective properties of the rings, in particular at visible wavelengths. The temperature and color variation with phase angle may be a result of scattering within the regolith, as well as scattering between individual particles or clumps in a many-particle-thick layer. Initial results from our joint studies will be presented.
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**Author(s): Linda J. Spilker[4]**, Estelle Deau[5], Ryuji Morishima[6], Gianrico Filacchione[3], Matt Hedman[2], Phil Nicholson[1], Josh Colwell[7], Todd Bradley[7], Mark Showalter[5], Stu Pilorz[5], Shawn Brooks[4], Mauro Ciarniello [3]
**Institution(s):** *1. Cornell University, 2. Idaho University, 3. INAF-IAPS, 4. JPL, 5. SETI Institute, 6. UCLA, 7. University of Central Florida*

### 218.02 – Multi-frequency VLA Observations of Saturn’s Rings

We will present the calibration and analysis of recent VLA observations on Saturn and its rings at Q, K, Ku and X band (0.7 – 3.6 cm). These observations were collected in January 2015 using 8-hr tracks in the CnB array configurations to map the system at high spatial resolution (comparable to the resolution of available microwave Cassini datasets) while remaining sensitive to large scale structure. These data complement and extend Cassini observations obtained with its 2.2-cm radiometer. The significant reduction in the emissivity of water-ice at 3.6 cm relative to that at 0.7 cm results in a strong differential response to the fractional abundance of non-icy material in the rings, which is observable with VLA. The VLA data will confirm and extend our previous non-icy material distributions derived from Cassini data. Increased non-icy material contamination and changes in the particle size distribution affect the brightness temperatures noticeably differently at shorter wavelengths (0.7 - 2 cm). Therefore, the multi-wavelength nature of the VLA dataset will enable us to disentangle brightness temperature variations from changes in the particle size distribution and non-icy material abundance. We will present an update on the analysis of both the VLA dataset as well as the ongoing analysis of the Cassini observations.

**Author(s): Zhimeng Zhang[2]**, Alexander Hayes[2], Imke de Pater[6], Phillip Nicholson[2], Michael Janssen[3], Jeffrey Cuzzi[1], David Dunn[5], Bryan Butler[4]
**Institution(s):** *1. Ames Research Center, 2. Cornell University, 3. Jet Propulsion Laboratory, 4. National Radio Astronomy Observatory, 5. Sierra College, 6. University of California at Berkeley*

### 218.03 – Heating Saturn's Clumpy Rings

We model Cassini CIRS data using a Monte Carlo radiative transfer -- thermal balance technique first developed for protostellar disks, with the goals of:
1. Exploring whether the A- and B-ring temperatures' variation with viewing angle is consistent with the wake structures suggested by the observed azimuthal asymmetry in optical depth, by analytic arguments, and by numerical N-body modeling.
2. Better constraining the shape, size, spacing and optical depths of substructure in the A-ring, using the unexpectedly high temperatures observed at equinox. If the wake features have high enough contrast, Saturn-shine may penetrate the gaps between the wakes and heat the
ring particles both top and bottom.
3. Determining how much of the heating of the A- and B-rings' unlit sides is due to radiative transport and how much is due to particle motions, especially vertical motions. This will help in constraining the rings' surface densities and masses.

**Author(s): Neal J. Turner[1]**, Ryuji Morishima[2], Linda J Spilker[1]
**Institution(s):** *1. JPL/Caltech, 2. UCLA IGPP*

### 218.04 – Detections of Propellers in Saturn's Rings using Machine Learning: Preliminary Results

We report on the initial analysis of the output of a tool designed to identify persistent, non-axisymmetric features in the rings of Saturn. This project introduces a new paradigm for scientific software development. The preliminary results include what appear to be new detections of propellers in the rings of Saturn.
The Planetary Data System (PDS), working with the NASA Tournament Lab (NTL), Crowd Innovation Lab at Harvard University, and the Topcoder community at Appirio, Inc., under the umbrella “Cassini Rings Challenge”, sponsored a set of competitions employing crowd sourcing and machine learning to develop a tool which could be made available to the community at large. The Challenge was tackled by running a series of separate contests to solve individual tasks prior to the major machine learning challenge. Each contest was comprised of a set of requirements, a timeline, one or more prizes, and other incentives, and was posted by Appirio to the Topcoder Community. In the case of the machine learning challenge (a “Marathon Challenge” on the Topcoder platform), members competed against each other by submitting solutions that were scored in real time and posted to a public leader-board by a scoring algorithm developed by Appirio for this contest.
The current version of the algorithm was run against ~30,000 of the highest resolution Cassini ISS images. That set included 668

images with a total of 786 features previously identified as propellers in the main rings. The tool identified 81% of those previously identified propellers. In a preliminary, close examination of 130 detections identified by the tool, we determined that of the 130 detections, 11 were previously identified propeller detections, 5 appear to be new detections of known propellers, and 4 appear to be detections of propellers which have not been seen previously. A total of 20 valid detections from 130 candidates implies a relatively high false positive rate which we hope to reduce by further algorithm development. The machine learning aspect of the algorithm means that as our set of verified detections increases so does the pool of “ground-truth” data used to train the algorithm for future use.

**Author(s): Mitchell K. Gordon[2]**, Mark R. Showalter[2], Jennifer Odess [1], Ambi Del Villar[1], Andy LaMora [1], Jin Paik[3], Karim Lakhani [3], Rinat Sergeev [3], Kristen Erickson [5], Carol Galica [5], Edwin Grayzeck[4], Thomas Morgan [4], William Knopf [5]
**Institution(s):** *1. Appirio, Inc, 2. Carl Sagan Center, SETI Institute, 3. Crowd Innovation Lab/NASA Tournament Lab at Harvard University, 4. Goddard Space Flight Center, 5. NASA Headquarters*

### 218.05 – Characteristics of Small Scale Wave Structure Near Strong Janus Inner Lindblad Resonances

Regions of compression and rarefaction within Saturn’s rings include Inner Lindblad Resonances (ILR) at spiral density waves and spiral bending waves at vertical resonances along with smaller-scale self-gravity and overstability waves. However, few investigations have searched for structure at scales under 100 meters.
We investigate Cassini UVIS HSP stellar occultation profiles collected between May 19 2005 and June 2 2013 (Cassini revolutions 8 - 191) within and near strong A ring and B ring spiral density waves. We report an unexpected number of statistically-significant gaps in ring optical depth within the density waves generated at strong resonances. While the frequency of gaps differs across resonance locations, size distribution power laws at similar regions have similar indices. We compare the frequency of gaps between the peaks, troughs and intermediate regions of the ILR spiral density waves.

**Author(s): Zarah Brown[1]**, Morgan Rehnberg[1], Larry Esposito[1], Nicole Albers[1], Miodrag Sremčević[1]
**Institution(s):** *1. University of Colorado Boulder/LASP*

### 218.06 – Direct numerical modeling of Saturn's dense rings at high optical depth

Saturn's B ring exhibits complex optical depth structure of uncertain origin. We are investigating the extent to which viscous overstability and/or gravitational wakes can give rise to this structure, via discrete particle numerical simulations. We use the parallelized *N*-body tree code *pkdgrav* with a soft-sphere collision model for detailed treatment of particle collisional physics, including multi-point persistent contact with static, sliding, rolling, and twisting friction forces. This enables us to perform local simulations with millions of particles, realistic sizes, and configurable material properties in high-optical-depth ring patches with near-linear scaling across multiple processors. Recent code improvements to the collision search algorithm provide a further roughly factor of 2 speedup. We present results from the first year of this study in which a library of simulations with different optical depths was constructed. Parameters explored include normal (dynamical) optical depths between 0.5 (approximately 100,000 particles) and 4.0 (approximately 8.3 million particles) in ring patches of dimension 6 by 6 critical Toomre wavelengths, using material parameters ranging from highly elastic smooth spheres to rough "gravel"-like particles. We also vary the particle internal densities to enhance (low density)/suppress (high density) viscous overstability in order to compare against gravitational instability in these different regimes. These libraries will be used to carry out simulated observations for comparison with Cassini CIRS temperature measurements and UVIS occulation data of Saturn's dense rings.

**Author(s): Derek C. Richardson[2]**, Ronald-Louis Ballouz[2], Ryuji Morishima[1]
**Institution(s):** *1. Univ. of California, 2. Univ. of Maryland*

### 218.07 – A survey of the Saturnian ring edges: Results from double star occultations

The Cassini Ultraviolet Imaging Spectrograph (UVIS) High Speed Photometer (HSP) has recorded more than 150 stellar occultations of Saturn's rings. About one third are observations involving double stars, where each star contributes its own, independent light curve. For each light curve, its footprint, as projected into the ring plane and depending on observation geometry, samples a different region in the ring. Here, we focus on ring edges. Each occultation then yields two independent edge measurements at two different times and longitudes. We infer relative changes in optical depth and radial position over an azimuthal distance as short as 20 meters. These relative measurements require neither photometric nor geometric calibration and inform on the small-scale variability of structure/features with relative resolutions an order of magnitude higher than typically achieved.
The Encke and Keeler gap edges as well as the outer B and A ring edges show radial excursions on the order of tens of meters. These radial variations are, in comparison to the common multi-mode analysis of edge kinematics, high-frequency components with corresponding m numbers of $m>5000000$. We note that spatial dimensions inferred here are 10-100 times smaller than those of features Region A and B at the B ring edge or "Peggy"-type objects at the A ring edge, and are comparable to individual self-gravity wakes or clumps/particles. The Titan and Huygens ringlets inner and outer edges, on the other hand, are, in comparison, highly regular and smooth with radial variations of only a few meters. Nevertheless they show changes in normal optical depth on the order of 0.4, well above the expected margin due to intrinsic stellar variability. We also identified three features in the C ring that show little radial variability and can thus be considered smooth. Interestingly, this irregularity or raggedness of the edges - manifestation of intrinsic small-scale structure of the ring - is stronger with increasing radial distance from Saturn. This is consistent with the current understanding that larger structures form in regions of weaker tidal forces or perturbed regions such as the A and B ring edges.
This work is supported by the Cassini project.

**Author(s): Nicole Albers[1]**
**Institution(s):** *1. LASP/University of Colorado*

### 218.08 – Modeling Cassini Occultations for High Resolution Simulations of Saturn’s Rings

We present the preliminary results of attempts to accurately model Cassini occultations numerically with high-resolution patch simulations of Saturn’s rings. The simulations use particle distributions that match measurements of surface densities from density waves and particle sizes distributions that extend down to radii of a decimeter or smaller. Synthetic occultation measurements are produced using ray tracing techniques with geometries that match those of various Cassini observations for comparison.

**Author(s): Mark C. Lewis[1]**, Josh E. Colwell[2]
**Institution(s):** *1. Trinity Univ., 2. University of Central Florida*

### 218.09 – Simulating “Straw” in the Keeler Gap Region

Previous simulations by Lewis and Stewart (2005) indicated that gravity wakes at the edge of the Encke Gap region could grow to kilometers in length through the systematic motion of the ring material produced by the interaction with Pan. Recent simulations of the Keeler gap region indicate that this same process can occur there as well if there is sufficient surface density to sustain the clustering of particles. These simulations use a single large, fixed cell and include the eccentricity and inclination of Daphnis. These factors lead to time variability that is not seen at the Encke gap. We show where and how these form at the Keeler Gap, and how they might appear in occultation and imaging observations.

**Author(s): Alexander K Hansen[1]**, Mark C Lewis[1]
**Institution(s):** *1. Trinity University*

### 218.10 – Physics of Tidal Disruption of Big Objects at the Close Encounter to Saturn

The origin of Saturn's main rings is still debated. According to the "Nice model" of Late Heavy Bombardment, planets could experience significant amount of close encounters with bodies scattered from primordial Kuiper belt that surrounded the giant planets. Such primordial belt could have been significantly massive and may have contained a larger number of big objects than currently observed in the Kuiper Belt. In this work, we revisit the physical processes of tidal disruption of such big object passing inside the Saturn's Roche limit and discuss the possibility of the mass implantation around Saturn as a result of the tidal disruption. [Charnoz et al. 2009. Icarus 199, 413-428] utilized an analytical formula that is derived from simply assuming uniform distribution of energy within a body [Dones 1991. Icarus 92, 194-203] to obtain masses that are captured onto bound orbits around planet after close encounter. However, the physical processes of tidal disruption remained unclear, and thus we might need to re-assess the captured mass. In this work, we perform SPH simulations of close encounters of homogeneous and differentiated bodies around Saturn in order to investigate how such objects could be tidally destructed and how much mass could be captured around Saturn as a result of the destruction. We find that our numerical results are not always consistent with Dones' (1991) formula that, in general, significantly overestimates or underestimates the captured mass as the pericenter distance of the passing object becomes larger, depending on the mass of objects. Effects of rotation and self-gravity within the body will be also investigated. We show that there is a wide range of outcomes for tidal disruption and that the implantation of rings is possible.

**Author(s): Ryuki Hyodo[2]**, Sébastien Charnoz[2], Keiji Ohtsuki3, Hidenori Genda[1]
**Institution(s):** *1. Earth-Life Science Institute, Tokyo Institute of Technology, 2. Institut de Physique du Globe de Paris, 3. Kobe University*

### 218.11 – Orbit Averaging in Perturbed Planetary Rings

The orbital period is typically much shorter than the time scale for dynamical evolution of large-scale structures in planetary rings. This large separation in time scales motivates the derivation of reduced models by averaging the equations of motion over the local orbit period (Borderies et al. 1985, Shu et al. 1985). A more systematic procedure for carrying out the orbit averaging is to use Lie transform perturbation theory to remove the dependence on the fast angle variable from the problem order-by-order in epsilon, where the small parameter epsilon is proportional to the fractional radial distance from exact resonance. This powerful technique has been developed and refined over the past thirty years in the context of gyrokinetic theory in plasma physics (Brizard and Hahm, Rev. Mod. Phys. 79, 2007). When the Lie transform method is applied to resonantly forced rings near a mean motion resonance with a satellite, the resulting orbit-averaged equations contain the nonlinear terms found previously, but also contain additional nonlinear self-gravity terms of the same order that were missed by Borderies et al. and by Shu et al. The additional terms result from the fact that the self-consistent gravitational potential of the perturbed rings modifies the orbit-averaging transformation at nonlinear order. These additional terms are the gravitational analog of electrostatic ponderomotive forces caused by large amplitude waves in plasma physics. The revised orbit-averaged equations are shown to modify the behavior of nonlinear density waves in planetary rings compared to the previously published theory. This reserach was supported by NASA's Outer Planets Reserach program.

**Author(s): Glen R. Stewart[1]**
**Institution(s):** *1. Univ. of Colorado*

### 218.12 – A new look back at the structure of Uranus' narrow rings

With the Cassini mission to Saturn providing new insights into how rings work, a new examination of the available Uranus ring data will provide further insights into the rings' structure and dynamics, as well as the planetary interior. We investigate the fine-scale quasiperiodic optical depth variations within the Uranian rings observed in the Voyager 2 radio and stellar occultations. Previous investigations of these patterns within the ε, δ, and γ rings suggested that some of these may be density waves at locations of eccentric Lindblad resonances with the satellites Cordelia and Ophelia (Porco and Goldreich 1987 *AJ*) as well as possible unidentified satellites (Horn et al. 1988 *Icarus*, Gresh et al. 1989 *Icarus*, and Yanamandra-Fisher 1992 *ASR*). We revisit these structures as well as others in the α, β, 4, 5, and 6 rings using modern analytical techniques in order to better constrain their origins. The α and β rings exhibit highly periodic patterns, which have very different wavelengths in the different occultation cuts (even after accounting for the ringlets' width variations). We explore the possibility that these structures could be moonlet wakes, similar to those found in Saturn's rings near the small moons Pan and Daphnis.

**Author(s): Robert O Chancia[1]**, Matthew M Hedman[1], Richard G French[2]
**Institution(s):** *1. University of Idaho, 2. Wellesley College*

### 218.13 – Evolution of regolith depth and fractional pollution of Saturn's rings

We model the evolution of the fractional pollution of Saturn's rings, by calculating the ratio of exogenous meteoritic material to endogenous icy material native to the ring system. Comparison to ring spectra can constrain the age of the planet's ring system. We update our Markov-chain based model (Elliott and Esposito 2011) to numerically calculate the regolith depth and fractional pollution of a simulated system of ring particles for a given input meteoritic mass flux distribution into the system over long time scales. We use new mass flux values recently reported by Kempf et al. (EPSC 2015) derived from the Cassini Cosmic Dust Analyzer (CDA) to calculate new fractional pollution values, and calculate the bidirectional reflectance spectra using reflectance data of comet 67P/Churyumov–Gerasimenko obtained by the Alice UV spectrometer onboard the Rosetta spacecraft as the pollutant, as well as several other pollutant species for comparison to Cassini UVIS spectra.

**Author(s): Joshua Peter Elliott[2]**, Larry W Esposito[1]
**Institution(s):** *1. Laboratory for Atmospheric and Space Physics, University of Colorado, 2. National Ecological Observatory Network*

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## 219 – EPO - Scientist's Showcase, Programs, and Best Practices

### 219.01 – Discoveries in the Solar System: Spreading the Good Word

Solar system exploration in recent years has completely captured the interest of the public worldwide, and we as scientists can play a unique role in disseminating this information. The public wants to hear from us about the latest results from the Pluto flyby, to see the newest Titan image, to hear stories of the plucky Philae comet lander and to hear our thoughts on the Earth-like exoplanet, even if we are not directly involved in these missions or discoveries. They trust us, because they know our background makes us viable judges of the value of these endeavors. The public relies on us to distill the material, which is typically science-jargon-rich, into something inspiring and digestible by them in the time they have available. The best way to start reaching out is to find and distribute what most excites us, because it is clearly obvious when we're truly excited about something as opposed to just regurgitating the latest and greatest. If you like the latest picture from MSL because it looks like your back yard, show a picture of the two next to each other. We should be familiar with, and even solicit, the different outreach platforms, such as such as social media of various kinds, public talks in all shapes and forms, news venues, including radio and TV, and popular articles. Finally, we need to know our audience, prepare and practice. I have never given the exact same outreach talk twice, because the audience is always slightly different. The last two public talks I gave were carefully worded, practiced and even partly memorized, which gave me an edge of preparedness that allowed me to be more dynamic. Being involved in outreach, in the best way for you, will make you happier and better focused in your research, will ensure the public supports NASA, and will make a positive impact in the lives of many people.

**Author(s): Jani Radebaugh[1]**
**Institution(s):** *1. Brigham Young University*

### 219.02 – Exoplanet Science in the National Science Olympiad

The National Science Olympiad is one of the United States' largest science competitions, reaching over 6,000 schools in 48 states. The Olympiad includes a wide variety of events, stretching a full range of potential future STEM careers, from biological sciences to engineering to earth and space sciences. The Astronomy event has been a mainstay at the high school level for well over a decade, and nominally focuses on aspects of stellar evolution. For the 2014-2015 competition season, the event focus was aligned to include exoplanet discovery and characterization along with star formation. Teams studied both the qualitative features of exoplanets and exoplanetary systems and the quantitative aspects behind their discovery and characterization, including basic calculations with the transit and radial velocity methods. Students were also expected to have a qualitative understanding of stellar evolution and understand the differences between classes of young stars including T Tauri and FU Orionis variables, and Herbig Ae/Be stars. Based on the successes of this event topic, we are continuing this event into the 2015-2016 academic year. The key modification is the selection of new exoplanetary systems for students to research. We welcome feedback from the community on how to improve the event and the related educational resources that are created for Science Olympiad students and coaches. We also encourage any interested community members to contact your regional or state Science Olympiad tournament directors and volunteer to organize competitions and supervise events locally.

**Author(s): Thaddeus D Komacek[2]**, Donna Young[1]
**Institution(s):** *1. NASA Astrophysics Divison, 2. University of Arizona*

### 219.03 – PACA_Rosetta67P: Global Amateur Observing Support for ESA/Rosetta Mission

The PACA (Professional - Amateur Collaborative Astronomy) Project is an ecosystem of several social media platforms (Facebook, Pinterest, Twitter, Flickr, Vimeo) that takes advantage of the global and immediate connectivity amongst amateur astronomers worldwide, that can be galvanized to participate in a given observing campaign. The PACA Project has participated in organized campaigns such as Comet Observing Campaign (CIOC_ISON) in 2013 and Comet Siding Spring (CIOC_SidingSpring)in 2014. Currently the PACA Project is supporting ESA/Rosetta mission with ground-based observations of the comet 67P/Churyumov-Gerasimenko (CG) through its perihelion in August 2015 and beyond; providing baseline observations of magnitude and evolution from locations around the globe. Comet 67P/CG will reach its brightest post-perihelion and pass closest to Earth in November 2015. We will present the various benefits of our professional - amateur collaboration: developing and building a core astronomer community; defining an observing campaign from basic information of the comet from its previous apparitions; coordinating with professionals and the mission to acquire observations, albeit low-resolution, but on a long timeline; while addressing the creation of several science products such as the variation of its magnitude over time and the changing morphology. We will present some of our results to date and compare with observations from professionals and previous apparations of the comet. We shall also highlight the challenges faced in building a successful collaborative partnership between the professional and amateur observers and their resolution. With the popularity of mobile platforms and instant connections with peers globally, the multi-faceted social universe has become a vital part of engagement of multiple communities for collaborative scientific partnerships and outreach. We shall also highlight other cometary observing campaigns that The PACA Project has initiated to evolve this model of collaborative partnerships.

**Author(s): Padma A. Yanamandra-Fisher4**, Claudia Alexander[1], Efrain Morales[2], Christiana Feliciano-Rivera3
**Institution(s):** *1. CIT/Jet Propulsion Laboratory, 2. Jaicoa Observatory, 3. Slooh.com, 4. Space Science Institute*

### 219.04 – STEM education for teachers in the Rio Grande Valley

We have worked with elementary and middle school teachers in the Rio Grande Valley for the last 10 years bringing Earth and Space Science themed workshops to underserved areas of Texas. The Texas curriculum was also changed to include Astronomy and Space Science requirement in the tests students need to take to prove their academic preparedness. The teachers worked through a variety of inquiry-based, hands-on activities after a short presentation on the background science. In order to evaluate our effectiveness, we have asked the teachers to take pre- and post-workshop tests, and we asked them to fill out a self-reflective survey. We will report on our experiences, what works best with the teachers, and in what areas we still have a long way to go.
This work was supported by various NASA education grants and Cooperative agreements, as well as grants provided by the Texas Space Grant Consortium.

**Author(s): Judit Gyorgyey Ries[1]**, Margaret R. Baguio[1]
**Institution(s):** *1. Univ. of Texas, Austin*

### 219.05 – We're mass communicating: podcasting as outreach

The New York Times (July 18th, 2015) called podcasting "that rarest thing in the technology industry"; a subset of media showing sustained growth. That same article quotes an Edison Research report that found that roughly 1/5 Americans have listened to a podcast in the last month. The most popular podcasts receive a million downloads per episode, and over all podcasts, the median number of downloads per episode is ~150 (Libsyn statistics). The popularity and easy accessibility of podcasts make them an ideal vehicle for outreach.
There are several excellent podcasts covering planetary science, including Planetary Radio, produced by the Planetary Society, StarTalk Radio, several official NASA podcasts, and individual efforts such as Al Grauer's "Travelers in the Night" and Jane Jones' "What's up".
Spacepod is a weekly podcast on space exploration that launched in August 2015. Episodes feature an expert guest discussing an interesting aspect of their job for a general audience. Episodes have an intimate, conversational feel, letting the audience "hang out" with space scientists and engineers. Spacepod has shown strong growth since launch, and was featured in iTunes' "New and Noteworthy" section. Episodes can be found at www.listentospacepod.com, and the show tweets @listen2spacepod.

**Author(s): Carolyn R Nugent[1]**
**Institution(s):** *1. Caltech/IPAC*

### 219.06 – The Crossroads of Science and Faith

We have recently completed a 4-year project to produce a textbook for students that uniquely addresses the needs of the Christian homeschool community. It is also relevant for students of other faith and non-faith backgrounds. Two elements are at work: parents want their kids to become mature adults adhering to the faith of their upbringing, and students are challenged when they don't understand how to rationally discuss their beliefs in relation to many current scientific discoveries. To add to the polarization, a few scientists have spread an atheistic naturalistic worldview together with their teaching of science as if it was part of science itself. As a result many parents avoid materials they consider controversial and students later come to believe they must choose between science and their faith. The key to bridging this gap are professional astronomers who hold to a Christian worldview and who can speak both languages, understanding the complexities of both communities. The role of science educators is to teach science, not to impose worldviews. Science is well received by Christians when it is presented not as a threat to faith, but rather as a complementary way to understand God, leading to a more integrated view of reality. Our textbook boasts four hallmarks, providing students with: 1) An understanding of the relationship between faith and science with the goal of helping students to identify and integrate their own worldview. 2) Scientifically reviewed and accurate astronomical information. 3) Examples of scientists who have wrestled with science/faith issues and come to a coherent relationship between the two. And 4) exercises for the students to interact with the material in both faith and scientific areas. We hope this will be a resource to help parents who hold tightly to particular ideologies to be less closed to current scientific discovery and more excited about how new discoveries can bolster and enable their faith. We will present an overview of our materials, the positive experience we have had so far in testing our materials, and our goals for future training within the homeschool and church communities. For more information about the textbook see, http://www.glimpseofhissplendor.com/

**Author(s): Susan D. Benecchi3**, Gladys Kober[2], Paula Gossard[1]
**Institution(s):** *1. Carin University, 2. GSFC/NASA, 3. Planetary Science Institute*

### 219.07 – NASA SMD and DPS Resources for Higher Education Faculty

The NASA Education and Public Outreach Forums have developed and provided resources for higher education for the past six years through a cooperative agreement with NASA's Science Mission Directorate. Collaborations with science organizations, including AAS's Division of Planetary Sciences, have resulted in more tools, professional training opportunities, and dissemination of resources for teaching in the undergraduate classroom. Resources have been developed through needs assessments of the community and with input from scientists and undergraduate instructors. All resources are freely available.
NASA Wavelength (nasawavelength.org) is a collection of digital peer reviewed Earth and space science resources for formal and informal educators of all levels. All resources were developed through funding of the NASA Science Mission Directorate and have undergone a peer-review process through which educators and scientists ensure the content is accurate and useful in an educational setting. Within NASA Wavelength are specific lists of activities and resources for higher education faculty. Additionally, several resources have been developed for introductory college classrooms. The DPS Discovery slide sets are 3-slide presentations that can be incorporated into college lectures to keep classes apprised of the fast moving field of planetary science (http://dps.aas.org/education/dpsdisc). The "Astro 101 slide sets", developed by the Astro Forum, are presentations 5-7 slides in length on a new development or discovery from a NASA Astrophysics mission relevant to topics in introductory astronomy courses of discoveries not yet in textbooks. Additional resources guides are available for Astro 101 courses and include cosmology and exoplanets. (https://www.astrosociety.org/education /resources-for-the-higher-education-audience/).
Professional development opportunities are available to faculty to increase content knowledge and pedagogical tools. These include workshops at scientific meetings and online webinars that are archived for later viewing. For more information, visit the SMD E/PO community workspace at http://smdepo.org.

**Author(s): Sanlyn Buxner[6]**, Jennifer Grier[6], Bonnie Meinke7, Nick Schneider[8], Rusty Low4, Greg Schultz[1], James Manning5, Andrew Fraknoi3, Nicholas Gross[2]
**Institution(s):** *1. Astronomical Society of the Pacific, 2. Boston University, 3. Foothill College, 4. IGES, 5. NASA SMD Astro Forum, 6. Planetary Science Institute, 7. Space Telescope Science Institute, 8. University of Colorado*

### 219.08 – Space Scientists in Education and Public Outreach: A Summary of NASA Resources for Effective Engagement

The NASA Education and Public Outreach (E/PO) Forums developed and provided resources for scientists through a five-year cooperative agreement. Through this work, the Fourms have supported scientists who are involved in E/PO and who wish to become involved. Forums have conducted interviews, facilitated education oral and poster sessions, provided 'Help Desks' for more information, curated activities, as well as produced guides, pamphlets, and tips sheets. Our interviews with over 30 planetary scientists allowed us to identify needs and target gaps in resources, ensuring we could provide scientists with effective support and products. Interviews were conducted in collaboration with the AAS Division of Planetary Sciences, with the goal of better understanding scientists' requirements, barriers, attitudes, and perception of education and outreach work. We collected information about how scientists were engaged in E/PO activities (or not), what support they did or did not have, what resources they used in their efforts, and what resources they would like to have to support and improve their E/PO engagement. The Forums have convened and/or supported E/PO oral and poster sessions at a variety of annual meetings. These sessions allowed scientists to network, share lessons learned, and become aware of new resources and products. These meetings included the DPS, AAS, LPSC, AGU, ASP, IAU, and more. 'Help Desks' were offered to allow scientists the chance to have extended one-on-one conversations with E/PO providers in order to share their programs, and learn how to become involved. These have been particularly popular with early career scientists looking to extend their E/PO efforts. A host of education activities developed by the space science community have been archived at the NASA site "Wavelength" (nasawavelength.org). Special lists have been curated to allow scientists to easily target those activities that fit their particular needs, from engineering to higher education to outreach at public events. Guides, information sheets, and "How To's" have been developed to answer specific questions and needs that scientists have specifically expressed. These resources are openly available at the NASA SMD community site (smdepo.org).

**Author(s): Jennifer A. Grier3**, Sanlyn Buxner3, Nick Schneider[1], Bonnie Meinke4, Stephanie Shipp[2]
**Institution(s):** *1. LASP/University of Colorado, 2. Lunar and Planetary Institute, 3. Planetary Science Institute, 4. Space Telescope Science Institute*

### 219.09 – Best Practices in Pulic Outreach Events

Introduction
Each year the National Aeronautics and Space Administration (NASA) sponsors public outreach events designed to increase student, educator, and general public engagement in its missions and goals. NASA SMD Education's review of large-scale events, "Best Practices in Outreach Events," highlighted planning and implementation best practices, which were used by the Dawn mission to strategize and implement its Ceres arrival celebration event, *i C Ceres*.
Background
The literature review focused on best identifying practices rising from evaluations of large-scale public outreach events. The following criteria guided the study:
* Public, science-related events open to adults and children
* Events that occurred during the last 5 years
* Evaluations that included information on data collected from visitors and/or volunteers
* Evaluations that specified the type of data collected, methodology, and associated results

Best Practices: Planning and Implementation
The literature review revealed key considerations for planning implement large-scale events. Best practices included can be pertinent for all event organizers and evaluators regardless of event size. A summary of related best practices is presented below.
1) Advertise the event
2) Use and advertise access to scientists
* Attendees who reported an interaction with a science professional were 15% to 19% more likely to report positive learning impacts, (SFA, 2012, p. 24).
3) Recruit scientists using findings such as:
* High percentages of scientists (85% to 96%) from most events were interested in participating again (SFA, 2012).
4) Ensure that the event is group and, particularly, child friendly
5) Target specific event outcomes
Best Practices Informing Real-world Planning, Implementation and Evaluation
Dawn mission's collaborative design of a series of events, *i C Ceres*, including in-person, interactive events geared to families and live presentations, will be shared, with focus on the family event, and the evidence that scientist participation was a particular driver for the event's impact and success.
Science Festival Alliance (SFA). (2012). *Get inspired: A first look at science festivals*. Retrieved from http://sciencefestivals.org /news_item/get-inspired

**Author(s): Whitney Cobb[2]**, Sanlyn Buxner3, Stephanie Shipp[1]
**Institution(s):** *1. Lunar and Planetary Institute, 2. McREL International, 3. Planetary Science Institute*

### 219.10 – Lessons from a Train-the-Trainer Professional Development Program: The Sustainable Trainer Engagement Program (STEP)

The Sustainable Trainer Engagement Program (STEP) is a modified train-the-trainer professional development program being conducted by the Lunar and Planetary Institute (LPI). STEP has provided two cohorts of 6-8th grade science specialists and lead teachers in the Houston region with in-depth Earth and Space Science (ESS) content, activities, and pedagogy over 15 days each, aligned with Texas science standards. This project has two over-arching goals: to improve middle school ESS instruction, and to create and test an innovative model for Train-the-Trainer.
This poster will share details regarding STEP's activities and resources, program achievements, and its main findings to date.
STEP is being evaluated by external evaluators at the Research Institute of Texas, part of the Harris County Department of Education. External evaluation shows an increase after one year in STEP participants' knowledge (cohort 1 showed a 10% increase; cohort 2 showed a 20% increase), confidence in teaching Earth and Space Science effectively (cohort 1 demonstrated a 10% increase; cohort 2 showed a 20% increase), and confidence in preparing other teachers (cohort 1 demonstrated a 12% increase; cohort 2 showed a 20% increase). By September 2015, STEP participants led (or assisted in leading) approximately 40 workshops for about 1800 science teachers in Texas. Surveys of teachers attending professional development conducted by STEP participants show very positive responses, with averages for conference workshop evaluations ranging from 3.6 on a 4 point scale, and other evaluations averaging from 4.1 to 5.0 on a 5 point scale.
Main lessons for the team on the train-the-trainer model include: a lack of confidence by leaders in K-12 science education in presenting ESS professional development, difficulties in arranging for school or district content-specific professional development, the minimal duration of most school and district professional development sessions, and uncertainties in partnerships between scientists and educators.

**Author(s): Christine Shupla[2]**, Alicia Gladney[1], Heather Dalton[2], Keliann LaConte[2], Jeannette Truxillo[1], Stephanie Shipp[2]
**Institution(s):** *1. Harris County Department of Education, 2. Lunar and Planetary Institute*

### 219.11 – Inexpensive DAQ based physics labs

Quality Data Acquisition (DAQ) based physics labs can be designed using microcontrollers and very low cost sensors with minimal lab equipment. A prototype device with several sensors and documentation for a number of DAQ-based labs is showcased. The device connects to a computer through Bluetooth and uses a simple interface to control the DAQ and display real time graphs, storing the data in .txt and .xls formats. A full device including a larger number of sensors combined with software interface and detailed documentation would provide a high quality physics lab education for minimal cost, for instance in high schools lacking lab equipment or students taking online classes. An entire semester's lab course could be conducted using a single device with a manufacturing cost of under $20.

**Author(s): Benjamin Lewis[1]**, Shane Clark[1]
**Institution(s):** *1. Mississippi State University*

### 219.12 – Assessment of Impact on Students and Teachers of Student-led, inquiry-based planetary science instruction in Grades 3-8

The University of Houston is in the process of developing a flexible program that offers children an in-depth educational experience culminating in the design and construction of their own model Mars rover. The program is called the Mars Rover Model Celebration (MRC). It focuses on students, teachers and parents in grades 3-8. Students design and build a model of a Mars rover to carry out a student selected science mission on the surface of Mars. A total of 195 Mars Rover teachers from the 2012-2013, 2013-2014, and 2014-2015 cohorts were invited to complete the Mars Rover Teacher Evaluation Survey. The survey was administered online and could be taken at the convenience of the participant. So far ~90 teachers have participated with responses still coming in. A total of 1300 students from the 2013-2014 and 2014-2015 cohort were invited to submit brief self-assessments of their participation in the program. Teachers were asked to rate their current level of confidence in their ability to teach specific topics within the Earth and Life Science realms, as well as their confidence in their ability to implement teaching strategies with their students. The most striking increase in this area was the reported 48% of teachers who felt their confidence in teaching "Earth and the solar system and universe" increased "Quite a bit" as a result of their participation in the MRC program. The vast majority of teachers (86-100%) felt somewhat to very confident in their ability to effectively implement all of the listed teaching strategies. The most striking increases were the percentage of teachers who felt their confidence increased "Quite a bit" as a result of their participation in the MRC program in the following areas: "Getting students interested in and curious about science" (63%); "Teaching science as a co-inquirer with students" (56%); and "Continually find better ways to teach science" (59%). Student outcome analysis is pending correlation with final progress reports for the participating students. A key finding is that 354/365 responding students in the 2014-2015 cohort report substantial increase in science excitement owing to participation in the program.

**Author(s): Edgar Andrew Bering[2]**, Coleen Carlson[2], Kenneth Nieser[2], Elana Slagle[1]
**Institution(s):** *1. Starfish Education, 2. University of Houston*

### 219.13 – PUMAS: The On-line journal of Math and Science Examples for Pre-College Education

PUMAS – "Practical Uses of Math And Science" – is an on-line collection of brief examples showing how math and science topics taught in K-12 classes can be used in interesting settings, including every day life. The examples are written primarily by scientists, engineers, and other content experts having practical experience with the material. They are aimed mainly at classroom teachers to enrich their presentation of math and science topics. The goal of PUMAS is to capture, for the benefit of pre-college education, the flavor of the vast experience that working scientists have with interesting and practical uses of math and science. There are currently over 80 examples in the PUMAS collection, and they are organized by curriculum topics and tagged with relevant grade levels and curriculum topic benchmarks. The published examples cover a wide range of subject matter: from demonstrating why

summer is hot, to describing the fluid dynamics of a lava lamp, to calculating the best age to collect Social Security Benefits. The examples are available to all interested parties via the PUMAS web site: http://pumas.nasa.gov/.
We invite the community to participate in the PUMAS collection. We seek scientists and scientific thinkers to provide innovative examples of practical uses for teachers to use to enrich the classroom experience, and content experts to participate in peer-review. We also seek teachers to review examples for originality, accuracy of content, clarity of presentation, and grade-level appropriateness. Finally, we encourage teachers to mine this rich repository for real-world examples to demonstrate the value of math in science in everyday life.

**Author(s): Melissa G Trainer[1]**, Ralph A. Kahn[1]
**Institution(s):** *1. NASA Goddard Space Flight Center*

### 219.14 – DPS Planetary Science Graduate Programs Listing: A Resource for Students and Advisors

We began a web page on the DPS Education site in 2013 listing all the graduate programs we could find that can lead to a PhD with a planetary science focus. Since then the static page has evolved into a database-driven, filtered-search site. It is intended to be a useful resource for both undergraduate students and undergraduate advisers, allowing them to find and compare programs across a basic set of search criteria. From the filtered list users can click on links to get a "quick look" at the database information and follow links to the program main site.
The reason for such a list is because planetary science is a heading that covers an extremely diverse set of disciplines. The usual case is that planetary scientists are housed in a discipline-placed department so that finding them is typically not easy—undergraduates cannot look for a Planetary Science department, but must (somehow) know to search for them in all their possible places. This can overwhelm even determined undergraduate student, and even many advisers!
We present here the updated site and a walk-through of the basic features. In addition we ask for community feedback on additional features to make the system more usable for them. Finally, we call upon those mentoring and advising undergraduates to use this resource, and program admission chairs to continue to review their entry and provide us with the most up-to-date information.
The URL for our site is http://dps.aas.org/education/graduate-schools.

**Author(s): David R. Klassen[1]**, Anthony Roman[2], Bonnie Meinke[2]
**Institution(s):** *1. Rowan Univ., 2. Space Telescope Science Institute*

### 219.15 – A Guide for Scientists Interested in Researching Student Outcomes

Scientists spend years training in their scientific discipline and are well versed the literature, methods, and innovations in their own field. Many scientists also take on teaching responsibilities with little formal training in how to implement their courses or assess their students. There is a growing body of literature of what students know in space science courses and the types of innovations that can work to increase student learning but scientists rarely have exposure to this body of literature. For scientists who are interested in more effectively understanding what their students know or investigating the impact their courses have on students, there is little guidance. Undertaking a more formal study of students poses more complexities including finding robust instruments and employing appropriate data analysis. Additionally, formal research with students involves issues of privacy and human subjects concerns, both regulated by federal laws.
This poster details the important decisions and issues to consider for both course evaluation and more formal research using a course developed, facilitated, evaluated and researched by a hybrid team of scientists and science education researchers. HabWorlds, designed and implemented by a team of scientists and faculty at Arizona State University, has been using student data to continually improve the course as well as conduct formal research on students' knowledge and attitudes in science. This ongoing project has had external funding sources to allow robust assessment not available to most instructors. This is a case study for discussing issues that are applicable to designing and assessing all science courses. Over the course of several years, instructors have refined course outcomes and learning objectives that are shared with students as a roadmap of instruction. The team has searched for appropriate tools for assessing student learning and attitudes, tested them and decided which have worked, or not, for assessment in the course. Data from this assessment has led to many changes in the course to better meet the course goals. We will share challenges and lessons learned in our project to assist other instructors interested in doing research on student outcomes.

**Author(s): Sanlyn R Buxner3**, Ariel Anbar[1], Steve Semken[1], Chris Mead[1], Lev Horodyskyj[1], Viranga Perera[1], Geoffrey Bruce[1], David Schönstein[2]
**Institution(s):** *1. Arizona State University, 2. Smart Sparrow, 3. University of Arizona*

### 219.16 – Small Worlds Week: An online celebration of planetary science using social media to reach millions

In celebration of the many recent discoveries from New Horizons, Dawn, Rosetta, and Cassini, NASA launched Small Worlds Week, an online, social media driven outreach program leveraging the infrastructure of Sun-Earth Days that included a robust web design, exemplary education materials, hands-on fun activities, multimedia resources, science and career highlights, and a culminating social media event. Each day from July 6-9, a new class of solar system small worlds was featured on the website: Monday-comets, Tuesday-asteroids, Wednesday-icy moons, and Thursday-dwarf planets. Then on Friday, July 10, nine scientists from Goddard Space Flight Center, Jet Propulsion Laboratory, Naval Research Laboratory, and Lunar and Planetary Institute gathered online for four hours to answer questions from the public via Facebook and Twitter. Throughout the afternoon the scientists worked closely with a social media expert and several summer interns to reply to inquirers and to archive their chats. By all accounts, Small Worlds Week was a huge success with 37 million potential views of the social media Q&A posts. The group plans to improve and replicate the program during the school year with a more classroom focus, and then to build and extend the program to be held every year. For more information, visit http:// sunearthday.nasa.gov or catch us on Twitter, #nasasww.

**Author(s): Louis Mayo[1]**
**Institution(s):** *1. NASA's GSFC*

### 219.17 – "Travelers In The Night" in the Old and New Media

"Travelers in the Night" is a series of 2 minute audio programs based on current research in astronomy and the space sciences. After more than a year of submitting "Travelers In The Night" 2 minute audio pieces to NPR and Community Radio stations with limited success, a parallel effort was initiated by posting the pieces as audio podcasts on Spreaker.com and iTunes.
The classic media dispenses programming whose content and schedule is determined by editors and station managers. Riding the wave of new technology, people from every demographic group across the globe are selecting what, when, and how they receive information and entertainment. This change is significant with the Pew Research Center reporting that currently more than 60% of Facebook and Twitter users now get their news and/or links to stories from these sources. What remains constant is the public's interest in astronomy and space.
This poster presents relevant statistics and a discussion of the initial results of these two parallel efforts.

**Author(s): Albert D. Grauer[1]**
**Institution(s):** *1. University of Arizona*

### 219.18 – Helping students understand planet

**categories using "sensing" personification: Jupiter as want-to-be star, Earth as want-to-be Jupiter, etc.**

Students often, in learning about the classification of planets, consider the planets to be in strict categories (such as gas giants and terrestrial planets) and assume that these categories are drastically different in nature. This is not the case. Small objects such as asteroids have a weak gravitational pull such that they cannot hold an atmosphere, while terrestrial planets are capable of holding a gaseous (often transparent) atmosphere according to their larger mass. However, asteroids and terrestrial planets are very similar in composition (though not necessarily in homogeneity due to varying presence of collisional heating during formation). Meanwhile, gas giant planets (also often referred to as Jovian planets) such as Jupiter have been theorized to contain super-sized rocky terrestrial-like planets interior to their dense cloud covering. Hence, due then to their similar natures, the categorization of the terrestrial and gas giant planets is made not due to fundamental differences in the nature of the planets, a concept often ill-understood by students. Examining this further, the gas giants are planets whose masses, and hence gravitational ability to condense their gases, especially those close to their core, is less than those of stars wherein thermonuclear fusion initiates. This implies that stars also have terrestrial cores (albeit likely extremely densely packed), but the gaseous environments of hydrogen are dense enough to start and sustain this process of thermonuclear fusion. It is proposed here that seeing planets as fundamentally related to each other in composition though differing in size allows students to better understand the variety of planet types AND describing these as want-to-be (or wanna-be) in terms of ranking and according to a “sensing” personification that eschews anthropomorphism, animism, or teleology [see A. E. Tabor-Morris, “Thinking in terms of sensors: personification of self as an object in physics problem solving” Physics Education, 50.2 (Feb 2015) 203-209] to assist in putting this into perspective for students.

**Author(s): Anne Tabor-Morris[1]**
**Institution(s):** *1. Georgian Court University*

### 219.19 – New Horizons at Pluto: An Overview of Educational Activities / Outreach at Fernbank Science Center, Atlanta, Georgia (USA)

We report on educational activities and associated outreach at Fernbank Science Center (Atlanta, GA) in conjunction with the July 2015 New Horizons spacecraft encounter at Pluto. On encounter day, a public lecture about the dwarf planet was presented by Georgia’s NASA Solar System ambassador to kick off the arrival of the space probe at Pluto. In the months following the flyby, we presented a program called “Exploring New Horizons” in the Science Center’s Zeiss planetarium. This program is a digital full-dome presentation about the discovery of Pluto and its subsequent exploration – including an overview of the New Horizons mission. Since NASA continues to receive data from the probe, a brief update (tribute) is included at the end of each planetarium program that features the latest imagery and data from the dwarf planet. We anticipate running the planetarium program throughout the fall semester of 2015. With Pluto visible in the early evening autumn sky, observations are possible with Center’s 0.9 m telescope, which is open for public viewing on clear Thursday and Friday nights following the planetarium program. Although Pluto is somewhat faint through the telescope's eyepiece, it is visible and clearly identified within the surrounding starfield. Intermittent post-encounter lectures ("Messages from the Outer Solar System") have been given on Friday evenings as well. Finally, due to the continued interest in Pluto, we have developed a new outreach program about dwarf planets in general, geared towards 4th – 6th students.

**Author(s): Edward F. Albin[1]**, R. Scott Harris[1]
**Institution(s):** *1. Fernbank Science Center*

### 219.20 – Partnering to Enhance Planetary Science Education and Public Outreach Program

The Lunar and Planetary Institute (LPI) in Houston, Texas utilizes many partners to support its multi-faceted Education and Public Outreach (E/PO) program. The poster will share what we have learned about successful partnerships. One portion of the program is focused on providing training and NASA content and resources to K-12 educators. Teacher workshops are performed in several locations per year, including LPI and the Harris County Department of Education, as well as across the country in cooperation with other programs and NASA Planetary Science missions.
To serve the public, LPI holds several public events per year called Sky Fest, featuring activities for children, telescopes for night sky viewing, and a short scientist lecture. For Sky Fest, LPI partners with the NASA Johnson Space Center Astronomical Society; they provide the telescopes and interact with members of the public as they are viewing celestial objects. International Observe the Moon Night (InOMN) is held annually and involves the same aspects as Sky Fest, but also includes partners from Johnson Space Center’s Astromaterials Research and Exploration Science group, who provide Apollo samples for the event.
Another audience that LPI E/PO serves is the NASA Planetary Science E/PO community. Partnering efforts for the E/PO community include providing subject matter experts for professional development workshops and webinars, connections to groups that work with diverse and underserved audiences, and avenues to collaborate with groups such as the National Park Service and the Afterschool Alliance.
Additional information about LPI’s E/PO programs can be found at http://www.lpi.usra.edu/education. View a list of LPI E/PO’s partners here: http://www.lpi.usra.edu/education/partners/.

**Author(s): Heather Dalton[1]**, Stephanie Shipp[1], Christine Shupla[1], Andrew Shaner[1], Keliann LaConte[1]
**Institution(s):** *1. Lunar and Planetary Institute*

### 219.21 – Contextual Student Learning through Authentic Asteroid Research Projects using a Robotic Telescope Network

Skynet is a worldwide robotic telescope network operated by the University of North Carolina at Chapel Hill with active observing sites on 3 continents. The queue-based observation request system is simple enough to be used by middle school students, but powerful enough to supply data for research scientists. The Skynet Junior Scholars program, funded by the NSF, has teamed up with professional astronomers to engage students from middle school to undergraduates in authentic research projects, from target selection through image analysis and publication of results. Asteroid research is a particularly fruitful area for youth collaboration that reinforces STEM education standards and can allow students to make real contributions to scientific knowledge, e.g., orbit refinement through astrometric submissions to the Minor Planet Center. We have created a set of projects for youth to: 1. Image an asteroid, make a movie, and post it to a gallery; 2. Measure the asteroid’s apparent motion using the Afterglow online image processor; and 3. Image asteroids from two or more telescopes simultaneously to demonstrate parallax. The apparent motion and parallax projects allow students to estimate the distance to their asteroid, as if they were the discoverer of a brand new object in the solar system. Older students may take on advanced projects, such as analyzing uncertainties in asteroid orbital parameters; studying impact probabilities of known objects; observing time-sensitive targets such as Near Earth Asteroids; and even discovering brand new objects in the solar system.
Images are acquired from among seven Skynet telescopes in North Carolina, California, Wisconsin, Canada, Australia, and Chile, as well as collaborating observatories such as WestRock in Columbus, Georgia; Stone Edge in El Verano, California; and Astronomical Research Institute in Westfield, Illinois.

**Author(s): Vivian L. Hoette5**, Andrew W. Puckett[2], Tyler R. Linder[1], Sue Ann Heatherly3, Travis A. Rector4, Joshua B. Haislip[6], Kate Meredith5, Austin L. Caughey[2], Johnny E. Brown[2], Cameron B. McCarty[2], Kevin T. Whitmore[2]
**Institution(s):** *1. Astronomical Research Institute, 2. Columbus State University, 3. National Radio Astronomy Observatory, 4. University of Alaska Anchorage, 5. University of Chicago, 6. University of North Carolina at Chapel Hill*

### 219.22 – Spatial Reasoning Training Through Light Curves Of Model Asteroids

Recent research has demonstrated that spatial reasoning skills, long known to be crucial to math and science success, are teachable. Even short stints of training can improve spatial reasoning skills among students who lack them (Sorby et al., 2006). Teaching spatial reasoning is particularly valuable to women and minorities who, through societal pressure, often doubt their spatial reasoning skill (Hill et al., 2010). We have designed a hands on asteroid rotation lab that provides practice in spatial reasoning tasks while building the student's understanding of photometry. For our tool, we mount a model asteroid, with any shape of our choosing, on a slowly rotating motor shaft, whose speed is controlled by the experimenter. To mimic an asteroid light curve, we place the model asteroid in a dark box, shine a movable light source upon our asteroid, and record the light reflected onto a moveable camera. Students may then observe changes in the light curve that result from varying a) the speed of rotation, b) the model asteroid's orientation with respect to the motor axis, c) the model asteroid's shape or albedo, and d) the phase angle. After practicing with our tool, students are asked to pair new objects to their corresponding light curves. To correctly pair objects to their light curves, students must imagine how light scattering off of a three dimensional rotating object is imaged on a ccd sensor plane, and then reduced to a series of points on a light curve plot. Through the use of our model asteroid, the student develops confidence in spatial reasoning skills.

**Author(s): Julie Ziffer[2]**, Paul A Nakroshis[2], Benjamin T Rudnick[1], Maxwell J Brautigam[1], Tyler W Nelson[2]
**Institution(s):** *1. Falmouth High School, 2. University of Southern Maine*

### 219.23 – 3-D Printed Asteroids for Outreach Astronomy Education

3-D printed asteroids provide new opportunities for outreach astronomy education due to their low cost, interactive potential, and high interest value. Telescopes are expensive, bulky, fragile, and cannot be used effectively during the day. 3-D printing of asteroids combines exciting new technology with astronomy, appealing to a broader audience. The printed models are scientifically accurate, as their shapes have been modeled using light-curve inversion techniques using and occultation data to provide a jumping off point for discussions of these advanced and exciting topics.

**Author(s): April Russell[1]**
**Institution(s):** *1. Siena College*

### 219.24 – An Update on the NASA Planetary Science Division Research and Analysis Program

**Introduction:** NASA's Planetary Science Division (PSD) solicits its research and analysis (R&A) programs each year in Research Opportunities in Space and Earth Sciences (ROSES). Beginning with the 2014 ROSES solicitation, PSD changed the structure of the program elements under which the majority of planetary science R&A is done. Major changes included the creation of five core research program elements aligned with PSD's strategic science questions, the introduction of several new R&A opportunities, new submission requirements, and a new timeline for proposal submission.
**ROSES and NSPIRES:** ROSES contains the research announcements for all of SMD. Submission of ROSES proposals is done electronically via NSPIRES: http://nspires.nasaprs.com. We will present further details on the proposal submission process to help guide younger scientists. Statistical trends, including the average award size within the PSD programs, selections rates, and lessons learned, will be presented. Information on new programs will also be presented, if available.
**Review Process and Volunteering:** The SARA website (http://sara.nasa.gov) contains information on all ROSES solicitations. There is an email address (SARA@nasa.gov) for inquiries and an area for volunteer reviewers to sign up. The peer review process is based on Scientific/Technical Merit, Relevance, and Level of Effort, and will be detailed within this presentation.
**ROSES 2015 submission changes:** All PSD programs will continue to use a two-step proposal submission process. A Step-1 proposal is required and must be submitted electronically by the Step-1 due date. The Step-1 proposal should include a description of the science goals and objectives to be addressed by the proposal, a brief description of the methodology to be used to address the science goals and objectives, and the relevance of the proposed research to the call submitted to.

**Author(s):** Max Bernstein[1], Christina Richey[1], **Jonathan Rall[1]**
**Institution(s):** *1. NASA HQ*

### 219.25 – Astronomy Education & Outreach in South Africa

Although South Africa has evolved greatly in the 20 years since the end of apartheid, it remains a very divided country. The highest-performing students are comparable in ability to those in the US and Europe, but nearly all of these students are from priveleged Afrikaaner (European) backgrounds. The vast majority of students in the country are native African, and school standards remain very low across the country. It is common that students have no textbooks, teachers have only a high school education, and schools have no telephones and no toilets. By high school graduation, the majority of students have never used a web browser -- even students in the capital of Johannesburg. And while a few students are inspired by home-grown world-class projects such as the Square Kilometer Array (SKA) and Southern African Large Telescope (SALT), most remain unaware of their existence. Despite the poor state of education in the country, students work hard, are curious, and desire information from the outside world. Astronomy is one subject in which students in rural Africa often show exceptional interest. Perhaps astronomy serves as a 'gateway science,' linking the physically observable world with the exotic and unknown.
Here I report on many visits I have made to both rural and urban schools in South Africa during the 2013-2015 period. I have interacted with thousands of grade 7-12 students at dozens of schools, as well as taught students who graduated from this system and enrolled in local universities. I will present an assessment of the state of science education in South Africa, as well as a few broader suggestions for how scientists and educators in developed countries can best make an impact in Southern Africa.

**Author(s): Henry B. Throop[1]**
**Institution(s):** *1. PSI*

## 300 – Titan's Atmosphere and Surface

### 300.01 – Monstrous Ice Cloud System in Titan's Present South Polar Stratosphere

During southern autumn when sunlight was still available, Cassini's Imaging Science Subsystem discovered a cloud around 300 km near Titan's south pole (West, R. A. et al., AAS/DPS Abstracts, 45, #305.03, 2013); the cloud was later determined by Cassini's Visible and InfraRed Mapping Spectrometer to contain HCN ice (de Kok et al., Nature, 514, pp 65-67, 2014). This cloud has proven to be only the tip of an extensive ice cloud system contained in Titan's south polar stratosphere, as seen through the night-vision goggles of Cassini's Composite InfraRed Spectrometer (CIRS). As the sun sets and the gloom of southern winter approaches, evidence is beginning to accumulate from CIRS far-IR spectra that a massive system of nitrile ice clouds is developing in Titan's south polar stratosphere. Even during the depths of

northern winter, nothing like the strength of this southern system was evident in corresponding north polar regions.
From the long slant paths that are available from limb-viewing CIRS far-IR spectra, we have the first definitive detection of the $\nu_6$ band of cyanoacetylene ($HC_3N$) ice in Titan's south polar stratosphere. In addition, we also see a strong blend of nitrile ice lattice vibration features around 160 $cm^{-1}$. From these data we are able to derive ice abundances. The most prominent (and still chemically unidentified) ice emission feature, the Haystack, (at 220 $cm^{-1}$) is also observed. We establish the vertical distributions of the ice cloud systems associated with both the 160 $cm^{-1}$ feature and the Haystack. The ultimate aim is to refine the physical and possibly the chemical relationships between the two.
Transmittance thin film spectra of nitrile ice mixtures obtained in our Spectroscopy for Planetary ICes Environments (SPICE) laboratory are used to support these analyses.

**Author(s): Carrie Anderson[1]**, Robert Samuelson[2], Jason McLain[2], Richard Achterberg[2], F Michael Flasar[1], Stefanie Milam[1]
**Institution(s):** *1. NASA GSFC, 2. University of Maryland*

### 300.02 – Condensation of trace species to form ice layers in Titan's stratosphere

In addition to the organic haze particles produced photochemically in Titan's upper atmosphere, a number of trace gases are also created. These hydrocarbon and nitrile species include $C_2H_6$, $C_2H_2$, $C_4H_{10}$, HCN, $HC_3N$, $C_2H_5CN$ and many more. While both Voyager and Cassini observations have found evidence for ices (e.g. $C_4N_2$, HCN) in the atmosphere above Titan's poles, these species are also likely to condense at other latitudes forming optically thin ice layers in the stratosphere. A series of simulations have been conducted using Titan CARMA, a 1-D microphysics and radiative transfer model, to explore cloud particle formation with ~20 of Titan's trace hydrocarbon and nitrile gases. These species reach their condensation temperatures between 60 and 110 km. Most condense solely as ices, however, $C_3H_8$ will condense first near 70 km as a liquid and then freeze as the droplets descend toward the surface. $C_3H_8$ and $C_2H_6$ join $CH_4$ as a liquid at Titan's surface. Many ices have long condensation timescales resulting in particle radii ~1 µm or less. Several (including HCN, $C_3H_8$, $C_2H_2$) will grow 10-50 times larger. Expected condensation altitudes and particle sizes will be presented, as well as the implications for the optical properties of Titan's stratospheric aerosol particles.
This work was supported by the NASA Outer Planets Research program.

**Author(s): Erika L. Barth[1]**
**Institution(s):** *1. Southwest Research Inst.*

### 300.03 – Wind Shear May Produce Long-Lived Storms and Squall Lines on Titan

The impact of CAPE and wind shear on storms in a Titan-like environment are explored through numerical simulation. Numerical modeling indicates that both large-scale shear and CAPE environment control the dynamics of the clouds. This response to the large-scale environment is analogous to the behavior of deep convective clouds on Earth. The balance between shear and CAPE, as expressed through the bulk Richardson Number ($N_R$), is a good indicator of the response of a storm to its environment. Large $N_R$ results in short-lived single cell storms (Figure 1). As shear increases for a given CAPE, and $N_R$ decreases, the storms transition to a multicellular regime. Multicellular storms are longer-lived and are characterized by a downdraft generated cold pool that interacts with the background shear vorticity to initiate cells along the leading edge of the storm gust front (Figure 2). Very long-lived storms (>24 hours) propagating for 1000 km or more might be possible. The most intense multicellular systems simulated in this study behave similar to terrestrial squall lines, and very long-lived storms (>24 hours) propagating for 1000 km or more might be possible. Cloud outbursts and linear cloud features observed from ground and Cassini may be the result of these organized storm systems. Varying amounts of shear in the Titan environment might explain the variety of convective cloud expressions identified in Cassini orbiter and ground-based observations. The resulting distribution and magnitude of precipitation as well as surface winds associated with storms have implications on the formation of fluvial and aeolian features, including dunes, and on the exchange of methane with the surface and lakes.

**Author(s): Scot C.R. Rafkin[1]**, Erika Barth[1]
**Institution(s):** *1. SWRI*

### 300.04 – Asymmetric lake distribution on Titan mediated by methane transport due to atmospheric eddies

The observed north-south asymmetry in the distribution of Titan's seas and lakes has been proposed to be a consequence of orbital forcing affecting Titan's hydrologic cycle, as in the present the northern summer is longer but milder than its southern counterpart. Though recent general circulation models have simulated asymmetrical surface liquid distributions, the mechanism that generates this asymmetry has not been explained. In this work, we compare axisymmetric and three-dimensional simulations of Titan's atmospheric circulation with the Titan Atmospheric Model (TAM) [Lora et al. 2015, Icarus 250] to investigate the transport of moisture by the atmosphere. A significant hemispheric asymmetry only develops in the latter case, and we demonstrate that equatorward transport by high-latitude, baroclinic eddies is responsible. Eddies transport moisture from the high latitudes into the low and midlatitude cross-equatorial mean meridional circulation, producing an atmospheric "bucket brigade." The moisture transport by eddies is more intense in the south than in the north as a consequence of the orbital forcing, and therefore the result is net northward transport of methane, explaining the surface buildup in the north.

**Author(s): Juan M. Lora[1]**, Jonathan L. Mitchell[1]
**Institution(s):** *1. University of California*

### 300.05 – Seasonal Surface Temperature Changes on Titan

The Composite Infrared Spectrometer (CIRS) on Cassini has been measuring surface brightness temperatures on Titan since 2004 (Jennings et al. 2011; Cottini et al. 2012; Tan et al. 2015). Radiation from the surface reaches space through a window of minimum opacity in Titan's atmosphere near 19 microns wavelength. We mapped surface temperatures in five time periods, each about 2 years, centered on solar longitudes Ls = 313°, 335°, 0°, 28° and 53° degrees. Using zonally-averaged spectra binned in 10-degree latitude intervals, we clearly see the seasonal progression of the pole-to-pole temperature distribution. Whereas peak temperatures in the vicinity of the Equator have been close to 94 K throughout the Cassini mission, early in the mission temperatures at the North Pole were as low as 90 K and at the South Pole were 92 K. Late in the mission the pattern has reversed: 92 K in the north and 90 K in the south. Over 2005 to 2014 the peak temperature moved in latitude from about 15 S to 15 N. We estimate a seasonal lag of 0.2 Titan month. In 2010 the temperature distribution was approximately symmetric north and south, agreeing with Voyager 1 from one Titan year earlier. The surface temperatures follow closely the predictions of Tokano (2005). Our measurements may indicate a lower thermal inertia in the south than in the north.
Jennings, D.E. et al., ApJ Lett. 737, L15 (2011)
Cottini, V. et al., 2012. Planet. Space Sci. 60, 62 (2012)
Tan, S. P. et al., Icarus 250, 64 (2015)
Tokano, T., Icarus 204, 619 (2005)

**Author(s): Donald E. Jennings3**, Valeria Cottini[1], Conor A. Nixon3, Athena Coustenis[2], Tetsuya Tokano4
**Institution(s):** *1. Department of Astronomy, University of Maryland, 2. LESIA, Paris Obs., PSL-Research Univ., CNRS, Univ. Paris 06, Sorbonne Univ., Univ. Paris-Diderot, 3. NASA Goddard Space Flight Center, 4. Universität zu Köln*

### 300.06 – Titan's mid-latitude surface regions with Cassini VIMS and RADAR

The *Cassini-Huygens* mission instruments have revealed Titan to have a complex and dynamic atmosphere and surface. Data from the remote sensing instruments have shown the presence of diverse surface terrains in terms of morphology and composition, suggesting both exogenic and endogenic processes [1]. We define both the surface and atmospheric contributions in the VIMS spectro-imaging data by use of a radiative transfer code in the near-IR range [2]. To complement this dataset, the Cassini RADAR instrument provides additional information on the surface morphology, from which valuable geological interpretations can be obtained [3]. We examine the origin of key Titan terrains, covering the mid-latitude zones extending from 50°N to 50°S. The different geological terrains we investigate include: mountains, plains, labyrinths, craters, dune fields, and possible cryovolcanic and/or evaporite features. We have found that the labyrinth terrains and the undifferentiated plains seem to consist of a very similar if not the same material, while the different types of plains show compositional variations [3]. The processes most likely linked to their formation are aeolian, fluvial, sedimentary, lacustrine, in addition to the deposition of atmospheric products though the process of photolysis and sedimentation of organics. We show that temporal variations of surface albedo exist for two of the candidate cryovolcanic regions. The surface albedo variations together with the presence of volcanic-like morphological features suggest that the active regions are possibly related to the deep interior, possibly via cryovolcanism processes (with important implications for the satellite's astrobiological potential) as also indicated by new interior structure models of Titan and corresponding calculations of the spatial pattern of maximum tidal stresses [4]. However, an explanation attributed to exogenic processes is also possible [5]. We will report on results from our most recent research on the surface properties of Titan.

[1] Solomonidou et al. Icarus, accepted. [2] Solomonidou et al. JGR 119, 1729–1747, 2014. [3] Lopes et al. Icarus, in rev. [4] Sohl et al. JGR 119, 1013-1036, 2014. [5] Moore & Pappalardo, Icarus 212, 790-806, 2011.

**Author(s): Anezina Solomonidou[6]**, Rosaly M.C. Lopes[6], Athena Coustenis4, Michael Malaska[6], Sebastien Rodriguez3, Luca Maltagliati3, Pierre Drossart4, Michael Janssen[6], Kenneth Lawrence[6], Ralf Jaumann[2], Frank Sohl[2], Katrin Stephan[2], Robert H. Brown5, Emmanuel Bratsolis[1], Christos Matsoukas[1]
**Institution(s):** *1. Department of Physics, National and Kapodistrian University of Athens, 2. DLR, Institute of Planetary Research, 3. Laboratoire AIM, Université Paris Diderot, Paris 7/CNRS/CEA-Saclay, DSM/IRFU/SAp, 4. LESIA - Observatoire de Paris, CNRS, UPMC Univ. Paris 06, Univ. Paris-Diderot, 5. Lunar and Planetary Laboratory, University of Arizona, 6. NASA Jet Propulsion Laboratory, California Institute of Technology*

### 300.07 – Using the VIMS Dataset to Understand Titan's Hydrologic Cycle Through Cloud Characterization

Along with Earth, Titan is the only body in our Solar System to possess an active hydrologic cycle. Monitoring how Titan's methane-based hydrologic cycle varies with season over Saturn's 29.7-year orbital period is essential for understanding its climate system.
Using a newly developed radiative transfer pipeline, with updated HITRAN methane line parameters, we will present an ongoing analysis of the known cloud observations in the VIMS dataset. Although much work has gone into finding clouds in this dataset, little work has been done on understanding the characteristics of these clouds, barring a handful of individual analyses. Our pipeline allows for fast determination of these cloud characteristics including optical depth, altitude, and mean drop size. VIMS offers two advantages: providing consecutive observations of individual cloud systems to help diagnose formation mechanism and providing a decade long dataset to track seasonal variations, like those observed in cloud frequency and location. Characterizing clouds allows for an understanding of seasonally varying formation mechanisms, traces Titan's atmospheric methane content across seasonal timescales, and can indicate clouds that could potentially have precipitated to provide context for interpreting observed surface features.
We will also present an update on an ongoing ground based- cloud monitoring campaign. This campaign, begun in April 2014, has (nearly) continually monitored Titan on a variety of telescopes for the past 1.5 years. To date, no cloud activity has been observed, despite the variety in observation techniques that multiple telescopes allow. This is interesting because large cloud outbursts were observed during the equivalent point in southern summer and suggest a dichotomy in the seasonal dynamics of Titan's atmosphere. Understanding when and with what frequency clouds begin to form in the north is crucial to understanding Titan's hydrologic cycle on seasonal time scales.

**Author(s): Paul Corlies[1]**, Alexander G. Hayes[1], Sebastien Rodriguez4, Mate Adamkovics5, Patricio Rojo3, Elizabeth P. Turtle[2]
**Institution(s):** *1. Cornell University, 2. John Hopkins Univ. Applied Physics Laboratory, 3. Universidad de Chile, 4. Universite Paris Diderot - Paris 7, 5. University of California, Berkeley*

### 300.08 – Hydrology-based understanding of Ontario Lacus in Titan's south pole

Ontario Lacus is the largest presently filled lake at the south pole of Titan. Many other large basins in south pole exist at lower elevations than Ontario Lacus but are currently empty. To find out what sets Ontario apart from those empty basins, we have carried a detailed hydrological assessment of Ontario Lacus. Topography of the region, as derived from Cassini RADAR altimetry was used to determine the catchment area of Ontario Lacus. We could map the areal extent of catchments as far as southern mid-latitudes. Clouds in southern mid and high latitudes have been observed by Cassini VIMS which indicate possible precipitation in those regions. Precipitation in southern mid-latitudes coupled with the large catchment areas of Ontario Lacus could be the reason behind it being filled. Our mass conservation calculations indicate that if runoff was the only contributor to the lake volume, then the lake might be filled within one Titan year (29.5 Earth years) in entirety. We also observe a non-linear relationship between the longest identifiable stream and the catchment area (Hack's Law) which is consistent with terrestrial hydrological systems and may help in further interpretation of the hydrology of Ontario Lacus.

**Author(s): Rajani D. Dhingra[2]**, Jason W. Barnes[2], Brian J. Yanites[2], Randolph L. Kirk[1]
**Institution(s):** *1. Astrogeology Science Center, United States Geological Survey, 2. University of Idaho*

### 300.09 – Near Infrared Spectroscopy of Liquid Hydrocarbon Mixtures for Understanding the Composition of Titan's Lakes

The presence of ethane and methane lakes on Titan was confirmed by the Cassini Visible and Infrared Mapping Spectrometer (VIMS) data in 2008, and has been investigated in further detail by the Cassini radar instrument (Brown et al, 2008; Pailloue et al, 2008). Modeled compositions suggest that the lakes are predominantly liquid ethane, with liquid methane, propane, and butane; however, pure liquid methane lakes (such as Ligeia Mare) may also be present (Cordier et al, 2009; Mastrogiuseppe et al, 2014). We present a proof-of-concept instrument, consisting of a near infrared (NIR) spectrometer with a fiber optic probe, in order to conduct non-invasive analyses of cryogenic fluids on planetary bodies. To determine the utility of spectroscopy for in-situ studies, we collected transmission spectra of hydrocarbon mixtures, pure methane and ethane endmembers, and nitrogen-saturated hydrocarbons in the NIR region between 900 to 2500 nm; liquid hydrocarbons were measured in a dewar filled with liquid nitrogen, contained within a glove bag pumped with gaseous nitrogen at a total oxygen concentration of < 0.1%. The resultant spectra contained key absorption features that allowed us to determine the relative abundances of each endmember, and the effects temperature and dissolved nitrogen, based on the changes in peak intensity. Peak intensity, as well as integrated absorbance, full-width half-maximum, and peak location were calculated using a multi-peak fitting algorithm; we also adopted a simple linear mixing model which used pure ethane and methane spectra, as well as the measured mixtures, to calculate the linear coefficients of each endmember within the mixture. Resultant plots of changes in peak intensity with temperature (for methane), peak intensity with mole fraction of methane (or ethane), and comparisons of the modeled linear coefficients with the mole fraction of methane (or ethane) added will yield useful data on how methane, ethane, and dissolved nitrogen mix. Ideally, this information can also be used to better validate theoretical models on hydrocarbon mixing and nitrogen solubility, providing insight on the loss tangent measurements of Titan's lakes obtained by Mastrogiuseppe from radar altimetry data.

**Author(s): Bryne Hadnott[1]**, Robert Hodyss[2], Morgan Cable[2], Tuan Vu[2], Alexander Hayes[1]
**Institution(s):** *1. Cornell University, 2. Jet Propulsion Laboratory*

## 301 – Asteroid Surveys: See and Say

### 301.01 – NEOWISE Reactivation Mission Year One: Preliminary Asteroid Diameters and Albedos

The infrared NEOWISE project (Mainzer et al. 2011a) has measured diameters and albedos for ~20% of the known asteroid population, the majority of these measurements to date (Mainzer et al. 2011b, 2012, 2015; Masiero et al. 2011, 2012; Grav et al. 2011, 2012a; Bauer et al. 2013). Here, we expand the number of asteroids characterized by NEOWISE, deriving diameters and albedos for 7,959 asteroids detected between December 13, 2013, and December 13, 2014 during the first year of the Reactivation mission. 7,758 are Main Belt or Mars-crossing asteroids. 17% of these objects have not been previously characterized using WISE or NEOWISE thermal measurements. Diameters are determined to an accuracy of ~20% or better. If good-quality H magnitudes are available, albedos can be determined to within ~40% or better.

**Author(s): Carolyn Nugent[1]**, A Mainzer[2], J R Masiero[2], J Bauer[2], R M Cutri[1], T Grav[3], E Kramer[2], S Sonnett[2], R Stevenson[4], E Wright[5]
**Institution(s):** *1. Caltech/IPAC, 2. JPL, 3. Planetary Science Institute, 4. Self, 5. UCLA*

### 301.02 – NEOSurvey: An Spitzer Exploration Science Survey of Near Earth Object Properties

We are carrying out a Spitzer Cycle 11 (2015-2016) Exploration Science program entitled NEOSurvey in which we are observing 597 known Near Earth Objects (NEOs) in 710 hours of observing time. Each object is observed at 4.5 microns. The primary goal of our program is to use a thermal model to create a catalog of NEO diameters and albedos that can be used for a wide range of science goals. From this catalog we will derive the size distribution of NEOs down to 100 meters and measure the compositional distribution of NEOs as a function of size. We include in our target list only objects that are too faint to be detected by NEOWISE. This catalog is therefore highly complementary to existing and forthcoming samples, and will complete a database of diameters and albedos for nearly 2000 NEOs (including results from our previous Spitzer program, ExploreNEOs, as well as objects observed by NEOWISE). We will present the status of the program and results to date, some nine months into the execution of the program. All observational and model results are published immediately online at nearearthobjects.nau.edu . Support for this work is provided by the Spitzer Science Center.

**Author(s): David E. Trilling[5]**, Michael Mommert[5], Joseph Hora[2], Steve Chesley[3], Joshua Emery[6], Giovanni Fazio[2], Alan Harris[1], Michael Mueller[4], Howard Smith[2]
**Institution(s):** *1. German Aerospace Centre (DLR), 2. Harvard-Smithsonian Center for Astrophysics, 3. NASA/JPL, 4. Netherlands Institute for Space Research, 5. Northern Arizona University, 6. U. Tennessee, Knoxville*

### 301.03 – Main-Belt Source Regions for Potentially Hazardous Near-Earth Asteroids and Sample Return Targets

Spectroscopic and taxonomic information is now available for more than 1000 near-Earth objects (NEOs), thanks in large measure to the NASA IRTF long-term NEO spectral reconnaissance program we call the MIT-Hawaii Near-Earth Object Spectroscopic Survey (MITHNEOS) [1]. This sample comprises about 10% of the total NEO population, including Potentially Hazardous Asteroids (PHAs), and finds that all defined main-belt asteroid classes are also present within the near-Earth population. Using this largest available NEO dataset and dynamic source region models (such as [2]) we will present new results on the provenance of PHAs, source regions for each of the asteroid taxonomic classes, and pinpoint sources for major meteorite classes such as H, L, and LL ordinary chondrites. In finding these correlations, we find that source region signatures for B-, C-, and Cg-type NEOs include Jupiter family comets, further adding interest to the sampling of these classes by impending missions [3, 4]. This work is supported by the National Science Foundation Grant 0907766 and NASA Grant NNX10AG27G.
[1] Tokunaga, A. et al. (2006) *BAAS* 38, 59.07. [2] Bottke, W.F. et al. (2002), *Icarus* 156, 399. [3] Lauretta, D. S. et al. (2015), *MAPS* 50, 834. [4] Abe, M. et al. (2012) *39th COSPAR*, Abstract H0.2-7-12.

**Author(s): Richard P. Binzel[2]**, F. E. DeMeo[2], B. J. Burt[2], D. Polishook[2], T. H. Burbine[2], N. Moskovitz[1], S. J. Bus[4], A. Tokunaga[4], M. Birlan[3]
**Institution(s):** *1. Lowell Observatory, 2. MIT, 3. Paris Observatory, 4. University Hawaii*

### 301.04 – The Bias-Corrected Taxonomic Distribution of Mission-Accessible Small Near-Earth Objects

Although they are thought to compose the majority of the Near-Earth object (NEO) population, the small (d < 1 km) near-Earth asteroids (NEAs) have not yet been studied as thoroughly as their larger cousins. Sub-kilometer objects are amongst the most abundant newly discovered NEOs and are often targets of opportunity, observable for only a few days to weeks after their discovery. Even at their brightest (V ~ 18), these asteroids are faint enough that they must be observed with large ground-based telescopes.
The Mission Accessible Near-Earth Object Survey (MANOS) began in August 2013 as a multi-year physical characterization survey that was awarded survey status by NOAO. MANOS will target several hundred mission-accessible NEOs across visible and near-infrared wavelengths, ultimately providing a comprehensive catalog of physical properties (astrometry, light curves, spectra). Fifty-seven small, mission-accessible NEAs were observed between mid 2013 and mid 2015 using GMOS at Gemini North & South observatories as well as the DeVeny spectrograph at Lowell Observatory's Discovery Channel Telescope. Archival data of 43 objects from the MIT-UH-IRTF Joint Campaign for NEO Spectral Reconnaissance (PI R. Binzel) were also used. Taxonomic classifications were obtained by fitting our spectra to the mean reflectance spectra of the Bus asteroid taxonomy (Bus & Binzel 2002). Small NEAs are the likely progenitors of meteorites; an improved understanding of the abundance of meteorite parent body types in the NEO population improves understanding of how the two populations are related as well as the biases Earth's atmosphere imposes upon the meteorite collection.
We present classifications for these objects as well as results for the debiased distribution of taxa
(as a proxy for composition) as a function of object size and compare to the observed fractions of ordinary chondrite meteorites and asteroids with d > 1 km. Amongst the smallest NEOs we find an unexpected distribution of taxonomic types that differs from both large NEOs and meteorites.
We acknowledge funding support from NASA NEOO grant number NNX14AN82G.

**Author(s): Mary L Hinkle[6]**, Nicholas Moskovitz[4], David Trilling[6], Richard P Binzel[5], Cristina Thomas[7], Eric Christensen[1], Francesca DeMeo[2], Michael J Person[5], David Polishook[8], Mark Willman[3]
**Institution(s):** *1. Catalina Sky Survey, 2. Harvard-Smithsonian Center for Astrophysics, 3. Institute for Astronomy - U. Hawaii, 4. Lowell Observatory, 5. MIT, 6. Northern Arizona University, 7. PSI, 8. Weizmann Institute of Science*

### 301.05 – Constraining the shape distribution and binary fractions of asteroids observed by NEOWISE

Knowing the shape distribution of an asteroid population gives clues to its collisional and dynamical history. Constraining light curve amplitudes (brightness variations) offers a first-order approximation to the shape distribution, provided all asteroids in the distribution were subject to the same observing biases. Asteroids observed by the NEOWISE space mission at roughly the same heliocentric distances have essentially the same observing biases and can therefore be inter-compared. We used the archival NEOWISE photometry of a statistically significant sample of Jovian Trojans, Hildas, and Main belt asteroids to compare the amplitude (and by proxy, shape) distributions of L4 vs. L5 Trojans, Trojans vs. Hildas of the same size range, and several subpopulations of Main belt asteroids.
For asteroids with near-fluid rubble pile structures, very large light curve amplitudes can only be explained by close or contact binary systems, offering the potential to catalog and characterize binaries within a population and gleaning more information on its dynamical evolution. Because the structure of most asteroids is not known to a high confidence level, objects with very high light curve amplitudes can only be considered candidate binaries. In Sonnett et al. (2015), we identified several binary candidates in the Jovian Trojan and Hilda populations. We have since been conducting a follow-up campaign to obtain densely sampled light curves of the binary candidates to allow detailed shape and binary modeling, helping identify true binaries. Here, we present preliminary results from the follow-up campaign, including rotation properties.
This research was carried out at the Jet Propulsion Laboratory (JPL), California Institute of Technology (CalTech) under a contract with the National Aeronautics and Space Administration (NASA) and was supported by the NASA Postdoctoral Program at JPL. We make use of data products from the *Wide-field Infrared Survey Explorer*, which is a joint project of the University of California, Los Angeles, and JPL/CalTech, funded by NASA. This publication also makes use of data products from NEOWISE, which is a project of JPL/CalTech, funded by the Planetary Science Division of NASA.

**Author(s): Sarah M. Sonnett[1]**, Amy Mainzer[1], Tommy Grav[3], Joseph Masiero[1], James Bauer[1], Pierre Vernazza[2], Judit Gyorgyey Ries[4], Emily Kramer[1]
**Institution(s):** *1. Jet Propulsion Laboratory, 2. Laboratoire d'Astrophysique de Marseille, 3. Planetary Science Institute, 4. University of Texas at Austin*

### 301.06 – Hilda Asteroid Compositions as an Observational Test of Giant Planet Migration Models

Multiple lines of evidence indicate that planetary migration is a key part of the evolution of planetary systems. Planetary migration models of the solar system suggest that the Jupiter Trojan and Hilda stable resonances were repopulated during giant planet migration. We have completed a 4-year, multi-epoch photomteric multi-color survey of Hilda asteroids in order to determine individual object composition. The colors of ~500 Hildas are now known, a factor of 3 increase in objects with determined compositions compared to the start of our observations. We report the results of our survey in the context of the predictions from current dynamical migration models, identify the model inconsistent with the compositional results, and address future observational data that is required in addition to Hilda asteroid compositions to validate the Nice and Grand Tack models.
This work supported by the University of Minnesota Undergraduate Research Scholarship Program and NASA Planetary Astronomy Grant NNX13AJ11G.

**Author(s): Erin L. Ryan[3]**, Charles E. Woodward[1], Benjamin Sharkey[1], Keith S. Noll[2]
**Institution(s):** *1. Minnesota Institute for Astrophysics, University of Minnesota, 2. NASA GSFC, 3. University of Maryland*

### 301.07 – The Pan-STARRS search for Near Earth Objects

The two Pan-STARRS telescopes, located on Haleakala, Hawaii, are 1.8-meter diameter telescopes equipped with 1.4 Gigapixel cameras that deliver 7 square degree fields of view. The first telescope, Pan-STARRS1 (PS1), has been conducting a survey for Near-Earth Objects. The second telescope, Pan-STARRS2 (PS2) is nearing completion. The telescope was commissioned using an incomplete focal plane with only 18 good detectors (60 required). The camera is presently being upgraded, and will be operated from October 2015 with 60 detectors (some engineering grade). A final upgrade to the camera in early 2016 will make the telescope fully operational.
The two telescopes survey much of the sky accessible from Haleakala multiple times each lunation. The area surveyed ranges from +90 degrees in the north down to -47.5 degrees declination in the south. The “sweet spots” close to the Sun have been productive in discovery of large objects.
The PS1 survey is becoming more mature and productive, having discovered more than half of all NEOs in 2015 to date, and more than 60% of the larger NEOs and PHAs discovered in 2015. Both PS1 and PS2 deliver excellent astrometry and photometry. PS1 continues to discover a significant number of large (> 1km) NEOs. PS1 has become the leading discover of comets, discovering more than half of the new comets in both 2014 and 2015.
In good weather conditions, the discovery rate of NEO candidates by PS1 overwhelms the external NEO followup resources. particularly for fainter NEOs. As a result, we needed to repeat fields to recover NEO candidates. As PS2 matures, with a complete focal plane, and when the G96 camera upgrade is complete, the combination of these three telescopes will facilitate a higher NEO discovery rate, a better census of the NEOs in the sky, and better orbits for NEOs. This will in turn lead to a better understanding of the size and orbit distribution of NEOs. The Pan-STARRS NEO survey is also likely to discover asteroids suitable for the NASA asteroid retrieval mission.
Some early science highlights from the Pan-STARRS survey will be discussed.

**Author(s): Richard J. Wainscoat[2]**, Kenneth Chambers[2], Eva Lilly[2], Robert Weryk[2], Serge Chastel[2], Larry Denneau[2], Marco Micheli[1]
**Institution(s):** *1. ESA NEO Coordination Centre, 2. Univ. of Hawaii*

### 301.08 – Olivine-rich asteroids in the main asteroid belt

Olivine-dominated asteroids, classified as A-types with near-infrared spectral measurements are largely thought to be the mantle remnants of disrupted differentiated small bodies. These A-type asteroids hold clues to asteroid differentiation and to the collisional history of those differentiated bodies. Preliminary studies of the abundance and distribution of A-type asteroids were performed by Carvano et al. (2010) and DeMeo & Carry (2013, 2014) using the Sloan Digital Sky Survey (SDSS). To confidently identify these olivine-dominated A-type asteroids, however, near-infrared spectral measurements are needed to identify the distinct broad and deep 1-micron olivine absorption feature. Using the Sloan Digital Sky Survey Moving Object Catalog to select A-type asteroid candidates, we have performed a near-infrared spectral survey of over 70 asteroids with SpeX on the IRTF. We present the abundance and distribution of A-type asteroids throughout the main asteroid belt and compare these results with similar surveys for basalt-rich V-type asteroids (e.g. Moskovitz et al. 2008). This work is supported by NASA under grant number NNX12AL26G issued through the Planetary Astronomy Program.

**Author(s): Francesca E. DeMeo[2]**, David Polishook[2], Benoit Carry[3], Nick Moskovitz[1], Brian Burt[2], Rick Binzel[2]
**Institution(s):** *1. Lowell Observatory, 2. Massachusetts Institute of Technology, 3. Nice Observatory*

### 301.09 – Revealing Secrets of Triple Asteroid Systems with SPHERE

A multiple-asteroid system provides otherwise unattainable information about the intrinsic properties of the system itself as well as its formation and evolution. Comparative spectroscopy and imaging of two large multiple main-belt asteroids: (93) Minerva and (130) Elektra were performed using the newly commissioned Spectro-Polarimetric High-contrast Exoplanet Research instrument (SPHERE) on ESO's 8.2-m VLT. A new moon (S/2014 (130) 1), of the known binary asteroid (130) Elektra, was discovered based on the SPHERE observations, making (130) Elektra the sixth triple system detected in the asteroid belt. We will present the component-resolved near infrared spectra, from 0.9 to 1.6 micron, of the Minerva and the Elektra triple systems. We will also present the orbital solution and the dynamical simulations on the two moons of (130) Elektra.

**Author(s): Bin Yang[2]**, Zahed Wahhaj[2], Laurene Beauvalet[3], Franck Marchis[1], Christophe Dumas[4], Michaël Marsset[2]
**Institution(s):** *1. Carl Sagan Center of the SETI Institute, 2. European Southern Observatory, 3. Observatório Nacional, Rio de Janeiro, 4. TMT International Observatory*

## 302 – Formation of Planets, Satellites and Small Bodies

### 302.01 – The collisional evolution of chondritic parent bodies

Most meteorites are fragments form recent collisions in the asteroid belt. The collision speed between two objects of the asteroid belt is given by the eccentricity and inclination of their respective Keplerian orbits. Typical values are on the order of a few km $s^{-1}$. In such a hyper-velocity collision, the smaller collision partner (projectile) is destroyed, whereas, depending on the mass ratio of the colliding objects, a crater on the larger body (target) is formed or the target is entirely destroyed, too. The present size distribution of the asteroid belt suggests that an asteroid with 100 km radius is encountered ~$10^{14}$ times during the lifetime of the Solar System by objects larger than 10 cm in radius, the formed craters cover the surface of the asteroid about 100 times.
We will present a numerical study that simulates the statistical bombardment on an asteroidal surface and tracks the resulting morphological changes of the parent body due to the formation of craters, the compaction of the material beneath the craters as well as the formation of a regolith layer. The crater ejecta from recent impacts on a consolidated asteroid are then compared to the known meteorites, particularly concerning the distribution of shock stages. Comparing the compaction of ejected material from the simulated collisions that occurred during the last 20 Myrs, which is the mean cosmic ray exposure age of meteorites, with shock stages of meteorites, we find that meteorites most likely stem from smaller parent bodies that do not have a significant regolith layer. For larger objects that inevitably accrete regolith layers, a prediction of the thickness depending on the largest visible crater can be made. Additionally, we compare the crater distribution of an initially 100 km (radius) large object with a shape model of asteroid (21) Lutetia, assuming it to be initially formed spherical with a radius that is equal to its longest present ellipsoid length, and find a reasonable agreement. Following our study, predictions of the porosity of the surface and the interior of the asteroid as well as the shock stages of ejected material can be made.

**Author(s): Jürgen Blum[2]**, Eike Beitz[2], Mirta Gabriela Parisi[1]
**Institution(s):** *1. Instituto Argentino de Radioastronomia, 2. TU Braunschweig*

### 302.02D – Planetesimal Formation - Collisions of Decimeter Ice and Dust

The early stages (from µm to mm) as well as the late stages (from km to planet size) of planet formation are quite well understood. The intermediate stage of planetesimal formation is not understood in detail, yet. Several processes, such as bouncing or radial drift, can potentially stall growth beyond the millimeter or centimeter size range.
The collision dynamics of decimeter bodies are important in planetesimal formation models. They are interesting for coagulation models, as radial drift towards the central star becomes severe at sizes of decimeter to meter. But they are also crucial for gravitational instability models, because concentration mechanisms are believed to be strongest for decimeter bodies.
We performed various collision experiments with decimeter as well as centimeter bodies, made up of both silicate dust and water ice. We investigated threshold conditions, such as the threshold to fragmentation, which are especially interesting for the coagulation models.
Though mutual collisions might lead to bouncing or even fragmentation already at velocities that are much lower than relative velocities expected in PPDs, growth beyond decimeter sizes is still possible. Decimeter bodies start to decouple from to the surrounding gas, which results in relative velocities to smaller bodies of several m/s. In such collisions of bodies of different sizes, the bigger body can gain mass. This can be by direct mass transfer from the smaller body. Here, the accretion efficiency is a crucial parameter. Mass can also be transferred through gas-driven re-accretion of fragments of the smaller body, which are produced in the collision. The velocity and size distribution of the ejected fragments are significant for re-accretion.

**Author(s): Johannes Deckers[1]**, Jens Teiser[1], Gerhard Wurm[1]
**Institution(s):** *1. Universität Duisburg-Essen*

### 302.03 – Icy Collisions – Planet Building beyond the snowline

Collisions of small icy and dust particles beyond the “snow-line” are a key step in planet formation. Whilst the physical forces that underpin the aggregation of the smallest grains (van der Waals) and the largest planetessimals (gravity) are well understood, the processes involving mm – cm sized particles remain a mystery.
In a unique set of experiments, we investigated low velocity collisions of dust and icy particles in this size range under microgravity conditions – utilizing parabolic flight (e.g. Salter 2009, Hill 2015 (a) & (b)). Experiments were performed at cryogenic temperatures (below 140 K) for icy aggregates and ambient as well as cryogenic temperatures (80 – 220 K) for dust aggregates.
The kinetic analysis of the observed collisions of different aggregate types in different shapes and sizes revealed astonishing results – as the collisional properties of all investigated particles differ strongly from the usual assumptions in models of planet formation.
Here, we present a summary of the results on the collisions of icy particles as well as first results on the collisions of dust aggregates. Focus will be on the coefficient of restitution, which measures the loss of translational energy in bouncing collisions and is a key parameter in models of planet formation.

**Author(s): Sabrina Gaertner[2]**, Catherine Hill[2], Daniel Heisselmann[1], Juergen Blum[1], Helen Fraser[2]
**Institution(s):** *1. Technische Universitaet Braunschweig, 2. The Open University*

### 302.04 – Forming the Terrestrial Planets from an Annulus

We present results from the growth of planets directly from planetsimals initially constrained to a narrow annulus between 0.7-1.0 AU. The simulations examine the idea that the Earth/Mars mass ratio can be explained when the planets form from a truncated disk with an outer edge at 1.0 AU. Using the Lagrangian code known as LIPAD we present results on the role of fragmentation and the effects of interactions with the gas-disk on the evolution of a large number of planetesimals as they grow to planets.
In particular, we report on simulations where initially the solids in

the disk are planetesimals with the same initial radii (varied from run to run between 3 and 300 km), with and without fragmentation, and with and without the effects of a gas-disk. The presence of a gas disk strongly changes the outcomes of the first few million years of growth keeping accretion rates high through low relative velocity collisions. Meanwhile fragmention processes can produce small particles that, by way of dynamical friction, can provide some of the same dynamical affects as the gas-disk - though with the side effect of mass loss due to the grind of particles to small sizes and subsequent drift out of the annulus.
In sum, the final planetary systems sometimes produce Mars-analogs with appropriately small mass, but due to do diffusive spreading rather than violent scattering. However, they rarely produce objects as massive as Earth and Venus do to the same effect.

**Author(s): Harold F. Levison[1]**, Kevin Walsh[1]
**Institution(s):** *1. Southwest Research Inst.*

### 302.05 – Planetsimals to Planets - Revisiting Terrestrial Planet Formation

Nearly all previous models of terrestrial planet formation focus on either a short span of time or a narrow sliver of the disk to understand a specific mode of growth. The final stages of growth, the giant impact stage, are typically picked up after the growth of Moon- to Mars-sized embryos have grown and are spread throughout the disk.
Here, by way of simulations starting with 30 km planetesimals that span the entire inner region of the Solar System, from 0.7 to 3.0 au, we examine the growth throughout the entire disk. We find that the growth is strongly inside-out, with Mars-sized embryos formed inside of 1 au before any embryos are formed beyond 2 au. Furthermore we test various effects owing to the existence or timescale of dispersal of the gaseous solar nebula on the stages of growth and timing of instabilities.

**Author(s): Kevin J. Walsh[1]**, Harold F Levison[1]
**Institution(s):** *1. Southwest Research Institute*

### 302.06 – Moon formation coupled with the protolular disk

It is thought that the Moon accreted from the protolunar disk that was assembled after the last giant impact on Earth. Due to its high temperature, the protolunar disk may act as a thermochemical reactor in which the material is processed before being incorporated into the Moon. Outstanding issues like devolatilisation and istotopic evolution are tied to the disk evolution, however its lifetime, dynamics and thermodynamics are unknown. Here, we numerically explore the long term viscous evolution of the protolunar disk using a one dimensional model where the different phases (vapor and condensed) are vertically stratified.
Our major innovation is that we compute at the same time the proto-moon growth along with the disk evolution, and calculate the thermodynamical equilibrium of the proto-lunar seed as it grows. We will discuss the long term dynamics, thermodynamics, cooling timescale and possibility for volatile depletion. We will show that due to different effective viscosities substantial fractionation of volatiles and refractory material is possible.
Finally we will compare different scenarios of moon impacts (standard, sub-earths, fast spinning Earth) and their different advantages for explaining today’s moon material content.

**Author(s): Sebastien Charnoz[1]**, Lisa Bugnet[1], Chloé Michaut[1]
**Institution(s):** *1. Université Paris Diderot*

### 302.07 – Lunar volatile depletion due to incomplete accretion within an impact-generated disk

The Moon likely formed from a disk produced by a giant impact with the Earth. The Moon and the bulk silicate Earth (BSE) share many compositional similarities (e.g., Ringwood 1979; Dauphas et al. 2014). However compared with the BSE, the Moon is more depleted in volatile elements, including moderately volatile K and Na, as well as more highly volatile elements, e.g., Zn (e.g., O’Neill 1991; Taylor & Wieczorek 2014). The origin of this depletion is poorly understood. Prior results suggest escape (e.g., Paniello et al. 2012), but at least hydrodynamic escape appears minimal for expected disk conditions (Nakajima & Stevenson 2014).
In the limit of no escape and a closed system, a depletion could instead result if disk volatiles were preferentially accreted by the Earth rather than by the Moon. Taylor et al. (2006) advocated that the lunar depletion pattern is most consistent with incomplete condensation from an initially high temperature vapor, with the accretion of condensates by the Moon “cut-off” at a temperature allowing incorporation of a small component of alkalis (e.g., K and Na) but only a tiny fraction of more volatile elements (e.g., Zn). Neither the mechanism that would produce the cut-off, nor what the relevant cut-off temperature would be in an oxygen-rich protolunar disk (e.g., Visscher & Fegley 2013), were known.
We identify a mechanism wherein a depletion results because disk volatiles are preferentially accreted by the Earth rather than by the Moon. The Moon may acquire the final tens to 60% of its mass from melt originating from the inner portions of the disk (Salmon & Canup 2012). Initially the inner disk melt is hot and volatile-poor, but as the disk cools, volatiles condense. We combine dynamical, thermal and chemical models to show that delivery of inner disk material to the Moon effectively ends as gravitational interactions cause the Moon’s orbit to expand away from the disk, with this cut-off occurring prior to condensation of key depleted elements. The portion of the Moon derived from the inner disk is then volatile depleted, even without escape. This mechanism could produce part or all of the observed depletion pattern, depending primarily on the degree of mixing within the Moon.

**Author(s): Robin M. Canup[2]**, Channon Visscher[1], Julien Salmon[2], Bruce Fegley3
**Institution(s):** *1. Dordt College, 2. Southwest Research Inst., 3. Washington University*

### 302.08 – Formation of Phobos and Deimos in an extended circum-Martian accretion disk

Recent exploration of Phobos by Mars Express has renewed the interest in the origin of the Martian moons, which remains an open issue. New studies have recently focused on accretion of debris in a circum-Martian disk. Craddock (Icarus, 2011) has proposed a scenario of formation of such a disk (about $10^{-4}$ to $10^{-3}$ % the mass of Mars) from a giant collision occurred early in Mars' history. Rosenblatt and Charnoz (Icarus, 2012) have shown that moonlets can be formed, with Phobos and Deimos masses, in a compact disk close to the planet. Nevertheless, the orbit of these moonlets rapidly recedes back to Mars and the moonlet system vanishes in much less than 1 Gy.
Citron at al. (Icarus, 2015) have modeled the formation of a disk of debris resulting from a giant collision but with a larger mass (0.1 % of Mars' mass) than in Craddock (2011). They have shown that most of the disk mass is concentrated close to the planet but a small part can extend beyond the synchronous limit (6 Mars' radii). We study here the accretion of debris in an extended disk, focusing in the edge of this disk where surface density of material is the lowest. However, we take into account the gravitational influence of the more massive bodies formed in the denser part of the disk. Our results highlight the driven mechanisms of accretion in a circum-Martian disk of debris.

**Author(s): Pascal Rosenblatt[2]**, Sébastien Charnoz[1], Mariko Dunseath-Terao3, Kevin Dunseath3, Antony Trinh[2]
**Institution(s):** *1. Laboratoire AIM, Université Paris Diderot/CEA /CNRS, 2. Royal Observatory of Belgium, 3. Université de Rennes-I*

### 302.09 – Testing Migration of the Jupiter Trojan Asteroids in the Lab

Today’s Jupiter Trojan asteroids may have orininated in the Kuiper Belt (eg. Morbidelli et al. *Nature* 2005, Nesvorny et al. *ApJ* 2013) and migrated to capture at their present locations. If this is the case, it is expected that their surfaces will contain chemical traces of this history. No distinct spectral bands have been conclusively identified in the literature, however, visible and near-infrared spectra of Kuiper Belt, Centaur, and Trojan populations each show two sub-populations distinguished by their spectral slopes (Brown et al. *ApJL* 2011; Emery et al. *AJ* 2011). The slopes are all positive (or "red"), steepest in the Kuiper Belt, and least steep in the Trojan population. Here we test the hypothesis that the asteroids formed spanning a stability line for a critical substance; in this case we test sulfur, as $H_2S$. The hypothesis is that irradiating mixed ices containing $H_2S$ will result in a refractory residue of steeper slope than the same composition without the $H_2S$. We have simulated this history in the Minos chamber at the Icy Worlds Simulation Laboratory at NASA's Jet Propulsion Laboratory. Ices that will be discussed include a 3:3:3:1 mixture of $H_2S$: $NH_3$: $CH_3OH$: $H_2O$; and a 3:3:1 mixture of $NH_3$: $CH_3OH$: $H_2O$. After deposition at 50 K, the ices were irradiated with a beam of 10 keV electrons to form the refractory crust. The ices were then warmed (while continuing irradiation) to 120 K and observed for several days. Reflectance spectra were collected throughout the experiment in the visible and infrared. The spectral slope increased dramatically after irradiation of the mixture containing $H_2S$, while the spectral slope for the mixture without any sulfur changed very little. This is consistent with sulfur being the critical component determining which of the spectral populations an object belongs to in the present inventory of outer solar system objects. Quantitative analysis is underway. *This work has been supported by the Keck Institute for Space Studies (KISS). The research described here was carried out at the Jet Propulsion Laboratory, Caltech, under a contract with the National Aeronautics and Space Administration (NASA) and at the Caltech Division of Geological and Planetary Sciences.*

**Author(s): Michael Poston[1]**, Jordana Blacksberg[1], Mike Brown[1], Elizabeth Carey[2], Robert Carlson[2], Bethany Ehlmann[1], John Eiler[1], Kevin Hand[2], Robert Hodyss[2], Ahmed Mahjoub[1], Ian Wong[1]
**Institution(s):** *1. California Institute of Technology, 2. Jet Propulsion Laboratory*

## 304 – Gerard P. Kuiper Prize: Chemistry of Planetary Atmospheres: Insights and Prospects, Yuk Yung (Caltech)

### 304.01 – Chemistry of Planetary Atmospheres: Insights and Prospects

Using observations from the Mariners, Pioneers, Vikings, Voyagers, Pioneer Venus, Galileo, Venus Express, Curiosity, Cassini, New Horizons, and numerous observatories both in orbit of Earth and on the ground, I will give a survey of the major chemical processes that control the composition of planetary atmospheres. For the first time since the beginning of the space age, we understand the chemistry of planetary atmospheres ranging from the primitive atmospheres of the giant planets to the highly evolved atmospheres of terrestrial planets and small bodies. Our understanding can be distilled into three important ideas: (1) The stability of planetary atmospheres against escape of their constituents to space, (2) the role of equilibrium chemistry in determining the partitioning of chemical species, and (3) the role of disequilibrium chemistry, which produces drastic departures from equilibrium chemistry. To these three ideas we must also add a fourth: the role of biochemistry at Earth's surface, which makes its atmospheric chemistry unique in the cosmochemical environment. Only in the Earth's atmosphere do strong reducing and oxidizing species coexist to such a degree. For example, nitrogen species in the Earth's atmosphere span eight oxidation states from ammonia to nitric acid. Much of the Earth's atmospheric chemistry consists of reactions initiated by the degradation of biologically produced molecules. Life uses solar energy to drive chemical reactions that would otherwise not occur; it represents a kind of photochemistry that is special to Earth, at least within the Solar System. It remains to be seen how many worlds like Earth there are beyond the Solar System, especially as we are now exploring the exoplanets using Kepler, TESS, HST, Spitzer, soon to be launched missions such as JWST and WFIRST, and ground-based telescopes. The atmospheres of the Solar System provide a benchmark for studying exoplanets, which in turn serve to test and extend our current understanding of planetary atmospheres. Ultimately, we may be able to answer these profound questions: Are we alone in the universe? What makes a planet habitable? How does life originate? And what is the destiny for life on our own planet?

**Author(s): Yuk Yung[1]**
**Institution(s):** *1. Caltech*

## 305 – MAVEN Mission to Mars: Results on Upper Atmosphere, Ionosphere, Solar-Wind Interactions, and Escape to Space, Bruce Jakosky (University of Colorado)

### 305.01 – MAVEN Mission to Mars: Results on Upper Atmosphere, Ionosphere, Solar-Wind Interactions, and Escape to Space

The Mars Atmosphere and Volatile Evolution (MAVEN) spacecraft has been orbiting Mars since 21 September 2014 and collecting data in science mode since 16 November 2014. The science objectives of the MAVEN mission are to characterize the upper atmosphere and ionospheric structure and composition, the interactions of the sun and the solar wind with the planet, and the processes driving loss of gas from the atmosphere to space. Our goal is to understand the chain of processes leading to escape today, learn how to extrapolate back in time, and determine the integrated loss of atmosphere over Martian history. Measurements are being collected from all of the science instruments in our normal mapping orbit and through multiple "deep dip" campaigns. Results are providing a first-time comprehensive look at the upper-atmospheric system surrounding Mars, and are elucidating the key processes and history of the atmosphere. Results will be integrated into a coherent view of the processes controlling the upper-atmosphere system and the escape to space.

**Author(s): Bruce M. Jakosky[1]**
**Institution(s):** *1. Univ. of Colorado*

## 306 – New Views on Inner Solar Systems and Extreme Planets, Rebekah Dawson (University of California, Berkeley)

### 306.01 – New Views on Inner Solar Systems and Extreme Planets

An abundance of exoplanets have been discovered with orbital periods shorter than Mercury's, including thousands of planets and planet candidates found by the Kepler Mission and over a hundred by radial velocity surveys. The abundance and properties of these short-period planets have inspired new views on planet formation and evolution in the inner regions of solar systems. I will review results that have caused major shifts or debates in theories of planet formation, including where and when planets (and their building blocks) form. I will highlight problems that constraints from the large observed population of exoplanets are particularly well-suited to address, despite our limited knowledge of most individual exoplanets. I will also argue for the power of the most extreme exoplanets to serve as "exceptions that prove the rule" for theories of how planets form and evolve. Ongoing statistical and theoretical studies, as well as complementary exoplanet observations from upcoming missions, will help address outstanding questions in planet formation.

**Author(s): Rebekah Ilene Dawson[1]**
**Institution(s):** *1. University of California, Berkeley*

## 307 – Asteroid Spin States

### 307.01 – A path to asteroid bulk densities: Simultaneous size and shape optimization from optical lightcurves and Keck disk-resolved data

A reliable bulk density of an asteroid can be determined from the knowledge of its volume and mass. This quantity provides hints on the internal structure of asteroids and their origin. We compute volume of several asteroids by scaling sizes of their 3D shape models to fit the disk-resolved images, which are available in the Keck Observatory Archive (KOA) and the Virtual Observatory Binary Asteroids Database (VOBAD). The size of an asteroid is optimized together with its shape by the All-Data Asteroid Modelling inversion algorithm (ADAM, Viikinkoski et al., 2015, A&A, 576, A8), while the spin state of the original convex shape model from the DAMIT database is only used as an initial guess for the modeling. Updated sets of optical lightcurves are usually employed. Thereafter, we combine obtained volume with mass estimates available in the literature and derive bulk densities for tens of asteroids with a typical accuracy of 20-50%.
On top of that, we also provide a list of asteroids, for which (i) there are already mass estimates with reported uncertainties better than 20% or their masses will be most likely determined in the future from Gaia astrometric observations, and (ii) their 3D shape models are currently unknown. Additional optical lightcurves are necessary in order to determine convex shape models of these asteroids. Our web page (https://asteroid-obs.oca.eu/foswiki/bin/view /Main/Photometry) contains additional information about this observation campaign.

**Author(s): Josef Hanus3**, Matti Viikinkoski2, Franck Marchis4, Josef Durech1
**Institution(s):** *1. Astronomical Institute, Faculty of Mathematics and Physics, Charles University in Prague, V Holesovickach 2, 18000 Prague, Czech Republic, 2. Department of Mathematics, Tampere University of Technology, PO Box 553, 33101 Tampere, Finland, 3. Laboratoire Lagrange, UMR7293, Universite de la Cote d'Azur, CNRS, Observatoire de la Cote d'Azur, Blvd de l'Observatoire, CS 34229, 06304 Nice cedex 4, France, 4. SETI Institute Mountain View, Mountain View, CA, United States*

### 307.02 – A Review of Asteroid Rotation Statistics with and without the Results from Wide-field Surveys

Several recent wide-field surveys, e.g., Waszczak *et al.* (2015) and Chang *et al.* (2015), have added more than 10,000 asteroid rotation rates to the asteroid lightcurve database (LCDB), Warner *et al.* (2009). In previous works, Harris *et al.* (2012), Warner *et al.* (2011), we explored the possible effects on asteroid rotational statistics with the large infusion of results from such surveys, especially if using "sparse" data sets, e.g., those with fewer than 60 data points from a short span of 2-4 nights.
Now that such data sets exist, we examine asteroid rotation statistics with and without the results from the surveys, looking at two specific points: 1) the possible biases introduced when using survey data and 2) assuming that the stated results are statistically useful, what the larger data set now tells us about asteroid rotation rates.
For point #1, there appears to be the expected substantial biases against low amplitude and very short or long period lightcurves with the period problems stemming from the observing cadence and limited number of observations. Furthermore, the two latest surveys found periods for only about 20% of all observed objects, meaning that only the "easier" results were found. While the two surveys tended to go deeper and, therefore, work smaller objects, that raises yet another bias: success in finding a period depends on brightness. As a result, we would urge caution when interpreting spin properties versus size.
For point #2, we first note that the vast majority of objects observed by the two surveys were in the broad regions of the inner or outer main-belt. Significantly, less than 10 NEAs were observed. For this reason, it makes it difficult to compare the effects of YORP, as seen by rotation rate distribution, on small asteroids at different distances. When considering main-belt objects with $10 < D < 40$ km, the difference between plots with and without survey data show essentially the same Mawellian-like distribution.

**Author(s): Brian D. Warner1**, Alan W Harris3, Robert D Stephens2
**Institution(s):** *1. Center for Solar System Studies - Palmer Divide Station, 2. Center for Solar System Studies - Trojan Station, 3. MoreData!*

### 307.03 – Rotational Properties of Jupiter Trojan 1173 Anchises

Anchises (1173) is a large Trojan asteroid librating about Jupiter's L5 Lagrange point. Here we examine its rotational and lightcurve properties by way of data collected over a 3.5 year observing campaign. The length of the campaign means that data were gathered for more than a quarter of Anchises' full orbital revolution which allows for accurate determinations of pole orientation and bulk shape properties for the asteroid that can then be compared to results of previous work (i.e. French 1987, Horner et al. 2012). In addition to light curves, photometric data taken during this campaign could potentially detect color differences between hemispheres as the viewing geometry changes over time. Understanding these details about a prominent member of the Jupiter Trojans may help us better understand the history of this fascinating and important group of asteroids.

**Author(s): Joseph Chatelain1**, Todd Henry4, Linda French2, David Trilling3
**Institution(s):** *1. Georgia State University, 2. Illinois Wesleyan University, 3. Northern Arizona University, 4. RECONS Institute*

### 307.04 – Improved Algorithms for Radar-Based Reconstruction of Asteroid Spin States and Shapes

Earth-based radar is a powerful tool for gathering information about bodies in the Solar System. Radar observations can dramatically improve the determination of the physical properties and orbital elements of small bodies (such as asteroids and comets). An important development in the past two decades has been the formulation and implementation of algorithms for asteroid shape reconstruction based on radar data.
Because of the nature of radar data, recovery of the spin state depends on knowledge of the shape and vice versa. Even with perfect spin state information, certain peculiarities of radar images (such as the two-to-one or several-to-one mapping between surface elements on the object and pixels within the radar image) make recovery of the physical shape challenging. This is a computationally intensive problem, potentially involving hundreds to thousands of free parameters and millions of data points.
The method by which radar-based shape and spin state modelling is currently accomplished, a Sequential Parameter Fit (SPF), is relatively slow, and incapable of determining the spin state of an asteroid from radar images without substantial user intervention. We implemented a global-parameter optimizer and Square Root Information Filter (SRIF) into the asteroid-modelling software *shape*. This optimizer can find shapes more quickly than the current method and can determine the asteroid's spin state.
We ran our new algorithm, along with the existing SPF, through several tests, composed of both real and simulated data. The simulated data were composed of noisy images of procedurally generated shapes, as well as noisy images of existing shape models. The real data included recent observations of both 2000 ET70 and 1566 Icarus.
These tests indicate that SRIF is faster and more accurate than SPF. In addition, SRIF can autonomously determine the spin state of an asteroid from a variety of starting conditions, a considerable advance over the existing algorithm. We will present the results of these comparisons, along with several visualizations of the shape and spin state fitting process.

**Author(s): Adam Greenberg1**, Jean-Luc Margot1
**Institution(s):** *1. University of California, Los Angeles*

### 307.05 – Rotation Frequencies of Small Jovian Trojan Asteroids: An Excess of Slow Rotators

Several lines of evidence support a common origin for, and possible hereditary link between, cometary nuclei and jovian Trojan asteroids. Due to their distance and low albedos, few comet-sized

Trojans have been studied. We discuss the rotation properties of Jovian Trojan asteroids less than 30 km in diameter. Approximately half the 131 objects discussed here were studied using densely sampled lightcurves (French *et al.* 2015a, b); Stephens *et al.* 2015), and the other half were sparse lightcurves obtained by the Palomar Transient Factory (PTF; Waszczazk *et al.* 2015).
A significant fraction (~40%) of the objects in the ground-based sample rotate slowly (P > 24h), with measured periods as long as 375 h (Warner and Stephens 2011). The PTF data show a similar excess of slow rotators. Only 5 objects in the combined data set have rotation periods of less than six hours. Three of these fast rotators were contained in the data set of French *et al.*; these three had a geometric mean rotation period of 5.29 hours. A prolate spheroid held together by gravity rotating with this period would have a critical density of 0.43 gm/cm3, a density similar to that of comets (Lamy *et al.* 2004).
Harris *et al.* (2012) and Warner *et al.* (2011) have explored the possible effects on asteroid rotational statistics with the results from wide-field surveys. We will examine Trojan rotation statistics with and without the results from the PTF.

**Author(s): Linda M. French3**, Robert D. Stephens[1], David J. James[2], Daniel Coley[1], Kyle Connour3
**Institution(s):** *1. Center for Solar System Studies, 2. Cerro Tololo Interamerican Observatory, 3. Illinois Wesleyan Univ.*

### 307.06 – Internal turmoil of small primitive bodies: rock-water-organic processing as context for Bennu and JU

The OSIRIX-REx (NASA, 101955 Bennu) and Hayabusa 2 (JAXA, 1999 JU3) missions are set to explore small, porous and primitive asteroids (C and B type). Such bodies should contain organic compounds and hydrated minerals. Thus, it is of great interest to decipher the internal structure and composition, how it evolved and how representative is the surface of the bulk interior. For this we need to understand the physical conditions which drive the chemical evolution of water and organic-rich material through a porous medium, as even main-belt asteroids of various sizes could have incorporated water ice upon formation. Indeed, the meteoritic record reveals such evidence, in the form of hydrated minerals, mostly in the CI, CM and CR carbonaceous chondrites, which also indicate that more complex physical-chemical interactions, under various conditions, must have happened early on and set the compositions and lithologies we observe today. The precursor bodies may have also undergone early evolution and internal processing of mineral and organic reservoirs. If conditions are met and sustained, exothermic reactions (e.g., serpentinization and Fischer-Tropsch), can contribute greatly to the overall heating balance and compositional variation.
Our thermal evolution code can deal with mixtures of water, silicate minerals and organic compounds, with relevant transitions and interactions, as a function of the thermodynamic variables. We will utilize the robustness of the code to examine different origin and early evolution scenarios, such as parent-body evolution, increased collision input early on, orbital evolution at further/closer perihelia, varied initial composition and buried reservoirs of volatile compounds. We will further examine the boundary conditions in surface and near-surface layers, by calculating heat transfer effects in granular material, including conduction, radiation and advection between particles and pores. The granular material can further react to vapor flows and small impacts, effectively changing the diffusivity and conductivity of surface layers.
We will present preliminary integrative models for internal evolution, from formation to current state, as a reactive rock-water-organic porous system.

**Author(s): Gal Sarid[1]**
**Institution(s):** *1. Florida Space Institute, U. of Central Florida*

### 307.07 – Preliminary Light Curve Results of NEOs from the Characterization and Astrometric Follow-Up Program at Adler Planetarium

We are nearing the halfway mark of a two-year program for near-Earth object (NEO) astrometric follow-up and characterization utilizing 500 hours of observing time per year with the Astrophysical Research Consortium (ARC) 3.5-meter telescope at Apache Point Observatory (APO). Our observing is divided into two-hour blocks approximately every other night for astrometry (see poster by K. A. Nault et al.) and several half-nights per month for spectroscopy (see poster by M. Hammergren et al.) and light curve studies.
We present preliminary results from variable photometry observations as part of the characterization portion of the Adler Planetarium's NEO program. The frequent scheduling of half-night observing time allows us to capture data for small NEOs near the time when they are closest to Earth before their apparent magnitudes rapidly diminish beyond the range of detectability. We searched for variability in newly discovered NEOs that had close approaches to Earth near the time of observation. These include 2014 RQ17, 2014 SB145, 2014 SF304, 2014 WO4, 2014 WY119, and 2015 BC. In addition, we observed 2340 Hathor and 2007 EC when they each made a close approach to Earth to compare with light curves and magnitude variation constraints from previous apparitions. We will construct light curves for all of the objects listed above and determine rotational periods for those with sufficient temporal coverage.
The targets were selected from candidates in the JPL NEO Earth Close Approaches table, Arecibo planetary radar targets, and the Goldstone asteroid radar schedule. Due to the sensitivity of AGILE, we restricted our targets to those with apparent magnitudes in V less than 19 magnitudes.
Observations were made using the frame transfer CCD camera AGILE on the ARC 3.5-meter telescope. AGILE has a field-of-view of 2.2'x2.2' and a plate scale of 0.258"/pixel with 2x2 binning.
This work is based on observations obtained with the Apache Point Observatory 3.5-meter telescope, which is owned and operated by the Astrophysical Research Consortium. We gratefully acknowledge support from NASA NEOO award NNX14AL17G, and thank the University of Chicago Department of Astronomy and Astrophysics for observing time in 2014

**Author(s): Melissa J. Brucker[1]**, Kristie A. Nault[1], Mark Hammergren[1], Jennifer Sieben[2], Geza Gyuk[1], Michael R. Solontoi3
**Institution(s):** *1. Adler Planetarium, 2. Illinois Wesleyan University, 3. Lynchburg College*

### 307.08 – Spin-Spin Coupling in Asteroidal Binaries

Gravitationally bound binaries constitute a substantial fraction of the small body population of the solar system, and characterization of their rotational states is instrumental to understanding their formation and dynamical evolution. Unlike planets, numerous small bodies can maintain a perpetual aspheroidal shape, giving rise to a richer array of non-trivial gravitational dynamics. In this work, we explore the rotational evolution of triaxial satellites that orbit permanently deformed central objects, with specific emphasis on quadrupole-quadrupole interactions. Our analysis shows that in addition to conventional spin-orbit resonances, both prograde and retrograde spin-spin resonances naturally arise for closely orbiting, highly deformed bodies. Application of our results to the illustrative examples of (87) Sylvia and (216) Kleopatra multi-asteroid systems implies capture probabilities slightly below ~10% for leading-order spin-spin resonances. Cumulatively, our results suggest that spin-spin coupling may be consequential for highly elongated, tightly orbiting binary objects.

**Author(s): Konstantin Batygin[1]**, Alessandro Morbidelli[2]
**Institution(s):** *1. California Institute of Technology, 2. Observatoire de la Côte d'Azur*

### 307.09 – Surprise! The oft-ignored Moon might actually be important for changing the spins of asteroids during Earth flybys

Analysis near-Earth asteroid archival data has revealed that asteroids with Earth MOIDs (minimum orbit intersection distance; a proxy for flyby distance) smaller than 1.0-1.5 lunar distances have a systematically larger dispersion in spin rate than more distant flybys (Siu, et al. 2015, DPS). While tidal torques during close encounters are expected to alter the spin states of asteroids (e.g. Scheeres et al. 2000, Icarus), there is no intrinsic reason to expect the observed sharp transition in spin rate distribution at 1.0-1.5 lunar distances, as tidal forces drop off smoothly with distance. While the Moon itself is too diminutive to directly alter the spin-states of asteroids, we show that its presence is enough to significantly affect asteroid encounter trajectories. Asteroids entering the Earth-Moon system are subject to three-body dynamics (due to the combined gravitational effects of the Earth and Moon). Depending on the flyby geometry, the Moon can act as a temporary sink for the asteroid's geocentric orbital energy. This allows some fraction of asteroids to have closer approaches with the Earth than expected when considering the Earth-Moon barycenter alone. In rare cases (~0.1%) this process enables the capture of temporary moons around the Earth (Granvik et al. 2012, Icarus). Asteroids that undergo these "enhanced" flybys can have both closer-than-expected encounter distances (resulting in more significant tidal perturbations), and repeated encounters with the Earth and Moon before leaving the system (resulting in the accumulation of multiple tidal interactions). By numerically solving the circular restricted three-body problem, we show that this process naturally produces a sharp transition in the asteroid population: asteroids with MOIDs less than 1.5 lunar distances can undergo these enhanced close approaches, possibly explaining the sharp transition in the dispersion of asteroid spin rates at this distance. Future work will investigate the efficiency of this process, and the relationship between the physical response of the asteroid to tidal perturbations and the statistical distribution of asteroid spin rates.

**Author(s): James Tuttle Keane3**, Hosea C. Siu[2], Nicholas A. Moskovitz[1], Richard P. Binzel[2]
**Institution(s):** *1. Lowell Observatory, 2. Massachusetts Institute of Technology, 3. University of Arizona*

### 307.10 – Distributions of spin axes and shapes of asteroids

We developed a new simplified model for the determination of shapes and spin states of asteroids to fully exploit photometric data sparse in time (few measurements per night) which are produced by all-sky surveys and were re-calibrated into the Lowell photometric database by Bowell et al. (2014). We model asteroids as geometrically scattering triaxial ellipsoids. The model compares observed values of mean brightness and the dispersion of brightness with computed values obtained from the parameters of the model – ecliptical longitude $\lambda$ and latitude $\beta$ of the pole and the ratio $a/b$ of axes of the ellipsoid. These parameters are optimized to get the best agreement with the observation. We revealed that the distribution of $\lambda$ for the main-belt asteroids is anisotropic (in agreement with findings of Bowell et al. (2014)) and dependent on the inclination of orbit (for sin $i$ < 0.04 there is an excess of $\lambda$ ~ 70° +/- 180°). We are looking for a physical or observational mechanism that would explain this distribution. From the analysis of the distribution of $a/b$ we found that larger asteroids ($D$ > 25 km) are more often spherical ($a/b$ ~ 1) than the smaller.

**Author(s): Helena Cibulkova[1]**, Josef Durech[1], Mikko Kaasalainen3, Edward Bowell4, Dagmara Oszkiewicz[2]
**Institution(s):** *1. Astronomical Institute of the Charles University, 2. Astronomical Observatory Institute, A. Mickiewicz University, 3. Department of Mathematics, Tampere University of Technology, 4. Lowell Observatory*

### 307.11 – Looking for Kilometer-Sized Super-Fast-Rotators Using PTF

We have carried out three 6-field (~40 square deg each) asteroid rotation surveys using PTF with 10 min cadence to searh for kilometer-sized super-fast rotators (SRF) in 2014 Nov, 2015 Jan, and 2015 Feb. From these surveys, we found several SFR candidates showing reasonable folded lightcurves. With these candidates, we estimate that the population of SFR is ~0.1% of rubble-pile asteroid.

**Author(s): Chan-Kao Chang[1]**, Hsing-Wen Lin[1], Wing-Huen Ip[1]
**Institution(s):** *1. Institute of Astronomy, National Central University, Taiwan*

### 307.12 – Nutation damping in viscoelastic tumbling rotators

Presently, 138 asteroids show signs of being in non-principal spin states (Warner et al. 2009, updated September 2015). Such spin is often called `tumble' or `wobble'. The instantaneous rotation axis of a wobbling body performs nutation about the direction of the (conserved) angular-momentum vector. Incited by collisions and YORP, wobble is mitigated by internal dissipation due to the nutation-caused alternating stresses inside the asteroid.
The knowledge of the timescale related to the damping of the nutation angle is complementary to the knowledge of the timescales associated with collisions and YORP. Previous evaluations of the nutation relaxation rate were based on an inherently inconsistent approach that may be called "Q-model". First, the elastic energy in a periodically deforming rotator was calculated in assumption of the deformation being elastic. Therefrom, the energy dissipation rate was determined by introducing an ad hoc quality factor Q. This ignored the fact that friction (and the ensuing existence of Q) is due to deviation from elasticity.
We use the viscoelastic Maxwell model which naturally implies dissipation (as any other viscoelastic model would). In this approach, we compute the power and damping time for an oblate ellipsoid and a prism. Now, the viscosity assumes the role of the product μQ in the empirical Q-model, with μ being the rigidity. Contrarily to the Q-model, our model naturally gives a null dissipation for a shape tending to a sphere. We also explore when the constant part of the stress can be ignored in the derivation of the damping time. The neglect of prestressing turns out to be legitimate for the mean viscosity exceeding a certain threshold value.

**Author(s): Julien Frouard[1]**, Michael Efroimsky[1]
**Institution(s):** *1. US Naval Observatory*

### 307.13 – Photometric Follow-up of Asteroid 4660 Nereus and Reanalysis of its YORP Effect

We carried out new photometric observations of small near-Earth asteroid 4660 Nereus in 2013 and reanalyzed the secular change in the asteroid rotation period due to the YORP effect. The shape and pole orientation of Nereus have been derived from the radar observations, which predicts that a detectable change could occur in a few years (Brozovic et al., 2009). Since the YORP-induced linear change of rotation period leads to a phase lag that is quadratic in time, we examined it by comparing 22 lightcurves observed in 1997-2013 with the modeled ones. The new dataset of lightcurves enabled us to further constrain the solutions of the asteroid rotational state, and we found that it would be difficult to reproduce the observed lightcruves with a constant-period model.

**Author(s): Kohei Kitazato4**, Shinsuke Abe[2], Masateru Ishiguro3, Yukihiro Ishibashi[1], Yuhei Takagi5, Masanao Abe[1]
**Institution(s):** *1. Japan Aerospace Exploration Agency, 2. Nihon University, 3. Seoul National University, 4. University of Aizu, 5. University of Hyogo*

## 308 – Asteroid Observational Surveys

### 308.01 – The Near-Earth Object Camera: A Next-Generation Minor Planet Survey

The Near-Earth Object Camera (NEOCam) is a next-generation asteroid and comet survey designed to discover, characterize, and track large numbers of minor planets using a 50 cm infrared telescope located at the Sun-Earth L1 Lagrange point. Proposed to NASA's Discovery program, NEOCam is designed to carry out a comprehensive inventory of the small bodies in the inner regions of our solar system. It address three themes: 1) quantify the potential hazard that near-Earth objects may pose to Earth; 2) study the origins and evolution of our solar system as revealed by its small body populations; and 3) identify the best destinations for future robotic and human exploration. With a dual channel infrared imager that observes at 4-5 and 6-10 micron bands simultaneously through the use of a beamsplitter, NEOCam enables measurements of asteroid diameters and thermal inertia. NEOCam complements existing and planned visible light surveys in terms of orbital element phase space and wavelengths, since albedos can be determined for objects with both visible and infrared flux measurements. NEOCam was awarded technology development funding in 2011 to mature the necessary megapixel infrared detectors.

**Author(s): Amy K. Mainzer[2]**, Edward L. Wright4, James Bauer[2], Tommy Grav3, Roc M. Cutri[1], Joseph Masiero[2], Carolyn R Nugent[1]
**Institution(s):** *1. IPAC/Caltech, 2. JPL, 3. PSI, 4. UCLA*

### 308.02 – Asteroid Detection Results Using the Space Surveillance Telescope

From 1998-2013, MIT Lincoln Laboratory operated a highly successful near-Earth asteroid search program using two 1-m optical telescopes located at the MIT Lincoln Laboratory Experimental Test Site (ETS) in Socorro, N.M. In 2014, the Lincoln Near-Earth Asteroid Research (LINEAR) program successfully transitioned operations from the two 1-m telescopes to the 3.5-m Space Surveillance Telescope (SST) located at Atom Site on White Sands Missile Range, N.M. This paper provides a summary of first-year performance and results for the LINEAR program with SST and provides an update on recent improvements to the moving-object pipeline architecture that increase utility of SST data for NEO discovery and improve sensitivity to fast-moving objects. Ruprecht et al. (2014) made predictions for SST NEO search productivity as a function of population model. This paper assesses the NEO search performance of SST in the first 1.5 years of operation and compares results to model predictions.
This work is sponsored by the Defense Advanced Research Projects Agency and the National Aeronautics and Space Administration under Air Force Contract #FA8721-05-C-0002. The views, opinions, and/or findings contained in this article/presentation are those of the authors / presenters and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government. Distribution Statement A: Approved for public release, distribution unlimited.

**Author(s): Jessica D. Ruprecht[1]**, Gregory Ushomirsky[1], Deborah F. Woods[1], Herbert E. M. Viggh[1], Jacob Varey[1], Mark E. Cornell[2], Grant Stokes[1]
**Institution(s):** *1. MIT Lincoln Laboratory, 2. MIT/LL ETS Field Site*

### 308.03 – Absolute magnitudes and slope parameters for 250,000 asteroids observed by Pan-STARRS1.

Absolute magnitude (H) of an asteroid is used for the determination of its diameter and apparent brightness. The observed brightness changes as a function of asteroid's geometry with respect to the Sun and Earth and surface properties of the asteroid which is described by a phase function depending on the slope parameter (G). H and G parameters are derived from mostly optical observations of asteroids. Nowadays, databases of asteroid observations contain millions of entries, coming from multiple telescopic surveys employing different photometric calibrations and standards. They usually lack information on photometric errors and photometric precision is truncated above the photometric accuracy of current major surveys. We derived H and G of almost 250,000 asteroids observed by a single survey – Pan-STARRS1 - during its first 15 months of operation. 1,250,000 detections in our sample were filtered by morphological parameters and photometric quality and achieved photometric errors less than 0.04 mag. Our method was based on Monte Carlo technique and a sparse Bayesian marginalization over taxonomic classification, light curve amplitude and period and both Bowell's (1989) and Muinonen's (2010) phase functions. Resulting H and G values were derived with statistical and systematic uncertainties and errors. The method was tested by comparison with accurate results for about 500 asteroids provided by Pravec et al. (2012) and results agree with Oszkiewicz et al. (2012) work. Our results confirm that the bias discovered by Juric et al. (2002) and confirmed by Parker et al. (2008) and Pravec et al. (2012) is still present in Minor Planet Center photometry. The trend of G depending on semi-major axis was confirmed as well. Derived table of H and G and other relevant parameters is publicly available at http://www.ifa.hawaii.edu /NEO/. This work was supported by NASA grant No. NNX12AR65G.

**Author(s): Peter Veres[2]**, Robert Jedicke[1], Alan Fitzsimmons3, Larry Denneau[1], Mikael Granvik4, Bryce Bolin5, Serge Chastel[1], Richard Wainscoat[1]
**Institution(s):** *1. Institute for Astronomy, University of Hawaii, 2. Jet Propulsion Laboratory, California Institute of Technology, 3. Queen's University, 4. University of Helsinki, 5. UNS-CNRS-Observatoire de la Cote d'Azur*

### 308.04 – Dormant Comets in the Near-Earth Asteroid Population

The population of near-Earth objects comprises active comets and asteroids, covering a wide range of dynamical parameters and physical properties. Dormant (or extinct) comets, masquerading as asteroids, have long been suspected of supplementing the near-Earth asteroid (NEA) population. We present a search for asteroidal objects of cometary origin based on dynamical and physical considerations. Our study is based on albedos derived within the ExploreNEOs program and is extended by adding data from NEOWISE and the Akari asteroid catalog. We use a statistical approach to identify asteroids on orbits that resemble those of short-period near-Earth comets using the Tisserand parameter with respect to Jupiter, the aphelion distance, and the minimum orbital intersection distance with respect to Jupiter. We identify a total of 23 near-Earth asteroids from our sample that are likely to be dormant short-period near-Earth comets and, based on a de-biasing procedure applied to the cryogenic NEOWISE survey, estimate both magnitude-limited and size-limited fractions of the NEA population that are dormant short-period comets. We find that 0.3-3.3% of the NEA population with H <= 21, and 9(+2/-5)% of the population with diameters d >= 1 km, are dormant short-period near-Earth comets. We also present an observation program that utilizes the 1.8m Vatican Advanced Technology Telescope (VATT) on Mt. Graham, AZ, to identify dormant comet candidates and search for activity in these objects. Our targets are NEAs on comet-like orbits, based on the dynamical criteria derived in the above study, that are accessible with the VATT (V <= 22). We identify dormant comets based on their optical spectral slope, represented by V-R color measurements, as albedo measurements for most of these objects are not available. For each target we measure and monitor its V magnitude in order to reveal activity outbreaks. We also search for extended emission around our targets using deep imaging and a point-spread-function subtraction technique that allows us to obtain an upper limit on the dust production rate in each target. We present preliminary results from this program. This work is supported in part by funding from the Spitzer Science Center.

**Author(s): Michael Mommert4**, Alan W. Harris[1], Michael Mueller7, Joseph L. Hora[2], David E. Trilling4, Matthew Knight3, William F. Bottke[8], Cristina Thomas[6], Marco Delbo'5, Josh P. Emery9, Giovanni Fazio[2], Howard A. Smith[2]
**Institution(s):** *1. Deutsches Zentrum fuer Luft- und Raumfahrt, 2. Harvard-Smithsonian CfA, 3. Lowell Observatory, 4. Northern Arizona University, 5. Observatoire de la Cote d'Azur, 6. PSI, 7. SRON, 8. SWRI, 9. University of Tennessee*

### 308.05 – The Asteroid 2015 KA122

The Asteroid "2015 KA122" was discovered on May 25/2015 by the Catalina Sky Survey. This object is not well known. Its absolute magnitude, of 23.2, indicates a diameter of about 70 meters. The asteroid was at aproximately 3.3 lunar distances from the Earth, on June 6/2015. It has an orbital period of 2.11 years. From our Observatory, located in Pasto-Colombia, we captured several

pictures, videos and astrometry data during three days. Our data was published by the Minor Planet Center (MPC) and also appears at the web page of NEODyS. Our observatory's code at the MPC is "H78". Pictures of the asteroid were captured with the following equipment: 14" LX200 GPS MEADE (f/10 Schmidt-Cassegrain Telescope) and STL-1001 SBIG camera. Astrometry was carried out, and we calculated the orbital elements. We obtained the following orbital parameters: eccentricity = 0.4089630 +/- 0.00189, semi-major axis = 1.64254884 +/- 0.00505 A.U, orbital inclination = 12.68490 +/- 0.039 deg, longitude of the ascending node = 73.14715 +/- 0.0013 deg, argument of perihelion = 214.82393 +/- 0.007 deg, orbital period = 2.11 years (768.90 days), mean motion = 0.46819485 +/- 0.00216 deg/d, perihelion distance = 0.97080706 +/- 0.000119 A.U, aphelion distance = 2.31429061 +/- 0.0103 A.U. The parameters were calculated based on 81 observations (2015 June 3-5) with mean residual = 0.343 arcseconds. Our videos appear in the following links:
http://spaceweathergallery.com
/indiv_upload.php?upload_id=113197
http://spaceweathergallery.com
/indiv_upload.php?upload_id=113238&
PHPSESSID=f2lkigjogsfgcmi1rscc9jil36
http://spaceweathergallery.com
/indiv_upload.php?upload_id=113257

**Author(s): Alberto Quijano Vodniza[1]**, Mario Rojas Pereira[1]
**Institution(s):** *1. University of Narino Observatory*

### 308.06 – Target-of-Opportunity Characterization of 100-Meter Class Near-Earth Asteroids

It is generally believed that minor planet rotation periods smaller than ~2 hours are indicative of non-negligible tensile strength for these objects [1]. This would put limits on the degree of fracture or even suggest a monolithic structure for fast rotating asteroids. Combining rotations rates with spectral information for 100-meter class Near-Earth asteroids (NEAs) can provide an even better understanding of the physical properties and collisional history of the smaller members of the asteroid population, which are also those that will impact the Earth with the most frequency.
Robust characterization of 100-meter class asteroids is usually limited to when these objects make close approaches to the Earth. The observing window for such studies is usually weeks, days, or, for the smallest members of this population, just a single day or two bracketing their closest approach to Earth. For many, the only optimal occasions for investigation for the foreseeable future occur immediately after discovery. Therefore, these are truly targets-of-opportunity.
As part of an effort to obtain astrometric data on newly discovered near-Earth asteroids using the Magdalena Ridge Observatory's (MRO) 2.4-meter telescope, a program has been implemented to obtain rotation rate and spectral information on 100-meter class and smaller NEAs [2]. Prioritized are recently discovered objects that have limited observing prospects. Results thus far have shown that, although slow rotators do exists in this size regime, about 70% of our targets with absolute magnitude H>22 have rotation periods less than 2 hours. In addition, approximately 20% of our targets have indicated tumbling behavior, with primary periods ranging from hours to minutes. Therefore, any origin model must be consistent with the observed rotation rate distribution, allow for the existence of a significant fraction of tumblers, and be consistent with the evolving spectral class distribution. For this effort, we quantify the observing window that exists for various objects in this size regime using the MRO 2.4-meter telescope. We then present a sample of recent lightcurve and spectral results from this program.
[1] Pravec et al., Asteroids III 2002
[2] Ryan and Ryan, DPS 2014

**Author(s): William Ryan[1]**, Eileen V. Ryan[1]
**Institution(s):** *1. NM Tech/MRO*

### 308.07 – Radar Observations of Near-Earth Asteroid (52760) 1998 ML14: Constraints from the 1998 and 2013 Apparitions

Ostro et al. (Meteoritics & Planetary Science, 36, 1225-1236, 2001) produced a shape model of the approximately 1-km diameter near-Earth asteroid (52760) 1998 ML14 using radar images taken with the Arecibo and Goldstone planetary radar systems in 1998. However, the spin state (pole orientation and rotation period) was not well determined in their modelling. The published shape model was produced using a 14.83 h sidereal rotation period, consistent with the synodic period of 14.98 ± 0.06 h found by optical observations in 1998 (Hicks & Weissman, IAU Circular 6987, 1, 1998). Optical observations in 2013 found a faster period of 14.28 ± 0.01 h (Warner, The Minor Planet Bulletin, 41, 2, 113-124, 2014). Further radar observations at Arecibo in 2013 are inconsistent with the 14.83 h sidereal period. Use of Arecibo radar images from both apparitions, with resolution as fine as 15 m per pixel, are best fit by a sidereal period within 1% of 14.28 h and constrain the pole orientation to within approximately ten degrees. An updated shape model will be presented using this new information. These improved constraints illustrate the power of multiple apparitions for better determining the true shapes and spin states of near-Earth asteroids.

**Author(s): Benjamin N. L. Sharkey3**, Patrick A. Taylor[1], Michael C. Nolan[2], Ellen S. Howell[2]
**Institution(s):** *1. Arecibo Observatory, 2. LPL/U. Arizona, 3. University of Minnesota - Twin Cities*

### 308.08 – Arecibo and Goldstone Radar Observations of the First-Recognized Binary Near-Earth Asteroid: (385186) 1994 AW1

Near-Earth asteroid (385186) 1994 AW1 was discovered at Palomar Observatory on 11 January 1994. Subsequent observations of this Amor family, Sa-class asteroid also identified it as the first candidate binary NEA, as indicated by multiple periodicities and possible mutual eclipsing/occulting events in the object's lightcurve. On 15 July 2015 this asteroid made its closest approach to Earth since its discovery, coming within 0.065 AU (25 lunar distances), and prompting an extended observation campaign using both the JPL-Goldstone and Arecibo Observatory planetary radars. Goldstone observations covered the 14-19 July period of closest approach (0.066-0.070 AU) while the object remained below Arecibo's observing horizon, with Arecibo picking up the observations between 20-30 July, as the object moved from 0.075 to 0.126 AU distance. At Goldstone, we were able to observe this object with range resolutions of 150 m using a Goldstone (DSS-14) to Green Bank Telescope (GBT) bistatic configuration, while at Arecibo, we conducted monostatic observations of 1994 AW1 using the 2380 MHz (12.6 cm) radar at resolutions of 30 m and 75 m.
As a result, and twenty years after its discovery, these observations have confirmed the binary nature of 1994 AW1, showing the primary body to be about 600 m in diameter, the secondary body to be about half the diameter of the primary, with the two orbiting a common center of mass at a distance of about 1.2 km apart. Delay-Doppler image comparisons of the primary over the course of six nights (at 30 m resolution) confirm a lightcurve-derived rotation period of 2.518 +/- 0.002 hr, as >90% longitude coverage was achieved, revealing a slightly elongated, irregular surface morphology. Delay-Doppler images of the secondary reveal an elongated, irregular body which appears to be tidally locked, with its long axis pointed towards the primary as it orbits with a period of about 22 hr (also consistent with the lightcurve analysis). These very early results point to a total system mass of (1.6 +/- 0.5) x 10^11 kg and a crude, mean system density estimate of 1400 +/- 500 kg/m^3. Additional analysis and shape-modeling will be presented.

**Author(s): James E. Richardson[1]**, Patrick A. Taylor[1], Edgard G. Rivera-Valentin[1], Linda A. Rodriguez-Ford[1], Lance A.M. Benner[4], Shantanu P. Naidu[4], Jon D. Giorgini[4], Michael W. Busch[7], Frank d. Ghigo[5], Adam Kobelski[5], Brian D. Warner[2], Alessondra Springmann[8], Sean E. Marshall3, Jordan K. Steckloff[6], Benjamin Sharkey9
**Institution(s):** *1. Arecibo Observatory (USRA), 2. Center for Solar System Studies, 3. Cornell University, 4. Jet Propulsion Laboratory, 5. National Radio Astronomy Observatory, 6. Purdue University, 7. SETI Institute, 8. University of Arizona, 9. University of Minnesota Twin Cities*

## 308.09 – LSST's Projected Near-Earth Asteroid Discovery Performance

The Large Synoptic Survey Telescope (LSST) is an ambitious project that has the potential to make major advances in Near-Earth Asteroid search efforts. With construction already underway and major optical elements complete, first light is set for 2020, followed by two years of commissioning. Once regular survey operations begin in 2022, LSST will systematically survey the observable sky over a ten-year period from its site on Cerro Pachon, Chile. With an 8.4 m aperture (6.5 m effective), 9.6 square degree field of view, and a 3.2-Gigapixel camera, LSST represents the most capable asteroid survey instrument ever built.
LSST will be able cover over 6000 square degrees of sky per clear night with single visit exposures of 30 s, reaching a faint limit of 24.5 mag in the r band. However the cadence of survey operations is a critical factor for the near-Earth asteroid search performance, and there are multiple science drivers with different cadence objectives that are competing to shape the final survey strategy. We examine the NEA search performance of various LSST search strategies, paying particular attention to the challenges of linking large numbers asteroid detections in the presence of noise.
Our approach is to derive lists of synthetic detections for a given instantiation of the LSST survey, based on an assumed model for the populations of solar system objects from the main asteroid belt inwards to the near-Earth population. These detection lists are combined with false detection lists that model both random noise and non-random artifacts resulting from image differencing algorithms. These large detection lists are fed to the Moving Object Processing System (MOPS), which attempts to link the synthetic detections correctly without becoming confused or overwhelmed by the false detections.
The LSST baseline survey cadence relies primarily on single night pairs of detections, with roughly 30-60 min separating elements of the pair. The strategy of using pairs is an aggressive and potentially fragile approach, but theoretically represents the most productive NEA search with the minimum impact on other LSST science drivers.

**Author(s): Steven R. Chesley[1]**, Peter Vereš[1]
**Institution(s):** *1. JPL*

## 308.10 – The Mission Accessible Near-Earth Object Survey (MANOS) — First Results

The Mission Accessible Near-Earth Object Survey (MANOS) began in August 2013 as a multi-year physical characterization survey that was awarded survey status by NOAO and has since expanded operations to include facilities at Lowell Observatory and the University of Hawaii. MANOS will target several hundred mission-accessible NEOs across visible and near-infrared wavelengths, providing a comprehensive catalog of physical properties (astrometry, light curves, spectra). Particular focus is paid to sub-km NEOs, where little data currently exists. These small bodies are essential to understanding the link between meteorites and asteroids, pose the most immediate impact hazard to the Earth, and are highly relevant to a variety of planetary mission scenarios. Observing these targets is enabled through a combination of classical, queue, and target-of-opportunity observations carried out at 1- to 8-meter class facilities in both the northern and southern hemispheres. The MANOS observing strategy enables the characterization of roughly 10% of newly discovered NEOs before they fade beyond observational limits.
To date MANOS has obtained data on over 200 sub-km NEOs and will ultimately provide major advances in our understanding of the NEO population as a whole and for specific objects of interest. Here we present first results from the survey including: (1) the de-biased taxonomic distribution of spectral types for NEOs smaller than ~100 meters, (2) the distribution of rotational properties for small objects with high Earth-encounter probabilities, (3) progress in developing a new set of online tools at asteroid.lowell.edu that will help to facilitate observational planning for the small body observer community, and (4) physical properties derived from rotational light curves.
MANOS is supported through telescope allocations from NOAO, Lowell Observatory and the University of Hawaii. We acknowledge funding support from NASA NEOO grant number NNX14AN82G and an NSF Astronomy and Astrophysics Postdoctoral Fellowship to N. Moskovitz.

**Author(s): Nicholas Moskovitz[2]**, Louis Avner[2], Richard Binzel[3], Brian Burt[2], Eric Christensen[1], Francesca DeMeo[3], Mary Hinkle[4], Michael Mommert[4], Michael Person[3], David Polishook[7], Robert Schottland[2], Hosea Siu[3], Audrey Thirouin[2], Cristina Thomas[5], David Trilling[4], Lawrence Wasserman[2], Mark Willman[6]
**Institution(s):** *1. CSS/UA, 2. Lowell Observatory, 3. MIT, 4. Northern Arizona University, 5. PSI, 6. University of Hawaii, 7. Weizmann Institute of Science*

## 308.11 – Albedo, Size and Taxonomy of the Small Body Populations Outside the Main Belt

Using the data from the WISE/NEOWISE mission we have derived albedo and size distributions of ~1200 Cybeles, ~1000 Hildas, ~1700 Jovian Trojans and a dozen irregular satellites of Jupiter and Saturn. These data increases by an order of magnitude our knowledge of the makeup of the small body populations between the Main Belt and Saturn. We find that all these populations are dominated by low albedo objects, with only the Cybeles (with less than 10%) having any significant fraction of possible interloper objects with albedo higher than 15%. Using the near-infrared albedos (in the 3.4 and 4.6μm bands, denoted W1 and W2 respectively) we were able to derive the taxonomic classifications of the largest objects in each population, showing that they are dominated by surfaces that are similar to C-, P- and D-type asteroids. The dominance of these dark, primitive surfaces indicate two possible formation scenarios. These small body populations may have been formed in situ beyond the snow line, potentially serving as bodies that can provide significant insight into the composition of the early Solar Nebula in the region of the current Giant Planets. Alternatively, they may be captured bodies that were perturbed from the region outside the Giant Planets as the planets migrated during the early stages of Solar System formation. This allows for insight into the composition of the Trans-Neptunian population by study of populations that are significantly closer, brighter and more accessible. The low percentages of potentially higher albedo, stony objects common in the Main Asteroid Belt indicates that only a few of these objects have embedded themselves into these populations, potentially imposing significant constraints on the migration of Jupiter inside its current orbit.

**Author(s): Tommy Grav[3]**, Amy Mainzer[2], James Bauer[2], Joseph R Masiero[2], Roc Cutri[1], Carrie Nugent[1], Sarah Sonnett[2], Emily A. Kramer[2]
**Institution(s):** *1. Infrared Processing and Analysis Center - California Institute of Technology, 2. Jet Propulsion Laboratory, 3. Planetary Science Institute*

## 308.12 – Results from the LCOGT Near-Earth Object Follow-up Network

Las Cumbres Observatory Global Telescope Network (LCOGT) has deployed a homogeneous telescope network of nine 1-meter and two 2-meter telescopes to five locations in the northern and southern hemispheres, with plans to extend to twelve 1-meter telescopes at 6 locations. The versitility and design of this network allows for rapid response to target of opportunity events as well as the long-term monitoring of slowly changing astronomical phenomena. The network's global coverage and the apertures of telescopes available make LCOGT ideal for follow-up and characterization of Solar System objects (e.g. asteroids, Kuiper Belt Objects, comets, Near-Earth Objects (NEOs)) and ultimately for the discovery of new objects.
LCOGT has completed the first phase of the deployment with the installation and commissioning of the nine 1-meter telescopes at McDonald Observatory (Texas), Cerro Tololo (Chile), SAAO (South Africa) and Siding Spring Observatory (Australia). This is complimented by the two 2-meter telescopes at Haleakala (Hawaii) and Siding Spring Observatory. The telescope network has been fully operational since May 2014, and observations are being executed remotely and robotically. Future expansion to sites in the Canary Islands and Tibet are planned for 2016.

The LCOGT near-Earth object group is using the network to confirm newly detected NEO candidates produced by the major sky surveys such as Catalina Sky Survey (CSS), PanSTARRS (PS1) and NEOWISE, with several hundred targets being followed per year. Follow-up astrometry and photometry of radar-targeted objects and those on the Near-Earth Object Human Space Flight Accessible Targets Study (NHATS) or Asteroid Retrieval Mission (ARM) lists are improving orbits, producing light curves and rotation periods, and better characterizing these NEOs. Recent results include the first period determinations for several of the Goldstone-targeted NEOs. In addition, we are in the process of building a NEO portal that will allow professionals, amateurs, and Citizen Scientists to plan, schedule, and analyze NEO imaging and spectroscopy observations and data using the LCOGT Network and to act as a coordination hub for the NEO follow-up efforts.

**Author(s): Sarah Greenstreet[2]**, Tim Lister[2], Edward Gomez[2], Eric Christensen[1], Steve Larson[1]
**Institution(s):** *1. Catalina Sky Survey, 2. Las Cumbres Observatory Global Telescope Network*

### 308.13 – Searching for a Differentiated Asteroid Family: A Spectral Survey of the Massalia, Merxia, and Agnia Families

Asteroid families were formed by catastrophic collisions or large cratering events that caused fragmentation of the parent body and ejection of asteroidal fragments with velocities sufficient to prevent re-accretion. Due to these formation processes, asteroid families should provide us with the opportunity to probe the interiors of the former parent bodies. Differentiation of a large initially chondritic parent body is expected to result in an "onion shell" object with an iron-nickel core, a thick olivine-dominated mantle, and a thin plagioclase/pyroxene crust. However, most asteroid families tend to show similar spectra (and therefore composition) among the members. Spectroscopic studies have observed a paucity of metal-like materials and olivine-dominated assemblages within the Main Belt asteroid families.
The deficit of olivine-rich mantle material in the meteorite record and in asteroid observations is known as the "Missing Mantle" problem. For years the best explanation has been the "battered to bits" hypothesis: that all differentiated parent bodies (aside from Vesta) were disrupted very early in the Solar System and the resulting olivine-rich material was collisionally broken down over time until the object diameters fell below our observational limits. In a competing hypothesis, Elkins-Tanton et al. (2013) have suggested that previous work has overestimated the amount of olivine produced by the differentiation of a chondritic parent body. We are conducting a visible and near-infrared wavelength spectral survey of asteroids in the Massalia, Merxia, and Agnia S-type Main Belt asteroid families. These families were carefully chosen for the proposed spectroscopic survey because they have compositions most closely associated with a history of thermal metamorphism and because they represent a range of collisional formation scenarios. In addition, the relatively young ages (under 400 Myr) of these families permit testing of the “battering to bits" timescale. We will present initial results from our ongoing spectral survey of these three Main Belt families and discuss evidence for differentiation among the family members.
We acknowledge funding support from the NASA Planetary Astronomy program.

**Author(s): Cristina A. Thomas3**, Lucy Lim[2], Nicholas Moskovitz[1], David Trilling4
**Institution(s):** *1. Lowell Observatory, 2. NASA GSFC, 3. NASA GSFC/USRA, 4. Northern Arizona University*

### 308.14 – Public Archiving and Curation of Spacewatch Data

Image data from Spacewatch's astrometry of asteroids date back to 1985. At this meeting we introduce data from the most voluminous mode of operation of Spacewatch to the web for public access. The survey with the Spacewatch 0.9-meter telescope has good astrometric and photometric accuracy and revisits the same cohorts of main belt asteroids at 4-day intervals by migrating the telescope pointings appropriately. This pattern has made possible multi-night prediscovery detections ("precoveries") of Near Earth Objects (NEOs) when they were distant, slowly moving, and therefore originally unnoticed, and is a similarly unique asset to other researches in the temporal domain. Limiting V magnitude is 20-21.5 and sky coverage is 1400 square degrees per lunation, three times per position. This survey has been in operation uniformly with the same equipment and procedure from 2003 to the present (2015), producing some 17 TB of imaging data. Processing includes documentation of instrumental parameters, bias subtraction, flat-fielding, defringing, positional registration, astrometric mapping, and indexing relevant image parameters to a searchable database. Tools for finding images that contain moving objects will be demonstrated at the meeting. Examples of applications of these data are prediscovery observations of NEOs and comets to improve knowledge of the objects' orbits. Asteroids whose orbits and albedos suggest that they might be dormant comets can also be checked for cometary features. Beyond the solar system, the cadence of the Spacewatch mosaic data will provide photometric sampling of variable stars and galaxies on time scales from tens of minutes to 12 years, a range rarely available from databases of this type.
Support of Spacewatch was/is from a JPL subcontract (2010-2011), NASA/NEOO grants, the Lunar and Planetary Laboratory, Steward Observatory, Kitt Peak National Observatory, the Brinson Foundation of Chicago, IL, the estates of R. S. Vail and R. L. Waland, and other private donors. We are also indebted to the MPC and JPL for their web services.

**Author(s): Jeffrey A. Larsen[2]**, Robert S. McMillan[1], Terrence H. Bressi[1], Ronald A. Mastaler[1], James V. Scotti[1], Andrew F. Tubbiolo[1]
**Institution(s):** *1. Lunar and Planetary Laboratory, University of Arizona, 2. US Naval Academy*

### 308.15 – Astrometric Results of NEOs from the Characterization and Astrometric Follow-up Program at Adler Planetarium

We present astrometric results of near-Earth objects (NEOs) targeted in fourth quarter 2014 and in 2015. This is part of Adler Planetarium’s NEO characterization and astrometric follow-up program, which uses the Astrophysical Research Consortium (ARC) 3.5-m telescope at Apache Point Observatory (APO). The program utilizes a 17% share of telescope time, amounting to a total of 500 hours per year. This time is divided up into two hour observing runs approximately every other night for astrometry and frequent half-night runs approximately several times a month for spectroscopy (see poster by M. Hammergren et. al.) and light curve studies (see poster by M. J. Brucker et. al.).
Observations were made using Seaver Prototype Imaging Camera (SPIcam), a visible-wavelength, direct imaging CCD camera with 2048 x 2048 pixels and a field of view of 4.78’ x 4.78’. Observations were made using 2 x 2 binning.
Special emphasis has been made to focus on the smallest NEOs, particularly around 140m in diameter. Targets were selected based on absolute magnitude (prioritizing for those with H > 25 mag to select small objects) and a 3σ uncertainty less than 400” to ensure that the target is in the FOV. Targets were drawn from the Minor Planet Center (MPC) NEA Observing Planning Aid, the JPL What’s Observable tool, and the Spaceguard priority list and faint NEO list. As of August 2015, we have detected 670 NEOs for astrometric follow-up, on point with our goal of providing astrometry on a thousand NEOs per year. Astrometric calculations were done using the interactive software tool Astrometrica, which is used for data reduction focusing on the minor bodies of the solar system. The program includes automatic reference star identification from new-generation star catalogs, access to the complete MPC database of orbital elements, and automatic moving object detection and identification.
This work is based on observations done using the 3.5-m telescope at Apache Point Observatory, owned and operated by the Astrophysical Research Consortium. We acknowledge the support from the NASA NEOO award NNX14AL17G and thank the University of Chicago Astronomy and Astrophysics Department for

observing time in 2014.

**Author(s): Kristie A Nault[1]**, Melissa J Brucker[1], Mark Hammergren[1], Geza Gyuk[1], Mike R Solontoi[2]
**Institution(s):** *1. Adler Planetarium, 2. Lynchburg College*

### 308.16 – The Las Cumbres Observatory (LCOGT) Network for NEO and Solar System Science

Las Cumbres Observatory Global Telescope Network (LCOGT) has deployed a homogeneous telescope network of nine 1-meter telescopes to four locations in the northern and southern hemispheres, with a planned network size of twelve 1-meter telescopes at 6 locations. This 1-meter network is in addition to the two 2-meter Faulkes Telescopes that have been operating since 2005. This network is very versatile and is designed to respond rapidly to target of opportunity events and also to perform long term monitoring of slowly changing astronomical phenomena. The global coverage of the network and the apertures of telescope available make LCOGT ideal for follow-up and characterization of Solar System objects e.g. Near-Earth Objects (NEOs), comets, asteroids and Kuiper Belt Objects and also for the discovery of new objects.
LCOGT has completed the first phase of the deployment with the installation and commissioning of the nine 1-meter telescopes at McDonald Observatory (Texas), Cerro Tololo (Chile), SAAO (South Africa) and Siding Spring Observatory (Australia). The telescope network has been fully operational since 2014 May, and observations are being executed remotely and robotically. Future expansion to sites in the Canary Islands and Tibet are planned for 2016-2017.
I will describe the Solar System science research that is being carried out using the LCOGT Network with highlights from the LCOGT NEO Follow-up Network, long-term monitoring of the Rosetta spacecraft target comet 67P and comet C/2013 A1 (Siding Spring) and work on Kuiper Belt Object occultation targets, including Pluto.

**Author(s): Tim Lister[1]**, Sarah Greenstreet[1], Edward Gomez[1], Eric Christensen[2], Stephen Larson[2]
**Institution(s):** *1. Las Cumbres Observatory, 2. University of Arizona*

### 308.17 – Searching for dormant comets in the NEO region using data from the Canadian Meteor Orbit Radar

Dormant comets (DCs) are objects that appear asteroidal but have cometary origins. Earth-approaching DCs may produce dust during their final active stages which potentially are detectable as weak meteor showers at the Earth. However, identifying DCs is difficult as they are observationally indistinguishable from asteroids. Past asteroid-stream searches have produced some possible linkages between asteroids and meteor showers, the most notable being the Geminids and 3200 (Phaethon) and the Quadrantids and (196256) 2003 EH1. However, a comprehensive survey to look for all possible weak streams from recent DC activity, including dynamical formation and evolution of early dust trails has yet to be performed. Here we report on the progress of a DC meteoroid stream survey whereby we have identified all DC candidates whose orbits are such that recent (last several hundred years) dust release would be currently detectable at the Earth. We have simulated the evolution of dust trails for all candidate DC-stream objects and generate predictions for the characteristics of the associated DC shower at Earth. We then perform a cued survey for such streams among the 15 mega meteoroid orbits measured by CMOR since 2002, using a wavelet-based search algorithm with probe sizes tuned to the expected shower characteristics. The search is focused on ~300 Earth-approaching asteroids that have dynamical characteristics of comets (or asteroids in cometary orbits, ACOs). For some cases we will also discuss the connection between the meteor data and astrophysical observations of the parent body itself.

**Author(s): Quan-Zhi Ye[1]**, Peter Brown[1]
**Institution(s):** *1. The University of Western Ontario*

### 308.18 – Meteor shower forecast improvements from a survey of all-sky network observations

Meteoroid impacts are capable of damaging spacecraft and potentially ending missions. In order to help spacecraft programs mitigate these risks, NASA's Meteoroid Environment Office (MEO) monitors and predicts meteoroid activity. Temporal variations in near-Earth space are described by the MEO's annual meteor shower forecast, which is based on both past shower activity and model predictions.
The MEO and the University of Western Ontario operate sister networks of all-sky meteor cameras. These networks have been in operation for more than 7 years and have computed more than 20,000 meteor orbits. Using these data, we conduct a survey of meteor shower activity in the "fireball" size regime using DBSCAN. For each shower detected in our survey, we compute the date of peak activity and characterize the growth and decay of the shower's activity before and after the peak. These parameters are then incorporated into the annual forecast for an improved treatment of annual activity.

**Author(s): Althea V Moorhead[1]**, Glenn Sugar[2], Peter G Brown3, William J Cooke[1]
**Institution(s):** *1. NASA, 2. Stanford University, 3. University of Western Ontario*

### 308.19 – Status of The Catalina Sky Survey

The Catalina Sky Survey (CSS) continues to be a key contributor to NASA's Near-Earth Object (NEO) survey effort, accounting for 42% of all new discoveries in the last calendar year (618 of 1,478). Recent upgrades and improvements include the routine, queue-scheduled remote operation of a 1.0-m telescope principally dedicated to the follow-up of newly discovered NEOs; enhancement of the moving object detection software resulting in a 10-15% increase in efficiency; reduction in acquisition overheads resulting in ~10% higher data throughput; and changes to the data reduction pipeline which have yielded overall better data quality (flat-fielding, astrometry and photometry). Significant instrumentation upgrades to the 1.5-m telescope (MPC code G96) and 0.7-m Schmidt telescope (MPC code 703) are underway, despite significant delays in procuring science-grade 10k x 10k detectors. The G96 camera has been fully assembled in the lab, and on-sky commissioning is imminent. When complete these new cameras will increase the fields-of-view of the 1.5-m and 0.7-m by 4.0x (to 5.0 sq. deg.) and 2.4x (to 19.4 sq. deg.), dramatically expanding the nightly coverage for both telescopes.
The Catalina Sky Survey is funded by NASA's Near-Earth Object Observation program (NNX15AF79G).

**Author(s): Eric J Christensen[1]**, David Carson Fuls[1], Alex R Gibbs[1], Albert D Grauer[1], Rik E Hill[1], Jess A Johnson[1], Richard A Kowalski[1], Stephen M Larson[1], Rose G Matheny[1], Frank C Shelly[1]
**Institution(s):** *1. The University of Arizona*

### 308.20 – A systematic search for undiscovered companions to near-Earth asteroids in radar images

Radar observations have been paramount to the characterization of small (<20 km) Near-Earth Objects (NEOs), specifically with regards to asteroid trajectories, shapes, spins, and multi-component systems. Binary systems make up a sizable fraction (~16%) of the asteroid population in near-Earth space. Their formation process is understood to be rotational fission caused by the YORP effect. Possible outcomes of post-fission dynamics include contact binaries, tightly and loosely bound binaries, and asteroid pairs. Radar images have been used to identify asteroid satellites that orbit near the primary component, but relatively little attention has been paid to the detection of more distant satellites. We are conducting a systematic search for faint and/or distant satellites in the Arecibo radar data archive. To this end, we have developed a software package to identify candidate objects in radar images and to differentiate these candidates from background noise using statistical analysis; preliminary results of the search will be presented at the meeting. Possible future applications include systematic measurements of asteroid radar properties (e.g., Doppler and range extents) that could become part of an

automated data reduction pipeline.

**Author(s): M. Oliver Bowman[1]**, Jean-Luc Margot[1]
**Institution(s):** *1. University of California Los Angeles*

### 308.21 – Serendipitous Observations of Asteroids by the K2 Mission

The K2 mission is using the unique assets of the Kepler space telescope to perform long-baseline, high-cadence, high-precision photometry of targets selected by the community. Unlike the original Kepler mission, the loss of two reaction wheels requires K2 to point near the ecliptic plane. As a result, thousands of faint asteroids can be seen to pass through the target pixel masks that are downlinked to earth after each ~75-day observing campaign. I will show how these serendipitous observations of asteroids can be used to obtain lightcurves for faint (V>18) objects which are otherwise challenging to target from the ground. In particular, I will demonstrate that the data are well-suited to identify small asteroids with rotation periods near or below the ~2 hour "spin barrier". I will also highlight the K2 data of other solar system bodies, including the comets, trans-Neptunian objects and Jupiter trojans for which dedicated pixel masks have been (or will be) downlinked. Owing to its ecliptic pointing and 1.4-meter diameter mirror, K2 is offering unique time-series photometry of small solar system bodies at a precision which is unlikely to be rivaled by the future, smaller-aperture photometric missions such as TESS and PLATO.

**Author(s): Geert Barentsen[1]**
**Institution(s):** *1. NASA Ames*

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## 309 – Formation of Planets, Satellites and Small Bodies

### 309.01 – Tidal Evolution of the Moon from a High-Obliquity Fast-Spinning Earth

In the conventional Giant Impact (GI) model of lunar formation, the Moon forms primarily from the debris of the impactor that is launched into Earth orbit. This is in conflict with extremely Earth-like isotopic composition of the Moon. All pre-2012 GI models relied on the classic picture of lunar tidal evolution (e.g. Goldreich 1965, Touma and Wisdom 1994) in which angular momentum (AM) of the Earth-Moon system has been conserved since lunar formation. Cuk and Stewart (2012) showed that a high-AM Earth-Moon system can lose AM through the evection resonance between the Moon and the Sun, allowing for GIs that are more conducive to incorporating Earth material into the Moon. More recently, Lock et al. (2015) show that a very-fast spinning Earth should be heavily coupled to the protolunar disk, resulting in the uniform composition of the Moon and Earth's mantle. While the geophysical and geochemical benefits of the high-AM GI are clear, further confirmation is needed that AM loss is both likely and consistent with observed lunar orbit. Not only does the evection resonance not explain the current 5-degree lunar inclination, but Chen and Nimmo (2013) show that the conventional model of lunar spin evolution (Ward 1975) would lead to large-scale damping of lunar inclination in the past. The prospect of a past high-inclination Moon requires complete revision of lunar tidal evolution models. We use a numerical integrator that follows both the orbit and the spin of the Moon, and find that the Moon was likely in non-synchronous rotation for a prolonged period during Cassini state transition, implying inclination damping in excess of that in synchronous rotation. We propose that the Moon's composition and past large inclination can be explained by Earth's post-GI obliquity of about 70 degrees, which led to instability of lunar orbit at the Laplace plane transition (Tremaine et al. 2009), causing AM loss, Earth obliquity reduction and lunar inclination excitation. Subsequent secular resonance between Earth's spin and the Moon's orbit further reduced Earth's obliquity to its present value.

**Author(s): Matija Cuk[2]**, Sarah Stewart3, Simon Lock[1], Douglas Hamilton4
**Institution(s):** *1. Harvard U., 2. SETI Institute, 3. UC Davis, 4. University of Maryland*

### 309.02 – Dynamical Sequestration of the Moon-Forming Impactor in Co-Orbital Resonance with Earth

Recent concerns about the giant impact hypothesis for the origin of the moon, and an associated “isotope crisis” are assuaged if the impactor was a local object that formed near Earth and the impact occurred relatively late. We investigated a scenario that may meet these criteria, with the moon-forming impactor originating in 1:1 co-orbital resonance with Earth. Using N-body numerical simulations we explored the dynamical consequences of placing Mars-mass companions in various co-orbital configurations with a proto-Earth having 90% of its current mass. We modeled configurations that include the four terrestrial planets as well as configurations that also include the four giant planets. In both the 4- and 8-planet models we found that a single additional Mars-mass companion typically remains a stable co-orbital of Earth for the entire 250 million year (Myr) duration of our simulations (33 of 34 simulations). In an effort to destabilize such a system we carried out an additional 45 simulations that included a second Mars-mass co-orbital companion. Even with two Mars-mass companions sharing Earth’s orbit most of these models (28) also remained stable for the entire 250 Myr duration of the simulations. Of the 17 two-companion models that eventually became unstable 12 impacts were observed between Earth and an escaping co-orbital companion. The average delay we observed for an impact of a Mars-mass companion with Earth was 101 Myr, and the longest delay was 221 Myr. Several of the stable simulations involved unusual 3-planet co-orbital configurations that could exhibit interesting observational signatures in plantetary transit surveys.

**Author(s): Stephen J. Kortenkamp[1]**, William J Hartmann[1]
**Institution(s):** *1. Planetary Science Institute*

### 309.03 – Thermal History and Volatile Partitioning between Proto-Atmosphere and Interior of Mars Accreted in a Solar Nebula

Recent precise Hf-W chronometry of Martian meteorites reveals that Mars had likely reached the half of its present mass within 3 Myr from the birth of the solar system (Dauphas and Pourmand, 2011). Hence, the accretion is considered to almost proceed within the solar nebula associated with the capture of nebula gas components. At the same time, the impact degassing may inevitably occur because impact velocity increases high enough for such degassing when a proto-planet gets larger than around lunar size. Thus, we can expect the formation of a hybrid-type proto-atmosphere that consists of nebula gas and degassed one.
This study analyzes the thermal structure of this proto-atmosphere sustained by accretional heating by building a 1D radiative-convective equilibrium model. Raw materials of Mars are supposed to be volatile-rich on the basis of the geochemical systematics of Mars meteorites (Dreibus and Wanke, 1988). The composition of degassed component comprised of $H_2$, $H_2O$, $CH_4$, and CO is determined by chemical equilibrium with silicate and metal under the physical condition of locally heated region generated by each impact (Kuramoto, 1997). Degassed component lies beneath the nebula gas atmosphere at altitudes below the compositional boundary height that would change depending on the amount of degassed component. The accretion time is taken to be from 1 to 6 Myr.
Our model predicts that the surface temperature exceeds the liquidus temperature of rock when a proto Mars grows larger than 0.7 times of its present mass for the longest accretion time case. In this case, the magma ocean mass just after the end of accretion is 0.2 times of its present mass if heat transfer and heat sources such as short-lived radionuclides are neglected in the interior. The corresponding amount of water dissolved into the magma ocean would be around 1.8 times the present Earth ocean mass. These

results suggest that the earliest Mars would be hot enough to form deep magma oceans, which promotes the core-mantle differentiation, and wet sufficient to make a deep-water ocean.

**Author(s): Hiroaki Saito[1]**, Kiyoshi Kuramoto[1]
**Institution(s):** *1. Hokkaido University*

### 309.04 – Energy Dissipation in the Full N-Body Problem

When accounting for the dissipation of energy, systems of finite density particles may achieve minimum energy resting states that are unattainable in the classic point-mass treatment of the N-Body Problem. These aggregates serve as a model for rubble pile asteroids, protoplanetary disk grains, and planetary ring particles. Analytical studies have shown all relative equilibria, both stable and unstable, as functions of angular momentum and energy for few-N systems of spheres; this approach likely applies to larger-N systems, with mathematical and topological complexity increasing with N and with the geometrical complexity of the constituents. Using these studies as a guideline, we simulate thousands of randomly generated small-N systems in order to determine the likelihood of achieving one resting configuration over another, provided that multiple minimum energy configurations exist for a constant angular momentum. By restricting our aggregates to rigid particles whose size is small enough to not compromise the rigidity of component bodies, our study effectively probes the dynamical-mechanical properties of a wide array of small solar system aggregates. We outline the effects of energy dissipation on such systems, primarily the effects of the coefficient of restitution whose value is the cumulative sum of mechanical deformations due to impact, in order to shed light on the early evolution of rubble-pile bodies.

**Author(s): Travis S.J. Gabriel[1]**, Daniel J. Scheeres[1]
**Institution(s):** *1. University of Colorado Boulder*

### 309.05 – Accretion of Cometary Nuclei in the Solar Nebula: Boulders, Not Pebbles

Comets are the most primitive bodies in the solar system. They retain a largely unprocessed record of conditions in the primordial solar nebula 4.56 Gyr ago, including the initial accretion of dust and ice particles into macroscopic bodies. Current accretion theory suggests that ice and dust aggregates grew to pebble (cm) sizes before streaming instabilities and gravitational collapse brought these pebble swarms together as km-sized (or larger) bodies. Recent imaging of the nucleus of comet 67P/Churyumov-Gerasimenko by the Rosetta OSIRIS camera team has revealed the existence of “goose bump” terrain on the nucleus surface and lining the interior walls of large, ~200 m diameter and 180 m deep cylindrical pits. These pits are believed to be sinkholes, formed when near-surface materials collapse into voids within the nucleus, revealing the fresh comet interior on the walls of the pits. The goose bump terrain consists of 3-4 m diameter “boulders” randomly stacked one on top of another. We propose that these boulders, likely with an icy-conglomerate composition, are the basic building blocks of cometary nuclei. This is the first observational confirmation of current accretion theories, with the caveat that rather than pebbles, the preferred size range is 3-4 m boulders for objects formed in the giant planets region of the solar system. The presence of icy grains beyond the solar nebula snow-line and the large heliocentric range of the giant planets region likely contribute to the formation of these larger boulders, before they are incorporated into cometary nuclei. This work was supported by NASA through the U.S. Rosetta Project.

**Author(s): Paul R. Weissman[1]**, Michael A'Hearn[2]
**Institution(s):** *1. Planetary Science Institute, 2. University of Maryland*

### 309.06 – Formation of giant planets’ cores by classical planetesimal accretion

In the core accretion scenario for formation of giant planets, solid-cores each with a roughly ten Earth masses first form, followed by gravitational capture of massive gaseous envelopes. Although recent models favor solid core growth by accretion of centimeter-sized pebbles, classical models in which embryos grow by accretion of km-sized planetesimals have not been fully understood. We perform a suite of simulations for accretion of solid cores, using a particle-based hybrid code that we have recently developed (Morishima 2015, Icarus 260, 368). The code uses an N-body routine for interactions with planetary embryos while a large number of small planetesimals are represented by a small number of tracers and tracer–tracer interactions are handled by a statistical routine. The initial surface densities of both solid and gas are assumed to be seven times the minimum mass solar nebula. The initial planetesimal size, r_0, is varied from 100 m to 100 km. Collisions are assumed to result in either merging or hit-and-run bouncing depending on impact velocity (Genda et al. 2012), while fragmentation is ignored. We find that embryos cannot usually grow to 10 Earth masses within 2 Myr, although it can happen in some cases. For the case of r_0 = 100 m, embryos can grow up to 6-7 Earth masses although they are quickly pushed toward the central star by planetesimals. For r_0 = 100 km, embryo masses can reach only two Earth masses within 2 Myr at best as their growth is slow. The case of r_0 = 1 km is found to be most promising, as growth of embryos is fast while their inward migration is not very rapid.

**Author(s): Ryuji Morishima[1]**
**Institution(s):** *1. University of California, Los Angeles*

### 309.07 – Two- and Three-dimensional simulations of atmospheric erosion by impacts

One of the key features of Earth-sized planets in this and other systems is the presence or absence of an atmosphere. A mechanism for atmsopheric loss post-formation is erosion by hypervelocity impacts by massive objects. We are carrying out simulations of the effects of hypervelocity impacts with the aim of assessing the efficiency of the process and disentangling the effects of impact erosion from other mechanisms such as thermal escape. For our overall project, we consider three types of planets: Mars-type, Earth-type, and a "super-Earth" (8 M_earth). Surface atmospheric pressures are 1, 10, and 100 bars. Three diameters of impactors are considered (4.6, 17, and 36.8 km) with impact velocities of 2, 4, 6, and 8 times the escape velocity of the target. Impact simulations can be divided between "local" and "global" cases depending on the geometry of the impact, chiefly the impactor size relative to the target planet and the depth of the atmosphere compared to the planet's radius. The calculations discussed here are local: the curvature of the planet and the radial dependence of the gravitational field are neglected. The impact simulations are carried out with the CTH code, developed at Sandia National Laboratory. CTH is a highly advanced code widely used in the planetary science community. It utilizes adaptive mesh refinement to concentrate computational resources at locations of physical interest in the simulation, such as shockfronts and material interfaces. It makes use of material strength models and advanced tabular equations of state such as ANEOS and the SESAME library. Post-impact analysis yields fluxes of material moving at escape speed or faster through the boundaries (chiefly the upper boundary at the exobase); we integrate the flux to get the total amount of escaping material. Although we track three kinds of material (impactor, target surface, atmosphere), here we report only on the last (escaping atmosphere). We will present results from 2D and 3D simulations of impacts, primarily for the largest impactor (36.8 km diameter). This work was supported by NASA Planetary Atmospheres Program award NNX14AJ45G. Computations were carried out on the NASA Pleiades NAS cluster at NASA Ames.

**Author(s): D. G. Korycansky[2]**, Kevin J. Zahnle[1], David C. Catling3
**Institution(s):** *1. NASA Ames Reseatch Center, 2. University of California Santa Cruz, 3. University of Washington*

### 309.08 – An experimental path to constraining the origin of Jupiter’s Trojan asteroids by identifying chemical fingerprints

We present an experimental study aimed at exploring the hypothesis suggested by recent dynamical models – that the Jupiter Trojan asteroids originated in the outer solar system, were scattered by the same instability responsibility for the radical rearrangement of the giant planets, and were subsequently captured in their current location (e.g. Morbidelli *et al.*, 2005, Nesvorny *et al.*, 2013). We seek to identify spectroscopic, chemical and isotopic properties that can tie the Trojan populations to these evolutionary pathways, providing experimental support of dynamical models, and providing testable hypotheses that can feed into the design of experiments that might be performed on potential future missions to these and other primitive bodies.
We present the results of experiments devised to explore the hypothesis that Kuiper Belt Objects (KBOs) represent the parent populations of the Trojan asteroids. Numerous thin ice films composed of select solar system volatiles ($H_2O$, $H_2S$, $CH_3OH$, $NH_3$) were grown in various mixtures to simulate compositional changes of icy bodies as a function of volatility and radial distance of formation from the Sun. Subsequent processing of these icy bodies was simulated using electron irradiation and heating. Visible reflectance spectra show significant reddening when $H_2S$ is present. Mid-infrared spectra confirm the formation of non-volatile sulfur-containing molecules in the products of $H_2S$-containing ices. These experiments suggest that the presence of specific sulfur-bearing chemical species may play an important role in the colors of both the KBOs and Trojans today. Finally, we discuss the role of the silicate component expected on the surface of the Trojan asteroids (Emery *et al.*, 2006), and the implications of a surface composed of silicates in intimate contact with the nonvolatile organic residues generated by ice irradiation.
*This work has been supported by the Keck Institute for Space Studies (KISS). The research described here was carried out at the Jet Propulsion Laboratory, Caltech, under a contract with the National Aeronautics and Space Administration (NASA) and at the Caltech Division of Geological and Planetary Sciences.*

**Author(s): Jordana Blacksberg[2]**, Ahmed Mahjoub[2], Michael Poston[1], Mike Brown[1], John Eiler[1], Bethany Ehlmann[1], Kevin Hand[2], Robert W Carlson[2], Robert Hodyss[2], Ian Wong[1]
**Institution(s):** *1. California Institute of Technology, 2. Jet Propulsion Laboratory*

### 309.09 – Into coldness: Where $CO_2$ ice collisions rule planet formation

In protoplanetary disks $CO_2$ appears in solid state beyond its snowline at 10AU. Being highly abundant, it can affect the properties of collisional growth in this region of the disk.
In this work we carried out laboratory collision experiments with ~100µm $CO_2$ ice particles and a wall covered with a $CO_2$ ice layer at 80K. Collision velocities varied between 0 - 2.5 m/s.
We measured the threshold velocity of 0.04m/s between sticking and bouncing and found onset of fragmentation for velocities above 0.75m/s. Furthermore we deduced models for the coefficient of restitution and the fragmentation strength, which are consistent with the experimental data.
We conclude that $CO_2$ ice shows a similar collisional behavior as silicate dust. Compared to $H_2O$ ice the sticking velocity is an order of magnitude smaller. One consequence is the loss of any „sticking advantage“ for $H_2O$ ice particles if they are mantled with $CO_2$ ice and planetesimal growth might be preferred in the zone between the $H_2O$ snowline and the $CO_2$ snowline.

**Author(s): Grzegorz Musiolik[1]**, Jens Teiser[1], Tim Jankowski[1], Gerhard Wurm[1]
**Institution(s):** *1. Universität Duisburg-Essen*

### 309.10 – Origin of the ices agglomerated by Comet 67P/Churyumov-Gerasimenko

The nature of the icy material accreted by comets during their formation in the outer regions of the protosolar nebula is a major open question in planetary science. Some scenarios of comet formation predict that these bodies agglomerated from clathrates crystallized in the protosolar nebula. Concurrently, alternative scenarios suggest that comets accreted amorphous ice originating from the interstellar cloud. Here we show that the recent N2/CO and Ar/CO ratios measured in the coma of the Jupiter family comet 67P/Churyumov-Gerasimenko by the ROSINA instrument aboard the European Space Agency's Rosetta spacecraft can help disentangling between these two scenarios.

**Author(s): Olivier Mousis3**, Jonathan I. Lunine[1], Adrienn Luspay-Kuti5, Tristan Guillot4, Bernard Marty[2], Peter Wurz7, Mohamad Ali-Dib[6], Kathrin Altwegg7, Myrtha Hässig7, Martin Rubin7, Pierre Vernazza3, Jack H. Waite5
**Institution(s):** *1. Cornell University, 2. CRPG-CNRS, Université de Lorraine, 3. Laboratoire d'Astrophysique de Marseille, 4. Observatoire de la Côte d'Azur, 5. SWRI, 6. Université de Franche-Comté, 7. University of Bern*

### 309.11 – Comet missions and what can still be done from ground

Much of the knowledge on comet nuclei that has become available since the 1P/Halley encounters in 1986, is based on space missions. The nucleus shape and some surface parameters (topography, morphology, thermal, optical behaviour, composition) can directly be determined through remote-sensing measurements at close encounters. At present, 8 comets have been visited. The information that became available from these missions is discussed in view to its relevance for understanding solar system formation. Emphasis is put on comets 81P/Wild-2, 9P/Tempel, 103/Hartley-3 and 67P/Churyumov-Gerasimenko. Furthermore, options and prospects are discussed on how to benefit more effectively from spacecraft data. If the knowledge coming from spacecraft data is properly transferred to other comets, it will provide new means to distinguish whether differences between comets, observed in the coma, reflect differences of the nucleus or are related to different environmental conditions of the comets at the time of observation. This in turn has important implications to the question of how and where comets were formed in the early solar system. Some unknowns can only be addressed if data exist of a statistically relevant number of comets, hence may remain open for a rather long time. Options will be discussed on how to approach these questions in the future.

**Author(s): Rita Schulz[1]**
**Institution(s):** *1. ESA Scientific Support Office*

## 310 – Titan's Surface and Atmosphere

### 310.01 – Geologic Conditions Required for the Fluvial Erosion of Titan’s Craters

In comparison to other icy satellites, Titan has a small number of impact craters on its surface. This suggests that it has a young surface and/or erosional processes that remove craters from its surface. The set of geological conditions on Titan that would allow craters to become unrecognizable by orbiting spacecraft such as Cassini is unclear. Initial results suggest that not all geologic conditions would allow for complete degradation of impact craters on Titan. Using a landscape evolution model, we explored a larger parameter space to determine the conditions under which a representative 40 km crater on Titan would be eroded. We focused on varying the values of parameters such as bedrock and regolith erodibility, sediment grain size, the weathering rate of the regolith, and whether or not the regolith was saturated with liquid hydrocarbons. We found that only after changing the saturation state of the regolith mid-way through the simulation was it possible to completely erode the crater. Since there are few craters on Titan, this suggests that during Titan’s geological history there may have been varying quantities of liquid on its surface. Titan is known to have a dense atmosphere, not unlike that of the Earth, that could allow for surface liquids to vary under a changing climate. The erosion rate could then also vary as a direct result of changing climatic conditions.

**Author(s): Rebeca Kinser[1]**, Catherine Neish5, Alan Howard4, Paul Schenk[2], Veronica Bray3
**Institution(s):** *1. Florida Institute of Technology, 2. Lunar and Planetary Institute, 3. University of Arizona, 4. University of Virginia, 5. University of Western Ontario*

### 310.02 – Usefulness and Limitations of Energy Limited Escape: Titan and Other Planetary Atmospheres

Because thermal conduction and IR cooling are inefficient heat transfer processes, adiabatic expansion leading to molecular escape is often the dominant cooling process for energy deposited in the upper atmosphere of planetary bodies. This led to the use of the energy-limited escape (EL) approximation in which the loss rate is roughly proportional to the heating rate, Q. In applying the EL approximation, it was also frequently assumed that the adiabatic expansion resulted in the gas outflow going sonic. Johnson et al. (2013) used molecular kinetic simulations of an atmosphere with a heated layer to show this was not necessarily the case and estimated a critical heating rate, $Q_c$. For Q greater than ~$Q_c$ a sonic point formed below the exobase where the gas properties were collision dominated. As Q increased above ~$Q_c$ sonic escape was eventually limited by the energy and number fluxes from the below the heated layer. In that case, adiabatic cooling did dominate upper atmosphere cooling, but the escape rate did not increase with increasing Q as predicted by the EL model. Instead, the escape rate remained nearly constant and the energy per molecule carried off increased nearly monotonically with Q. For heating rates from about twice $Q_c$ to more than an order of magnitude lower, the molecular escape rate was well approximated by the energy limited rate, but the upper atmospheric structure could not be described by a fluid model with a sonic point and escape was Jeans-like although the Jeans expressions was often a poor approximation. That is, molecules escape from well below the nominal exobase and collisions remained important well above it (Tucker et al. 2009; 2013) resulting in enhanced-Jeans-like escape (Volkov et al. 2011a,b; Erwin et al. 2013). Here we give a new expression for the escape rate produced by adiabatic cooling and expansion of the upper atmosphere and apply it to atmospheric loss from an early Titan atmosphere and related atmospheres.
Ref.: Erwin,J.T., et al.Icarus 226,375(2013);Johnson,R.E. et al.,ApJL768, L4(6pp);Errat:ApJL774,90(2013); Tucker,O.J. et al. PSS57,1889 (2009); Tucker,O.J., et al.Icarus 222,149(2013). Volkov,A.N., et al.Ap.J.Lett.729,L24(5pp)(2011a); ibid Phys. Fluids 23(2011b)

**Author(s): Robert E. Johnson[1]**, Alexey N Volkov[2], Orenthal J. Tucker3
**Institution(s):** *1. Univ. of Virginia, 2. University of Alabama, 3. University of Michigan*

### 310.03 – Titan's Seasonal Haze Variation from HST-STIS Image Cubes

Five STIS image cubes of Titan taken between 1997 and 2004 constrain Titan's seasonal haze variations during the season before the arrival of Cassini. Each image cubes contains wavelengths 530-1020 nm at 0.5 nm sampling with up to 0.05 arc-sec sampling in both spatial dimensions. By comparing reflectivities between different dates stepping from the continuum wavelengths into methane bands, we determined the changing physical parameters and the size and phase of the variation, including its altitude.
While Titan's north-south asymmetry is well know to change with Titan's seasons, HST and VIMS data showed its phasing to be spectrally dependent suggesting that the asymmetry does not change simultaneously at all altitudes.
Our principal component analysis of the STIS cubes revealed that the north-south asymmetry is separated in two distinct components, a larger component describing changes at altitudes below 80+/-20 km and a smaller component describing changes at altitudes above 150+/-50 km. Altitudes in between did not show any change at any latitude.
Both components have a different phasing, explaining phase shifts with wavelengths noted above. The high-altitude component switched the hemispherical asymmetry in 2001. The low-altitude component had a rolling asymmetry change, in 2002 at low altitudes, in 2003 at mid latitude, and in early 2004 at high altitudes.
Both components are due to variations of the aerosol opacity that are probably driven by global dynamics. The first component may also be partially due to a variation in the aerosol phase function and aerosol size, which may be due to variable condensation of gases such as HCN onto aerosols.
Equatorial latitudes have above average haze opacities at high altitudes but below average at low altitudes.
A new haze model gives the haze opacity as function of altitude, latitude, and time and fits the HST data well and even fits some Cassini results obtained after the HST observations fairly well. It predicts the next hemispherical asymmetry switch to occur in 2016 at high altitudes and 2017 through 2018 at low altitudes.
Deails are currently being published in the Icarus special issue on Titan. This research was supported by STScI through program AR12624.

**Author(s): Erich Karkoschka[1]**
**Institution(s):** *1. Univ. of Arizona*

### 310.04 – Titan's aerosol optical properties with VIMS observations at the limb of Titan

The study of Titan properties with remote sensing relies on a good knowledge of the atmosphere properties. The in-situ observations made by Huygens combined with recent advances in the definition of methane properties enable to model and interpret observations with a very good accuracy. Thanks to these progresses, we can analyze in this work the observations made at the limb of Titan in order to retrieve information on the haze properties as its vertical profiles but also the spectral behaviour between 0.88 and 5.2 µm.
To study the haze layer and more generally the source of opacities in the stratosphere, we use som observation made at the limbe of Titan by the VIMS instrument onboard Cassini. We used a model in spherical geometry and in single scattering, and we accounted for the multiple scattering with a parallel plane model that evaluate the multiple scattering source function at the plane of the limb.
Our scope is to retrieve informations about the vertical distribution of the haze, its spectral properties, but also to obtain details about the shape of the methane windows to disantangle the role of the methane and of the aerosols.
We started our study at the latitude of 55°N, with a image taken in 2006 with a relatively high spatial resolution (for VIMS). Our preliminary results shows the spectral properties of the aerosols are the same whatever the altitude. This is a consequence of the large scale mixing. From limb profile between 0.9 and 5.2 µm, we can probe the haze layer from about 500 km (at 0.9 µm) to the ground (at 5.2 µm). We find that the vertical profile of the haze layer shows three distinct scale heights with transitions around 250 km and 350 km. We also clearly a transition around 70-90 km that may be due to the top of a condensation layer.

**Author(s): Pascal Rannou3**, Benoit Seignovert3, Panayotis Lavvas3, Stéphane Lemouelic[2], Christophe Sotin[1]
**Institution(s):** *1. JPL/NASA, 2. LPGN/Université de Nantes, 3. University of Reims-Champagne Ardenne*

### 310.05 – Microphysical Modeling of Titan's Detached Haze Layer in a 3D GCM

We investigate the formation and seasonal cycle of the detached haze layer in Titan’s upper atmosphere using a 3D GCM with coupled aerosol microphysics. The base of the detached haze layer is defined by a local minimum in the vertical extinction profile. The detached haze is seen at all latitudes including the south pole as seen in Cassini images from 2005–2012. The layer merges into the winter polar haze at high latitudes where the Hadley circulation carries the particles downward. The hemisphere in which the haze merges with the polar haze varies with season. We find that the base of the detached haze layer occurs where there is a near balance between vertical winds and particle fall velocities. Generally the vertical variation of particle concentration in the detached haze region is simply controlled by sedimentation, so the concentration and the extinction vary roughly in proportion to air density. This variation explains why the upper part of the main haze layer, and the bulk of the detached haze layer follow exponential profiles. However, the shape of the profile is modified in regions where the vertical wind velocity is comparable to the particle fall velocity. Our simulations closely match the period when the base of the detached layer in the tropics is observed to begin its seasonal drop in altitude, and the total range of the altitude drop. However, the simulations have the base of the detached layer about 100 km lower than observed, and the time for the base to descend is slower in the simulations than observed. These differences may point to the model having somewhat lower vertical winds than occur on Titan, or somewhat too large of particle sizes, or some combination of both. Our model is consistent with a dynamical origin for the detached haze rather than a chemical or microphysical one. This balance between the vertical wind and particle fall velocities occurs throughout the summer hemisphere and tropics. The particle concentration gradients that are established in the summer hemisphere are transported to the winter hemisphere by meridional winds from the overturning Hadley cell. Our model is consistent with the disappearance of the detached haze layer in early 2014.

**Author(s): Erik J. Larson[2]**, Owen B Toon[2], Robert A West[1], A. James Friedson[1]
**Institution(s):** *1. Jet Propulsion Laboratory, 2. University of Colorado*

### 310.06 – Comparing the Treatment of Spherical and Fractal Particles in Titan's Atmosphere using CARMA

The nature of Titan's optically thick haze is of great interest in the study of its atmosphere. In an attempt to further understand the particle distribution and radiative properties of this haze we applied the Community Aerosol and Radiation Model for Atmospheres (CARMA), originally designed for Earth, to simulate the microphysical and radiative transfer properties of Titan's atmosphere. In the past, the model treated the haze particles as spheres, however, it is more accurate to treat the haze particles as fractals (Lavvas et al. 2010). We first simulated spherical particles to verify the model's consistency with past studies (i.e. Toon et al. 1992). We then ran simulations considering fractal haze particles. In both instances we considered a 600km atmosphere with a production zone centered at 300km from the surface. These particles, initially 0.0013 μm in radius, are then subject to vertical transport and coagulation processes affecting the size, number, and distribution of the particles. Our results for both cases show that for wavelengths of 550nm the optical depth and extinction of the atmosphere rapidly decreases above 400km, however, there is a greater concentration of fractal particles at altitudes above 400km than spherical particles by at least two orders of magnitude. Initial results indicate that above 400km there were approximately 2x105 fractal particles/cm3 whereas there were only at most 1x103 spherical particles/cm3 corresponding with a greater cumulative optical depth of Titan's atmosphere for fractal particles than spherical particles. The full effects of these results on the cumulative optical depth of the atmosphere are still being explored. This work was funded by the NASA Outer Planets research program.

**Author(s): Alexander Lanzano[1]**, Erika Barth[2]
**Institution(s):** *1. Laboratory for Atmospheric and Space Physics, 2. Southwest Research Institute*

### 310.07 – Soundings of Titan's atmosphere by Cassini using the two-way radio occultation technique

In December 2011 the Ultra Stable Oscillator aboard Cassini failed, and all subsequent radio occultations have been done using the two-way technique. The two-way technique uses a highly stable frequency reference on the ground rather than the on board USO. A pure X band tone is transmitted to the spacecraft, and that uplink signal as Cassini receives it is used as the frequency reference for the three returned S, X, and Ka band tones transmitted by the spacecraft. On May 17 and June 18 of 2014 two occultations of Cassini by Titan occured, during targeted Titan encounters T101 and T102, and were done using the two-way technique for the first time for Titan occultations. We present the four soundings of Titan's atmosphere obtained from the resulting data using the two way numerical inversion technique described in Schinder et al., Radio Science 50, 712. The ingress occultation on T101 occured at 66 N latitude and egress is at 46 S. On T102, ingress occured at 63 N and 66 S latitude. We will also place these results in context with the earlier Titan occultations (Schinder et al., Icarus 215, 460; Schinder et al., Icarus 221, 1020) done in one way mode.

**Author(s): Paul J. Schinder[1]**, F Michael Flasar3, Essam Marouf4, Richard French5, Aseel Anabtawi[2], Elias Barbinis[2]
**Institution(s):** *1. Cornell Univ., 2. Jet Propulsion Laboratory, 3. NASA Goddard Space Flight Center, 4. San Jose State University, 5. Wellesley College*

### 310.08 – Seasonal variations of temperature and composition at the Titan poles

We present an analysis of spectra acquired by Cassini/CIRS at high resolution from October 2010 until September 2014 in nadir mode ([1] & refs therein). Since 2010 we have observed the appearance at Titan's south pole of several trace species for the first time, such as $HC_3N$ and $C_6H_6$, observed only at high northern latitudes before equinox. We investigate here latitudes poleward of 50°S and 50°N from 2010 (after the Southern Autumnal Equinox) until 2014. For some of the most abundant and longest-lived hydrocarbons ($C_2H_2$, $C_2H_6$ and $C_3H_8$) and $CO_2$, the evolution in the past 4 years at a given latitude is not significant within error bars until mid-2013. More recently, these molecules show a trend for increase in the south. This trend is dramatically more pronounced for the other trace species, especially in 2013-2014, and at 70°S relative to 50°S. These two regions then demonstrate that they are subject to different dynamical processes in and out of the polar vortex region. For most species, we find higher abundances at 50°N compared to 50°S, with the exception of $C_3H_8$, $CO_2$, $C_6H_6$ and $HC_3N$, which arrive at similar mixing ratios after mid-2013. While the 70°N data show generally no change except a small decrease for most species within 2014, the 70°S results indicate a strong enhancement in trace stratospheric gases after 2012. The 663 $cm^{-1}$ $HC_3N$ and the $C_6H_6$ 674 $cm^{-1}$ emission bands appeared in late 2011/early 2012 in the south polar regions and have since then exhibited a dramatic increase in their abundances. At 70°S $HC_3N$, HCN and $C_6H_6$ have increased by 3 orders of magnitude over the past 3-4 years while other molecules, including $C_2H_4$, $C_3H_4$ and $C_4H_2$, have increased less sharply (by 1-2 orders of magnitude). This is a strong indication of the rapid and sudden buildup of the gaseous inventory in the southern stratosphere during 2013-2014, as expected as the pole moves deeper into winter shadow. Subsiding gases that accumulate in the absence of ultraviolet sunlight, evidently increased quickly since 2012 and some of them may also be responsible for the reported haze decrease in the north and its appearance in the south at the same time.
Reference : [1] Coustenis et al., 2015. Icarus, doi: 10.1016/j.icarus.2015.08.027

**Author(s): Athena Coustenis3**, Donald E. Jennings4, Richard K. Achterberg4, Georgios Bampasidis[1], Panayiotis Lavvas[2], Conor A. Nixon4, Nicholas A. Teanby5, Valeria Cottini4, Carrie M. Anderson4, F. Michael Flasar4
**Institution(s):** *1. Faculty of Physics, National and Kapodistrian University of Athens, 2. GSMA, Université Reims Champagne-Ardenne, 3. Laboratoire d'Etudes Spatiales et d'Instrumentation en Astrophysique (LESIA), Observatoire de Paris, PSL-Research Univ., CNRS, Univ. Pierre et Marie Curie Paris 06, Sorbonne Univ., Univ. Paris-Diderot, 4. NASA Goddard Space Flight Center, 5. School of Earth Sciences, University of Bristol,*

### 310.09 – Titan's Gas Behavior During the South Pole Fall

Titan's southern middle atmosphere has been showing several changes since the start of fall season in 2009. In 2012 a large cloud appeared [1], [2], [3], temperatures became very low and condensation and gas concentration at the South Pole increased [3], [4].

In this work we will show the results of gas abundances retrievals in the South Pole and their latitudinal variation changes as the cold season evolved with time.
We analyzed several Cassini Composite InfraRed Spectrometer (CIRS [5]) mid-infrared observations of the South Pole acquired during 2013-2014. The data coordinates were converted in order to be centered on the atmospheric pole and refer to the 1 mbar level and not to the surface. We first determine stratospheric temperatures from the same data and latitudes from the $n_4$ band of methane centered around 1300 $cm^{-1}$. We retrieve the temperature profiles applying a radiative transfer forward model combined with a non-linear optimal estimation inversion method [6]. We then retrieve the main gases abundances and track their variation with latitude using the same method.
Latitudinal changes of the main Titan's gases - $HC_3N$, $C_4H_2$, $C_6H_6$, $C_2H_2$, $C_2H_4$, $C_3H_8$ and HCN - show different trends in the Southern polar regions over 2014, when winter was getting closer. We observe a ring-shape in some of the gas abundance distributions, with a local maximum peak around -75 deg of latitude. We also observe an increase of abundance of most of the gases toward the south pole, as seen previously in the North during the winter. The observed increase of benzene over the South Pole is definitely evident and strong. **References:** [1] West, R. A. et al. (2013) *BAAS*, 45, 305.03. [2] Jennings, D. E. et al. (2012) *ApJ*, 754, L3. [3] de Kok, R. et al. (2014), *Nature*, 514, 7520, 65-67. [4] Vinatier S. et al. (2015) *Icarus,* Volume 250, p. 95-115. [5] Flasar et al. (2004) *Space Sci. Rev.*, 115, 169–297. [6] Irwin, P.G.J. et al. (2008) *J. Quant. Spectrosc. Radiat. Trans.*, 109, 1136–1150.

**Author(s): Valeria Cottini3**, Conor A. Nixon2, Richard K. Achterberg3, Donald E. Jennings2, Nicolas Gorius1, Patrick G J. Irwin4
**Institution(s):** *1. Catholic University of America, 2. NASA GSFC, 3. University of Maryland, 4. University of Oxford*

### 310.10 – Seasonal evolution of tropospheric $H_2$ on Titan from the Cassini CIRS investigation

Far-infrared Titan spectra obtained with the Composite Infra-Red Spectrometer on the Cassini spacecraft have been analyzed to study the latitude distribution of $H_2$ in the troposphere, as well as its temporal evolution over the period from March 2007 to August 2014. This analysis shows that the previously observed distribution, characterized by a 30%-70% enhancement at high Northern latitudes, has become more symmetrical since Equinox. Hence, the reversed pole-to-pole Hadley cell circulation established shortly after Equinox has been effective in equilibrating the $H_2$ mole fraction in both polar regions, although not effective enough to produce a reversal of the polar enhancements probably because of a long time constant for the transport of air masses from the stratosphere to the troposhere.

**Author(s): Régis Courtin1**
**Institution(s):** *1. LESIA - Observatoire de Paris*

### 310.11 – The Non-LTE Model of IR Emissions of Methane in the Titan's Atmosphere

Above about 400-450 km in Titan's atmosphere, the assumption of local thermodynamic equilibrium (LTE) breaks down for molecular vibrational levels of methane and various trace gases. Above this altitude non-LTE significantly impacts the formation of infrared ro-vibrational band emissions of these species observed in the limb viewing geometry. We present detailed model of the non-LTE in methane in the Titan's atmosphere based on a new extended database of the CH4 spectroscopic parameters calculated for this study. We analyze vibrational temperatures of various 12CH4 and 13CH4 levels as well as CH4 limb emissions in the 7.6 and 3.3 um spectral regions. The impact on these emissions of many weak one-quantum and combinational bands, which are missing in current databases, is studied. Implications for the non-LTE diagnostics of the Cassini CIRS and VIMS measurements are discussed.

**Author(s): Alexander Kutepov5**, Ladislav Rezac4, Artem Feofilov1, Michael Rey2, Andrei Nikitin3, Vladimir Tyuterev2
**Institution(s):** *1. Centre National de la Recherche Scientifique/École Polytechnique, 2. Groupe de Spectrométrie Moléculaire et Atmosphérique, UMR CNRS, 3. Laboratory of Theoretical Spectroscopy, Institute of Atmospheric Optics, 4. Max Planck Institute for Solar System Study, 5. The Catholic University of America*

### 310.12 – Transmission windows in Titan's lower troposphere: Implications for IR spectrometers aboard future aerial and surface missions

Titan's thick atmosphere contains a 1.5 - 5.7% methane mole fraction. Methane's possession of fundamental, overtone, and combination bands across much of the near and mid IR results in significant absorption in the atmosphere across this spectral region. The consequence is spectral windowing, such that Titan's surface can only be observed at a handful of methane transmission windows. The narrow width of these windows for observations from the top of the atmosphere (ToA) make only multispectral imaging of the surface possible. This limits the information that can be gleaned about the surface composition, which remains largely unknown. From ToA, there is effectively zero transmission at most wavelengths between the windows, so that improvements to the detectors or telescopes of IR spectrometers aboard orbital or flyby missions would not result in any appreciable widening of the windows. Only decreasing the methane column through which observations are made, with a future mission operating near or on the surface, would result in any widening of the windows. We present a new line-by-line radiative transfer model to quantify the window widths for an IR spectrometer aboard an aerial or surface mission to Titan. We take spectral line parameters from the HITRAN database (Rothmann et al. 2013) for methane and six trace gases, include N2-N2 and N2-H2 collision-induced absorptions as measured by McKellar 1989, and the haze extinction measured in situ by Huygens DISR. The number of vertical layers in the model is chosen to correspond with the high cadence of measurements of the physical conditions of Titan's atmosphere by Huygens HASI. We find that the transmission windows do not widen appreciably for an aerial mission operating at altitudes on the order of kilometers above the surface. For surface missions observing at distances of order 10 m, the windows widen considerably to encompass regions where absorptions from hydrated minerals, sulfates, and pentane and higher order alkanes could be detected with hyperspectral observations. We thus suggest that infrared remote sensing from surface rather than aerial platforms would be considerably better suited for characterizing Titan's surface composition.

**Author(s): George D McDonald2**, Paul M Corlies1, James J Wray2, Jason D Hofgartner1, Sarah M Hörst3, Alexander G Hayes1, Lucas R Liuzzo2, Jacob J Buffo2
**Institution(s):** *1. Cornell University, 2. Georgia Institute of Technology, 3. Johns Hopkins University*

### 310.13 – Lifting Entry & Atmospheric Flight (LEAF) System Concept Applications at Solar System Bodies With an Atmosphere

Northrop Grumman and L'Garde have continued the development of a hypersonic entry, semi-buoyant, maneuverable platform capable of performing long-duration (months to a year) in situ and remote measurements at any solar system body that possesses an atmosphere.
The Lifting Entry & Atmospheric Flight (LEAF) family of vehicles achieves this capability by using a semi-buoyant, ultra-low ballistic coefficient vehicle whose lifting entry allows it to enter the atmosphere without an aeroshell. The mass savings realized by eliminating the heavy aeroshell allows significantly more payload to be accommodated by the platform for additional science collection and return.
In this presentation, we discuss the application of the LEAF system at various solar system bodies: Venus, Titan, Mars, and Earth. We present the key differences in platform design as well as operational differences required by the various target

environments. The Venus implementation includes propulsive capability to reach higher altitudes during the day and achieves full buoyancy in the mid-cloud layer of Venus' atmosphere at night. Titan also offers an attractive operating environment, allowing LEAF designs that can target low or medium altitude operations, also with propulsive capabilities to roam within each altitude regime. The Mars version is a glider that descends gradually, allowing targeted delivery of payloads to the surface or high resolution surface imaging. Finally, an Earth version could remain in orbit in a stowed state until activated, allowing rapid response type deployments to any region of the globe.

**Author(s): Greg Lee[1]**, Ronald Polidan[1], Floyd Ross[1], Daniel Sokol[1], Steve Warwick[1]
**Institution(s):** *1. Northrop Grumman*

### 310.14 – Titan Science with the James Webb Space Telescope

The James Webb Space Telescope (JWST), scheduled for launch in 2018, is an ambitious next-generation large-aperture (6.5 m) space observatory focused on pushing the boundaries of infrared astronomy (0.6-28.0 μm). This long-wavelength focus gives it very substantial potential for solar system science, since the thermal emissions from the surfaces and atmospheres of many planets, moons and small bodies peak in this part of the spectrum. Here we report the findings of a task team convened to examine the potential for Titan science using JWST. These can be divided into five broad areas: (i) the surface, especially the rotational lightcurve; (ii) clouds in the lower atmosphere from direct imaging and near-IR spectroscopy; (iii) composition of the lower atmosphere, especially methane relative humidity; (iv) composition of the middle atmosphere, including thermal and fluorescent emissions from gases; (v) hazes in the middle atmosphere, including seasonal changes in hemispheric contrast. The capability of the major JWST instruments in each area is considered, and limitations such as potential saturation is noted and mitigation strategies (such as sub-arraying) discussed. Overall we find that JWST can make significant contributions to Titan science in many areas, not least in temporal monitoring of seasonal change after the end of the Cassini mission in 2017, in partnership with other next-generation observing facilities (TMT, GMT, EELT, ALMA).

**Author(s): Conor A. Nixon[6]**, Richard Achterberg[12], Mate Adamkovics[11], Bruno Bezard[7], Gordon Bjoraker[6], Thomas Cornet[2], Alexander Hayes[1], Emmanuel Lellouch[7], Mark Lemmon[8], Manuel Lopez Puertas[3], Sebastien Rodriguez[9], Christophe Sotin[5], Nicholas Teanby[10], Elizabeth Turtle[4], Robert West[5]
**Institution(s):** *1. Cornell University, 2. ESA ESAC, 3. Instituto de Astrofisica de Andalucia, 4. JHU APL, 5. JPL/Caltech, 6. NASA GSFC, 7. Observatoire de Paris, 8. Texas A&M University, 9. Universite Paris-Diderot, 10. University of Bristol, 11. University of California, 12. University of Maryland*

### 310.15 – Vertical Profiles and Isotopic Ratios in HCN and its Isotopologues from ALMA Observations of Titan

The photodissociation of methane ($CH_4$) and molecular nitrogen ($N_2$) provides the raw materials to create a suite of nitriles in Titan's atmosphere; the simplest and most abundant of these is hydrogen cyanide (HCN). The unprecedented sensitivity and spectral resolution of the Atacama Large Millimeter/Sub-millimeter Array (ALMA) permits the characterization of rotational transitions in this molecule and many of its isotopologues. In this study we leverage publicly available ALMA calibration observations of Titan taken between April and July 2014, each lasting around 160 seconds. We report the detection of a new HCN isotopologue on Titan, $H^{13}C^{15}N$, and use this along with high signal-to-noise observations of HCN, $H^{13}CN$, $HC^{15}N$, and DCN to determine the isotopic ratios $^{13}C/^{12}C$, $^{15}N/^{14}N$, and D/H. Isotopic ratios are known to diverge throughout the solar system in planetary atmospheres due to a variety of processes, including mass-dependent escape, photochemistry, and condensation. Therefore, accurate knowledge of isotopic ratios can provide important constraints on models of the origin and evolution of planetary atmospheres.

**Author(s): Edward M. Molter[1]**, Conor A. Nixon[1], Martin A. Cordiner[1], Steven B. Charnley[1], Patrick G. J. Irwin[2], Joseph Serigano[1], Nicholas A. Teanby3
**Institution(s):** *1. NASA Goddard Space Flight Center, 2. Oxford University, 3. University of Bristol*

### 310.16 – Spectral Maps of Titan's Surface

Titan's surface can be observed most clearly at 7 spectral regions that lie in between the strong methane bands in Titan's spectrum. Within these "windows", between 0.8 to 5 microns, the surface is nonetheless obscured by methane and haze, the latter of which is optically thick at lower wavelengths. Studies of Titan's surface must eliminate the effects of atmospheric extinction, which particularly at high latitudes, are not well constrained. A more general challenge in the study of planetary surfaces is the extraction of subtle spectral features from a large quantity of low-resolution data, which have dominant spectral trends, upon which lesser trends reside. This characteristic (a dominant spectral trend) is seen in Titan's data: images at all 7 wavelengths appear essentially the same, with the bright terrain relatively bright at all wavelengths and vise versa. The question arises as to how to discern and map the smaller and orthogonal spectral trends of Titan's surface in order to investigate the composition. Towards this goal we have constructed spectral maps of Titan's surface by minimizing the covariance matrix of the I/F values (and separately the surface albedo) at the 7 window wavelengths. This application of the Principal Components Analyses (PCA) yields the orthogonal spectral trends based on the variance of the I/F values, and, separately, the surface albedos derived from radiative transfer models. Here we will present some of the interesting spectral trends detected through the application of this method to small sections of Titan's surface.

**Author(s): Caitlin Ann Griffith[1]**, Paulo Penteado[1], Jake D Turner[2], Tymon Khamsi[1], Nicholas J. Montiel[1]
**Institution(s):** *1. University of Arizona , 2. University of Virginia*

### 310.17 – Titan's Length-of-Day Variations

The Cassini radar observation of Titan over several years show that the rotation period is slightly faster than the synchronous motion (Lorenz et al. 2008; Stiles et al. 2008 and 2011; Meriggiola 2012). The seasonal variation in the mean and zonal wind speed and direction in Titan's lower troposphere causes the exchange of a substantial amount of angular momentum between the surface and the atmosphere (Tokano and Neubauer, 2005; Richard et al. 2014). The rotation variation is affected by the influence of the atmosphere when we assume that Titan is a differentiated body and the atmosphere interacts only with the outer layer.
In this work, we calculate variations of Titan's length-of-day when the body is formed by two independent rotating parts and assuming that friction occurs at the interface of them. The tides are considered using the extension of two different theories -- the Darwin tide theory and Ferraz-Mello's creep tide theory -- to the case of one body formed by two homogeneous parts. The results are compared and their differences are discussed.

**Author(s): Hugo Alberto Folonier[1]**, Sylvio Ferraz-Mello[1]
**Institution(s):** *1. IAG-USP*

### 310.18 – FT-IR measurements of mid-IR propene ($C_3H_6$) cross sections and far-IR ammonia ($NH_3$) line intensities

We present spectroscopy measurements of propene ($C_3H_6$) in the mid-infrared and ammonia ($NH_3$) in the far-infrared from two different laboratory studies. **[1]** For propene ($CH_2$-CH-$CH_3$, *alias*. propylene), which was detected in the stratosphere of Titan [*Nixon et al. 2013*], temperature dependent cross sections in the 650 – 1530 $cm^{-1}$ (6.5 – 15.3 μm) have been measured from a series of high-resolution (0.0022 $cm^{-1}$) spectra of pure and $N_2$-mixture samples of $C_3H_6$ recorded at 150 – 296 K at Jet Propulsion Laboratory. The observed spectral features cover the strongest $\nu_{19}$

band with its outstanding Q-branch peak at 912 cm$^{-1}$ and three other strong bands of $\upsilon_{18}$, $\upsilon_{16}$ and $\upsilon_7$ at 990, 1442, and 1459 cm$^{-1}$, respectively. In addition, we have generated a HITRAN-format empirical '*pseudoline list*' containing line positions, intensities, and effective lower state energies by fitting all the observed spectra simultaneously. The results are compared with early work from relatively warm temperatures (278 – 323 K). **[2]** For ammonia ($NH_3$), we obtained multiple sets of high-resolution spectra in the THz and far-infrared region (50 – 650 cm$^{-1}$) at room temperature using AILES beamline at Synchrotron SOLEIL, France ($NH_3$). In this work, we have measured line intensities for more than 4500 transitions, and made quantum assignments for ~2900 lines including ~960 very weak $\Delta K = 3$ forbidden lines. Final results will be compared with the current databases (e.g., HITRAN, GEISA) and *ab initio* calculations. [*Research described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. Sung and Yu acknowledge the Synchrotron Soleil for the AILES beam line time.*]

**Author(s): Keeyoon Sung[2]**, Geoffrey C. Toon[2], Timothy J. Crawford[2], Shanshan Yu[2], John C. Pearson[2], Fridolin Kwabia Tchana[1], Laurent Manceron[1], Olivier Pirali[1]
**Institution(s):** *1. CNRS-Univ. Paris Est, 2. Jet Propulsion Laboratory*

## 311 – Jovian Planets Atmospheres and Interiors

### 311.01 – Uranus' Persistent Patterns and Features from High-SNR Imaging in 2012-2014

Since 2012, Uranus has been the subject of an observing campaign utilizing high signal-to-noise imaging techniques at Keck Observatory (Fry et al. 2012, Astron. J. 143, 150-161). High quality observing conditions on four observing runs of consecutive nights allowed longitudinally-complete coverage of the atmosphere over a period of two years (Sromovsky et al. 2015, Icarus 258, 192-223). Global mosaic maps made from images acquired on successive nights in August 2012, November 2012, August 2013, and August 2014, show persistent patterns, and six easily distinguished long-lived cloud features, which we were able to track for long periods that ranged from 5 months to over two years. Two at similar latitudes are associated with dark spots, and move with the atmospheric zonal flow close to the location of their associated dark spot instead of following the flow at the latitude of the bright features. These features retained their morphologies and drift rates in spite of several close interactions. A second pair of features at similar latitudes also survived several close approaches. Several of the long-lived features also exhibited equatorward drifts and latitudinal oscillations. Also persistent are a remarkable near-equatorial wave feature and global zonal band structure. We will present imagery, maps, and analyses of these phenomena.
PMF and LAS acknowledge support from NASA Planetary Astronomy Program; PMF and LAS acknowledge funding and technical support from W. M. Keck Observatory. We thank those of Hawaiian ancestry on whose sacred mountain we are privileged to be guests. Without their generous hospitality none of our groundbased observations would have been possible.

**Author(s): Patrick M. Fry[2]**, Lawrence A Sromovsky[2], Imke de Pater3, Heidi B Hammel[1], Phillip Marcus3
**Institution(s):** *1. AURA, 2. Univ. of Wisconsin, 3. University of California*

### 311.02 – Uranus' Hemispheric Asymmetries in Polar Cloud and Circulation Structures

We report on the north polar region of Uranus in the post-equinoctial era. Near-IR imaging with Keck 2 using NIRC2 in 2012-2014 revealed numerous small bright features, as well as small dark features, between 50 degrees N and the north pole. Tracking of these features yielded circulation patterns, with the remarkable result that the region from 60 degrees to at least 83 degrees rotates about the northern pole as a solid body, with a drift rate of 4.1 degrees/hour westward relative to the interior (Sromovsky et al. 2015, Icarus 258, 192-223). For the south pole, the same latitude region had dramatically different characteristics, as judged by 1986 Voyager and 2003 Keck observations. The southern region showed no discrete near-IR features; detailed circulation measurements in that region were based solely on low-contrast features in re-analyzed Voyager images (Karkoschka, 2015, Icarus 250, 294-307). They revealed a large gradient in drift rates, with values reaching twice that seen in the corresponding northern region.
The north-south asymmetry in circulation and cloud structure/morphology is surprising because the distribution of upper tropospheric methane is relatively symmetric: roughly constant over a region from 30 S to 30 N, and then declining at higher latitudes in both hemispheres. The methane distribution suggests symmetric down-welling motion in both polar regions, which would inhibit formation of condensation clouds there, in contrast to the observed dichotomy. Some asymmetry may be an effect of seasonal forcing, since the north versus south polar measurements were made during different seasons. If so, then major changes can be expected in the north polar region as Uranus proceeds toward its 2030 northern summer solstice. Hubble STIS observations expected in October of 2015 will further examine the vertical distribution and stability of the polar methane abundances. Future high-resolution imaging with Earth-based facilities will be able to track circulation changes (unless the developing north polar haze obscures trackable clouds).
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**Author(s): Heidi B. Hammel[1]**, Lawrence Sromovsky[2], Pat Fry[2], Imke de Pater3
**Institution(s):** *1. AURA, 2. U. Wisconsin, 3. UC Berkeley*

### 311.03 – Meridional trends in Neptune's background aerosol structure

We will present retrieval results for Neptune's aerosol structure in regions free of discrete cloud features, using data from the Keck OSIRIS integral field spectrograph and a two layer model for the aerosols. We use a Markov chain Monte Carlo algorithm to perform a thorough search of the parameter space; this analysis reveals a substantial decrease in the optical depth of the upper aerosol layer with increasing distance from the equator, similar to what is observed for the "upper haze" of Uranus in a simple two-cloud model (e.g., de Kleer et al. 2015). We also tentatively identify an increase in the optical depth of the deeper aerosol layer from the equator to the south pole, opposite to what is observed for Uranus but in agreement with the conclusions of Karkoschka & Tomasko (2011) for Neptune from HST-STIS spectroscopy. Finally, we will present our constraints on Neptune's methane profile and its latitude dependence, and discuss the significance of these results in terms of Neptune's global circulation.

**Author(s): Statia H. Luszcz-Cook[1]**, Katherine de Kleer3, Imke de Pater3, Mate Adamkovics3, Heidi B Hammel[2]
**Institution(s):** *1. American Museum of Natural History, 2. AURA, 3. University of California, Berkeley*

### 311.04 – Composition of the Upper Atmosphere of Neptune

It has been previously asserted that sulfur-bearing species such as CS and SO2 may be present in the upper atmosphere of Neptune, as remnants of cometary impacts (Iino et al., 2014). Based on the example of the SL9 event on Jupiter, CS in particular may be one of the most abundant tracers of past cometary impacts.
We present the results of our search for spectral (sub)mm signatures of HCN, CS, and $SO_2$ in Neptune's stratosphere, performed on archival public data from the Atacama Large Millimeter/submillimeter Array (ALMA) .
Neither CS or SO2 were detected on Neptune. We estimated an upper limit on the S/O stratospheric ratio significantly lower than the S/O ratio in comets, suggesting that S and O cannot both solely originate from a cometary impact.

**Author(s): Elizabeth Nance[1]**
**Institution(s):** *1. St. Mary's College of Maryland*

### 311.05 – Exploring the connections between dark spot dynamics and zonal wind structure on Uranus

The past several years have witnessed new observations revealing more clouds and long-lived features in the atmosphere of Uranus. Each new set of images provides new cloud-tracking data and the opportunity to assess the structure of the zonal winds on Uranus. This has led to a sequence of fits for the Uranian zonal winds with the latest entries being those proposed in Sromovsky et al. (2015). Karkoschka (2015) also provides a new view of the zonal winds, but in this case through reanalyzing the Voyager II observations. While all these profiles have in common features like a retrograde equatorial jet, the details of these profiles differ significantly. These differences can be further accentuated when considering the vorticity profiles derived from these zonal winds. As shown in LeBeau and Dowling (1998) and Hammel et al. (2009), atmospheric simulations using different zonal vorticity profiles suggest that the vorticity gradient can affect the dynamics of dark spot vortices in the atmosphere. Later work (Deng et al. 2009) has indicated that these dynamics may be further complicated by the presence of cloud companion features.
To further investigate these interactions, some of the most recent zonal profiles are used in simulations of Uranus with the Explicit Planetary Isentropic Coordinate (EPIC) atmospheric model. By inducing vortices at different latitudes, the effects of different zonal wind profiles on these features can be investigated. A methane microphysics model is used to generate representative companion clouds. The subsequent vortex and companion cloud motions can then be compared to observations, providing another tool in the effort to understand possible changes in the zonal wind structure of Uranus.
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X. Deng et al. 1st AIAA Atmospheric and Space Environments Conference, AIAA-2009-3643, 2009

**Author(s): Raymond P. Le Beau[2]**, Csaba Palotai[1]
**Institution(s):** *1. Florida Institute of Technology, 2. Saint Louis University*

### 311.06 – Convection in Uranus and Neptune

It is a common assumption of interior models that the outer planets of our solar system are convective, and that the internal temperature distributions are therefore adiabatic. If this assumption is not correct, the inferred internal structures of these planets can be different than typically thought. Therefore, exploring this topic is crucial for planetary characterization. We investigate how the internal temperature profiles of Uranus and Neptune depend on the treatment of layered-convection. We then use a set of possible temperature profiles associated with layered-convection together with density profiles derived from interior models that match the measured gravitational fields to derive the compositions of the planets. We find that the inferred compositions of both Uranus and Neptune are not very sensitive to the thermal profile. In addition, we show that calculating the thermal flux is important for understanding the energy transport mechanism in giant planets. Finally, we suggest that Neptune's interior is just at the boundary between being convective or conductive and both configurations are consistent with its thermal flux, while Uranus' interior is mostly conductive. This result is consistent with recent dynamo models and useful for understanding the origin of the magnetic fields of the planets.

**Author(s): Morris Podolak[1]**, Ravit Helled[1], Gerald Schubert[2]
**Institution(s):** *1. Tel Aviv University, 2. UCLA*

### 311.07 – Revisiting the Galileo Probe results by a stretched atmospheric mode

The Juno spacecraft will arrive at Jupiter in the late 2016. One of its major scientific target is to measure the deep water abundance through its Microwave Radiometer (MWR). Prior to the arrival of Juno, the only observation of the weather layer of Jupiter was the Galileo probe (Niemann et al. 1996; Wong et al. 2004), which returned puzzling results. In contrast to the detected 2 – 5 times enrichment of $CH_4$, $NH_3$ and $H_2S$ with respect to the solar values, the amount of water was severely subsolar. Three dimensional modeling (Showman & Dowling 2000) shows that dynamic dry downdrafts could create a huge trough in the material surface, such that air flowing through the hot spots undergoes a temporary increase in pressure by a factor of 2, though it is still too small to explain the Galileo probe results. Inspired by the 3D modeling result, we constructed a stretched atmospheric model to parameterize the alteration of the thermodynamic state of air parcel by dynamics. In our model, an air parcel is initially in its equilibrium condensation state and later has been dynamically stretched to higher pressure modeled by a multiplicative factor $S$. When $S$=1, the atmosphere is unaltered by dynamics, representing the equilibrium condensation model. We found that, when $S$=4, the mixing ratios of $H_2O$, $NH_3$ and $H_2S$ match all observations coming from the Galileo probe site. Thus, this stretch parameter provides a continuous representation of dynamic processes from the equilibrium condensation model to the Galileo probe results. We also show that the strength of stretch ($S$) can be retrieved from Juno/MWR limb darkening observations.

**Author(s): Cheng Li[1]**, Andrew P Ingersoll[1], Michael A Janssen[2]
**Institution(s):** *1. Caltech, 2. Jet Propulsion Laboratory*

### 311.08 – Updated Measurements of Saturn's Zonal Wind between 2004 - 2014 from Cassini ISS Images

We present updated zonal wind measurements of Saturn using Cassini ISS images taken between 2004 and 2014. We previously reported that there may be small seasonal changes in Saturn's zonal wind profile but measurement uncertainties prevented us from making definite statements. In our previous report, we used the zonal standard deviation of the wind vectors as a proxy for the measurement uncertainty. However, zonal standard deviation contains contributions from both real spatial variations in the wind speed as well as uncertainties in the measurements. This raised a difficulty in distinguishing small, real changes in the wind field from the uncertainties in the measurement. We have developed a technique which isolates real spatial variations from measurement uncertainties by analyzing the correlation fields produced in the two-dimensional Correlation Imaging Velocimetry (CIV) cloud-tracking wind measurement method. The CIV algorithm computes a wind vector by calculating the two-dimensional correlation between the pair of maps; a peak in the correlation is judged to be a match. We determine the size, shape, and orientation of the peak by fitting an ellipse to the peak and calculating the area, eccentricity, and orientation angle of the ellipse. Combining these metrics provides a measure of the uncertainty associated with individual wind vectors. Vectors with smaller, sharper, more circular peaks will have a smaller uncertainty than vectors with larger, flatter, more elliptical peaks. Using this new technique, our new measurements reveal small temporal changes in the zonal wind profiles. Our work has been supported by NASA PATM NNX14AK07G and NSF AAG 1212216.

**Author(s): John J Blalock[2]**, Kunio M Sayanagi[2], Andrew P Ingersoll[1], Shawn P Ewald[1], Ulyana A Dyudina[1]
**Institution(s):** *1. California Institute of Technology, 2. Hampton University*

### 311.09 – On the Ammonia Absorption on Saturn

The ammonia absorption bands centered at wavelengths of 645 and 787 nm in the visible spectrum of Saturn are very weak and overlapped with more strong absorption bands of methane. Therefore, the allocation of these bands is extremely difficult. In fact, the NH3 band 787 nm is completely masked by methane. The NH3 645 nm absorption band is superimposed on a relatively weak shortwave wing of CH4 band, in which the absorption maximum lies at the wavelength of 667 nm. In 2009, during the equinox on Saturn we have obtained the series of zonal spectrograms by scanning of the planet disk from the southern to the northern polar limb. Besides studies of latitudinal variation of the methane absorption bands we have done an attempt to trace the behavior of the absorption of ammonia in the band 645 nm. Simple selection of the pure NH3 profile of the band was not very reliable. Therefore, after normalizing to the ring spectrum and to the level of the continuous spectrum for entire band ranging from 630 to 680 nm in the equivalent widths were calculated for shortwave part of this band (630-652 nm), where the ammonia absorption is present, and a portion of the band CH4 652-680 nm. In any method of eliminating the weak part of the methane uptake in the short wing show an increased ammonia absorption in the northern hemisphere compared to the south. This same feature is observed also in the behavior of weak absorption bands of methane in contrast to the more powerful, such as CH4 725 and 787 nm. This is due to the conditions of absorption bands formation in the clouds at multiple scattering. Weak absorption bands of methane and ammonia are formed on the large effective optical depths and their behavior reflects the differences in the degree of uniformity of the aerosol component of the atmosphere of Saturn.

**Author(s): Victor G. Tejfel[1]**, A M Karimov[1], P G Lyssenko[1], G A Kharitonova[1]
**Institution(s):** *1. Fessenkov Astrophysical Institute*

### 311.10 – Saturn’s fast spin determined from its gravitational field and oblateness

Knowledge of the rotation period of a giant planet is crucial for constraining its internal structure and atmosphere dynamics. However, this physical property is not accurately determined in the case of Saturn. Spacecraft measurements of Saturn’s radio emission have revealed an uncertainty of nearly 10 minutes in its rotation period. Theoretical efforts to infer the rotation period have increased the uncertainty even more and at present, Saturn’s rotation period is thought to be between ~ 10h 32m and ~10h 47m. We present a new statistical optimization approach to determine Saturn’s rotation period. We find that by using its measured gravitational field and without imposing any constraints on the planetary shape and internal density profile Saturn’s rotation period can be determined to within several minutes. Moreover, if we include limits based on the observed planetary shape and possible density profiles, the rotation period can be determined to be 10h 32m 44s ± 46s. The success of our method is confirmed by applying it for Jupiter and reproducing exactly its measured rotation period which is well-known.

**Author(s): Ravit Helled[1]**, Eli Galanti [2], Yohai Kaspi[2]
**Institution(s):** *1. Tel-Aviv University, 2. The Weizmann Institute of Science*

### 311.11 – Waves and eddies simulated by high-resolution Global Climate Modeling of Saturn's troposphere and stratosphere

The longevity of the Cassini mission permitted a detailed analysis of Saturn's tropospheric storms, an exceptional coverage of Saturn's Great White Spot (and subsequent stratospheric warming), an assessment of the remarkable stability of the hexagonal polar jet, and the seasonal monitoring of Saturn's equatorial oscillation. Those observations open new questions that add to those related to the extent and forcing of Saturn's alternated jets. One of the best step forward to progress is to build a Global Climate Model (GCM) for giant planets by coupling an hydrodynamical solver (dynamical core) with physical models for external forcings on the fluid. We built a new GCM for Saturn both versatile and powerful enough to resolve resolve the eddies arising from hydrodynamical instabilities and forcing the planetary-scale jets, extend from the troposphere to the stratosphere with good enough vertical resolution, and use optimized radiative transfer to predict seasonal tendencies over decade-long giant planets' years. To that end, we coupled our seasonal radiative model tailored for Saturn with DYNAMICO, the next state-of-the-art dynamical core for Earth and planetary climate studies in our lab, using an original icosahedral mapping of the planetary sphere which ensures excellent conservation and scalability properties in massively parallel resources. Using a new petaflops acquisition by CINES (France), we run our GCM for Saturn down to unprecedented resolutions of 1/4° and 1/8°, and to run sensitivity tests at 1/2° resolution. Those high-resolution GCM runs show a detailed view into a striking variety of eddies and vortices on Saturn, as well as the arising of alternated banded jets, the formation of a polar vortex, the deformation of the polar jet into polygonal structures. We will assess the nature and characteristics of both eddies and eddy-driven features in the troposphere and in the stratosphere, using spectral and dynamical analysis. We will discuss how close our simulations are to the observed features by Cassini and other observational campaigns, and assess which processes are in need to be improved in our GCM. Perspectives for Jupiter's atmospheric modeling will also be described.

**Author(s): Aymeric Spiga5**, Sandrine Guerlet3, Yann Meurdesoif[6], Mikel Indurain3, Ehouarn Millour3, Thomas Dubos4, Mélody Sylvestre[2], Jérémy Leconte[1], Thierry Fouchet[2]
**Institution(s):** *1. Laboratoire d'Astrophysique de Bordeaux, Centre National de la Recherche Scientifique, 2. Laboratoire d'Etudes Spatiales et d'Instrumentation en Astrophysique, Université Pierre et Marie Curie, 3. Laboratoire de Météorologie Dynamique, Centre National de la Recherche Scientifique, 4. Laboratoire de Météorologie Dynamique, Ecole Polytechnique, 5. Laboratoire de Météorologie Dynamique, Université Pierre et Marie Curie, 6. Laboratoire des Sciences du Climat et de l'Environnement, Commissariat à l'Energie Atomique*

### 311.12 – Polar Disturbance Surrounding a Long Living Cyclone in Saturn’s Atmosphere

In 2014 and 2015 a large ‘dark spot’ about 6,000 km in length and located at planetocentric latitude +58.5° (+63° N planetographic) was tracked on the best ground-based amateur images of Saturn, revealing a long-lived feature, an uncommon phenomenon in Saturn’s atmosphere. Images captured by the Imaging Science Subsystem (ISS) onboard Cassini spacecraft showed the feature as a very contrasted dark spot in the MT3 filter, and barely visible in the deep sounding filters CB2 and CB3. On mid-May 2015 ground-based observations obtained by amateur astronomers operating small telescopes started to show a disturbance around this dark spot. Following the onset of this disturbance the drift of the dark spot remained unaltered and equal to the motion it had previously, but the
disturbance evolved zonally in a complex manner, giving hints of a kind of large scale phenomena in Saturn’s atmosphere of an unprecedented type. Unfortunately the orbital path of the Cassini spacecraft was not appropriate to see details of the disturbance at that time. Images by the Hubble Space Telescope (HST) WFC3 instrument obtained in director’s time (DDT) allow us to describe the detailed dynamics of the disturbance, while the study of its long-term evolution is possible thanks to the efforts of the community of amateur astronomers. In this work we analyze the dynamics of the region before the start of the disturbance and the dynamics and evolution of the disturbance after its onset.

**Author(s): Teresa Del Rio Gaztelurrutia4**, Agustín Sanchez-Lavega4, Arrate Antuñano4, Ricardo Hueso4, Santiago Pérez-Hoyos4, Jose F. Rojas4, Mike H. Wong3, Amy A. Simon[2], Imke de Pater3, Josep M. Gómez-Forrellad[1]
**Institution(s):** *1. Fundació Observatori Esteve Duran, 2. NASA Goddard Space Flight Center, 3. University of California, 4. University of the Basque Country (UPV/EHU)*

### 311.13 – Jupiter's auroral-related thermal infrared emission from IRTF-TEXES

Auroral processes on Jupiter can be observed at a large range of wavelengths. Charged particles of the solar wind are deflected by Jupiter’s magnetic field and penetrate the atmosphere at high latitudes. This results in ion and/or electron precipitation, which produces emission at X-ray, UV, visible, near-infrared and even radio wavelengths. These observations indicate three distinct features of the aurora: 1) filament-like *oval* structures fixed at the magnetic poles (~80°W (System III) in the south, ~180°W in the north), 2) spatially-continuous but transient aurora that fill these oval regions and 3) discrete spots associated with the magnetic footprints of Io and other Galilean satellites. However, observations in the thermal infrared indicate the aurora also modify the neutral atmosphere. Enhanced emission of $CH_4$ is observed coincident with the auroral ovals and indicates heightened stratospheric temperatures possibly as a result of joule heating by the influx of charged particles. Stronger emission is also observed of $C_2H_2$, $C_2H_4$, $C_2H_6$ and even $C_6H_6$ though previous work has struggled to determine whether this is a temperature or compositional effect. In order to quantify the auroral effects on the neutral atmosphere and to support the 2016 Juno mission (which has no thermal infrared instrument) we have performed a retrieval analysis of IRTF-TEXES (Texas Echelon Cross Echelle Spectrograph, 5- to 25-μm) spectra obtained on Dec 11th 2014 near solar maximum. The instrument slit was scanned east-west across high latitudes in each hemisphere and Jupiter's rotation was used to obtain ~360° longitudinal coverage. Spectra of $H_2$ S(1), $CH_4$, $C_2H_2$, $C_2H_4$ and $C_2H_6$ emission were measured at a resolving power of R = 85000, allowing a large vertical range in the atmosphere (100 – 0.001 mbar) to be sounded. Preliminary retrievals of the vertical temperature profile from $H_2$ S(1) and $CH_4$ measurements at 60°N, 180°W (on aurora), in comparison to 60°N, 60°W (quiescent) indicate the majority of auroral heating occurs from 10- to 1-μbar. We plan on further testing the temperature retrievals and adopting these results in the subsequent retrievals of $C_2H_2$, $C_2H_4$ and $C_2H_6$ to determine compositional contrasts.

**Author(s): James Sinclair[2]**, Glenn Orton[2], Thomas Greathouse[3], Leigh Fletcher[4], Patrick Irwin[1]
**Institution(s):** *1. Atmospheric, Oceanic and Planetary Physics, University of Oxford, 2. Jet Propulsion Laboratory, 3. Southwest Research Institute, 4. University of Leicester*

### 311.14 – Deriving Temperatures from the Homopause of Jupiter

Recently, Kim et al. (Icarus, 2015) derived homopause temperatures from several places on the north and south polar regions of Jupiter by analyzing the 3-μm spectro-images of $CH_4$, which were obtained using the Gemini Near-Infrared Spectrograph (GNIRS). The spectral resolution of the data was R~18,000, which is enough to resolve the sharp 3-μm emission lines of the P and Q branches of $CH_4$. From the next year's JUNO encounter with Jupiter, we are expecting low resolution spectra from JUNO's IR 2-5 μm spectrograph, whose resolution is only R~300 at 3 μm. We will present a method to derive homopause temperatures from low-resolution spectra utilizing the gross envelopes of the P, Q, R branch lines of $CH_4$. We will discuss possible sciences extracted from the constructed maps of homopause temperatures over the auroral or non-auroral regions of Jupiter.

**Author(s): Sang J. Kim[1]**
**Institution(s):** *1. Kyunghee Univ.*

### 311.15 – Photochemistry, mixing and transport in Jupiter's stratosphere constrained by Cassini

Jupiter's obliquity and eccentricity drive the seasonal forcing on its atmosphere. The seasonal variations on its stratospheric temperature through radiative heating and composition through photochemistry are smaller than for Saturn, due to a lower obliquity and eccentricity. Although the physical conditions in these two planets are different, the stratospheric photochemistry is initiated and controlled by the methane photolysis [1]. We adapted a 2D (altitude-latitude) seasonal photochemical model of Saturn [2] to Jupiter. We compare the seasonal effects on the atmospheric composition between these two planets. We use previous 1D photochemical models for the vertical mixing efficiency [1,3] and recent Cassini observations to constrain the meridional mixing efficiency and transport processes [4,5,6].
Cassini's flyby of Jupiter has allowed mapping its stratospheric temperature as a function of latitude [7]. It has also revealed the meridional distribution of hydrocarbons [8,9], which were suggested by earlier studies [10,4]. Previous models suggest that vertical mixing alone is not sufficient to reproduce the observations of $C_2H_2$ and $C_2H_6$ [5,6], and that meridional mixing is needed. We show that, in addition to meridional mixing, advective circulation is required to reproduce Cassini observations of $C_2H_6$. Preliminary results from our model suggest an equator-to-pole circulation cell in Jupiter's stratosphere, around 30-0.01 mbar.
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**Author(s): Vincent Hue[1]**, Franck Hersant[1], Thibault Cavalié[2], Michel Dobrijevic[1]
**Institution(s):** *1. LAB, Université de Bordeaux, CNRS, UMR 5804, 2. LESIA, Observatoire de Paris, CNRS, Université Paris 06, Université Paris-Diderot*

### 311.16 – Saturn's Stratospheric Water Vapor Distribution

Water is a sought after commodity in the solar system. It is used as an indication of life, planetary formation timescales, and signatures of past cometary impacts. In Saturn's atmosphere there are two sources of water: an internal primordial reservoir that is confined to the troposphere, and an external source of unknown origin that delivers water to the stratosphere. Potential sources of stratospheric water include: Saturn's main rings (via neutral infall and/or ions transported along magnetic field lines – "Ring Rain"), interplanetary dust particles, and the E-ring that is supplied with water from the plumes of Enceladus. Measuring the latitudinal and seasonal variation of $H_2O$ on Saturn will constrain the source of Saturn's stratospheric water.
Cassini's Composite InfraRed Spectrometer (CIRS) has detected emission lines of $H_2O$ on Saturn at wavelengths of 40 and 50 microns. CIRS also retrieves the temperature of the stratosphere using $CH_4$ lines at 7.7 microns. Using our retrieved temperatures, we derive the mole fraction of $H_2O$ at the 0.5-5 mbar level for comparison with water-source models. The latitudinal variation of stratospheric water vapor will be presented as a first step in understanding the external source of water on Saturn. The observed local maximum near Saturn's equator supports either a neutral infall from the rings or a source in the E-ring. We will look for secondary maxima at mid-latitudes to determine whether "Ring Rain" also contributes to the inventory of water in Saturn's upper atmosphere.

**Author(s): Brigette E. Hesman3**, Gordon L Bjoraker[1], Richard K Achterberg[3], Paul N Romani[1], Patrick G.J. Irwin[2]
**Institution(s):** *1. NASA GSFC, 2. Oxford University, 3. Univ. Maryland/NASA GSFC*

### 311.17 – Saturn's stratospheric temperature and composition in 2015 from Cassini/CIRS limb observations

As Cassini's solstice mission goes on, our understanding of Saturn's atmospheric seasonal evolution continues to build up. Infrared spectra acquired by Cassini/CIRS in limb viewing geometry in 2015 (end of spring in the northern hemisphere) are analysed to retrieve vertical profiles of the stratospheric temperature and hydrocarbon abundances at several latitudes spanning tropical, mid and high latitudes.
These new measurements reveal how the equatorial oscillation continues to propagate downward with time, and help better characterize its period. At 40N, the previously observed temperature anomaly and enrichment in hydrocarbons associated with the 2011 storm have since disappeared. Compared to previous measurements acquired between 2005 and 2012 (Guerlet et al., Icarus, 2009; Sylvestre et al., Icarus, 2015), these new limb measurements also allow the study of the warming and cooling

trends at different pressure levels associated with the change of seasons. These trends will be compared to predictions from a radiative climate model (Guerlet et al., Icarus, 2014).
We also report the detection of benzene and aerosols at 77N, which confirms that these compounds are enhanced in auroral regions compared to low and mid latitudes, as already derived from a previous measurement at 80S in 2007 (Guerlet et al., A&A, 2015). The aerosol optical depth is found twice lower at 77N in 2015 (end of spring in N. hemisphere) than that derived at 80S in 2007 (end of summer in S. hemisphere). However, whether this north/south difference stems from a permanent asymmetry or from a temporal variation of the aerosol optical depth cannot be assessed from these two measurements alone. We will discuss implications for the role of aerosols in the radiative forcing of the polar regions.

**Author(s): Sandrine Guerlet[1]**, Thierry Fouchet[2], Brigette Hesman3, Gordon Bjoraker3, Aymeric Spiga[1], Melody Sylvestre[2]
**Institution(s):** *1. Laboratoire de Meteorologie Dynamique, 2. LESIA, Observatoire de Paris, 3. NASA/GSFC*

### 311.18 – Effect of the 77 degree N Jet on Saturn's Hexagon Cloud Morphology

We study how Saturn's 77 degree N jet shapes the sharp edges of the hexagon. The hexagonal morphology is shaped by a meandering jetstream that encircles the north pole of Saturn at around 77 degree N planetographic latitude (Antunano et al. 2015). Laboratory and numerical models have demonstrated that a jetstream could develop a six-sided shape in two different ways. In the first, which we call the vortex street model, alternating pairs of cyclonic and anticyclonic vortices form through shear instabilities, and form a hexagonal pattern (Barbosa Aguiar et al. 2010; Morales-Juberias et al. 2011). In the second, which we call the meandering jet model, a jetstream accompanied by a sharp gradient of potential vorticity develops a meandering path without accompanying vortices (Morales-Juberias et al 2015). The observed wind field of Saturn's hexagon is consistent with that of the meandering jet model.
In the present study, we first present Cassini ISS images of the hexagon captured using various filters, and show that its cloud band boundary has a sharp contrast gradient along the path of the jetstream at 77 degree N. We hypothesize that this sharp boundary is a consequence of the transport barrier effect of the meandering jetstream. We further hypothesize that such sharp cloud boundaries cannot accompany a hexagonal jet formed through a vortex street scenario. We test our hypothesis by performing numerical simulations using the EPIC atmosphere model (Dowling et al. 1998, 2004). We use passive tracers to represent clouds in our simulations to study the mixing across the jetstream in both the vortex street and meandering jet scenarios, and test whether sharp hexagonal cloud morphology could be reproduced by either of the scenarios.
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**Author(s): Kunio M. Sayanagi[2]**, Raúl Morales-Juberías3, John J. Blalock[2], Richard G. Cosentino3, Andrew P. Ingersoll[1], Shawn P. Ewald[1], Ulyana A. Dyudina[1]
**Institution(s):** *1. California Institute of Technology, 2. Hampton University, 3. New Mexico Institute of Mining and Technology*

### 311.19 – The Ongoing Evolution of a Long-Lived Anticyclone in Saturn's Great Storm Region as seen by Cassini/VIMS

Once the home of the enigmatic String of Pearls feature on Saturn, the region of 34° N was the scene of a titanic storm system that swept around the planet in late 2010/2011. It left two things in its wake - a clear 5-µm bright zone around the planet, and a curious and persistent anticylone, both of which remain to this day. We have observed this anticyclone with Cassini/VIMS since 2011 and find that it seems to oscillate up and down latitudinally in this stormy region. Centered at 35.9° planetocentric latitude in May 2011, it drifted northward to 37.8° in 2012, hovered near 37° through 2013, then settled southward back down to ~35.9° in 2014. 2015 has it once again drifting northward to ~37°. It also periodically interacts with the dark band above it exchanging material in August 2013 and May 2015. We measured a prograde zonal drift speed of ~22 m/s in 2012, increasing as much as 60% through 2013, then relaxing back to a more moderate ~15 m/s in 2014 as the oval sagged southward. We expect its current 15.4 m/s rate to increase if it continues to drift northward in latitude, following the Voyager wind profile. The feature has varied in size as well, spanning 4.9° x 3.2° in 2011, elongating zonally to 7.3° x 2.9° by 2013, contracting in 2014 to an average of ~5.5° x ~2.9°, and growing again to ~9° x ~4° in 2015, with an extended tendril of material streaming off one edge in May. By August, it was symmetrically oval again. It has varied in terms of cloudiness, being ~90% 5-µm dark (obscured) in 2011, whereas by 2013 it was mostly bright (clear) with a thin dark edge, now returning to ~90% dark in 2015. By utilizing night observations to isolate thermal flux, we find that the mean 5-µm flux coming from the anticyclone has diminished steadily by about 50% since 2013. The storm latitude of ~34° N itself has remained remarkably 5-µm bright since 2011, but has begun to dim as well, and is now bisected by a thin dark cloudy ribbon which appears associated with the anticyclone. We are continuing to monitor the evolution of the anticyclone and the Storm Region over time with Cassini/VIMS.

**Author(s): Thomas W. Momary3**, Kevin H Baines5, Sarah Badman[2], Robert H Brown[6], Bonnie J Buratti3, Roger N Clark4, Philip D Nicholson[1], Christophe Sotin3
**Institution(s):** *1. Cornell University, 2. Lancaster University, 3. NASA/Jet Propulsion Laboratory, 4. Planetary Science Institute, 5. SSEC/University of Wisconsin-Madison, 6. University of Arizona*

### 311.20 – The search for atmospheric waves below the clouds of Jupiter using radio wavelength observations

We observed Jupiter at 2 cm wavelength with the VLA in early February 2015. This particular frequency is mostly sensitive to variations in ammonia opacity and probes a depth between 1 and 2 bars pressure; below the visible cloud deck at 0.7 bars. The data acquired was projected into a cartographic map of the planet following the technique of Sault et al. (2004). The horizontal resolution is ~1500 km and we have examined the map for atmospheric waves on these and larger scales. The map has revealed prominent features near 8N, in the North Equatorial Belt, where the 5 micron hotspot planetary wave feature also resides. The Great Red Spot is also prominent and has a noticeable meridional asymmetry. We will present our analysis of the spatial structure for the entire map and best fit of its wave feature spectrum.
Our research is supported by NRAO and NMT.

**Author(s): Rick Cosentino[1]**, Bryan Butler[2], Bob Sault[2], Raul Morales-Juberias[1], Amy Simon3
**Institution(s):** *1. New Mexico Institute of Mining and Technology, 2. NRAO, 3. Solar System Exploration Div., NASA/GSFC*

### 311.21 – Numerical Modeling of Normal-Mode Oscillations in Planetary Atmospheres: Application to Saturn and Titan

We have developed a numerical model to calculate the frequencies and eigenfunctions of adiabatic, non-radial normal-mode oscillations in the gas giants and Titan. The model solves the linearized momentum, energy, and continuity equations for the perturbation displacement, pressure, and density fields and solves Poisson's equation for the perturbation gravitational potential. The response to effects associated with planetary rotation, including the Coriolis force, centrifugal force, and deformation of the equilibrium structure, is calculated numerically. This provides the capability to accurately compute the influence of rotation on the modes, even in the limit where mode frequency approaches the rotation rate, when analytical estimates based on functional perturbation analysis become inaccurate. This aspect of the model makes it ideal for studying the potential role of low-frequency modes for driving spiral density waves in the C ring that possess relatively low pattern

speeds (Hedman, M.M and P.D. Nicholson, MNRAS 444, 1369-1388). In addition, the model can be used to explore the effect of internal differential rotation on the eigenfrequencies. We will (1) present examples of applying the model to calculate the properties of normal modes in Saturn and their relationship to observed spiral density waves in the C ring, and (2) discuss how the model is used to examine the response of the superrotating atmosphere of Titan to the gravitational tide exerted by Saturn.
This research was supported by a grant from the NASA Planetary Atmosphere Program.

**Author(s): Andrew James Friedson[1]**, Leon Ding[2]
**Institution(s):** *1. JPL, 2. Summer Undergraduate Research Fellow, Caltech*

### 311.22 – Analysis of Cassini UVIS Extreme and Far Ultraviolet Observations of Saturn's Atmosphere

The atmosphere of Saturn is mainly composed of $H_2$ and neutral atomic helium. The study of He 584 Å and H Lyman-α brightnesses is interesting as the EUV and FUV (Extreme and Far Ultraviolet) planetary airglow have the potential to yield useful information about mixing and other important parameters in its thermosphere. Time variation, asymmetries, and polar enhancement of the airglow are also possible and analysis already performed using the public archived Cassini mission data sets have shown we can solve some of the outstanding problems associated with these phenomena for Saturn.
Specifically, we have (1) examined epochal eddy mixing disparities in the Saturnian upper atmosphere and quantify temporal mixing variations that may have occurred in the upper atmosphere of Saturn, as may be evidenced in Cassini mission data, (2) quantified any enhanced mixing in the auroral regions of Saturn, and (3) performed a robust study of Saturnian H Lyman-α brightness with the view to discover any longitudinal H Lyman-α planetary asymmetry or "bulge" across the disc such as was discovered by Voyager at Jupiter, indicative of the distribution of atomic H and accounting for the observed flux and any variations from the normal temperature profile.
We have analyzed Cassini UVIS EUV and FUV airglow data from Saturn using sophisticated photochemical and radiative transfer models to investigate unexplained differences in the dynamical processes operating within its upper atmosphere. Powerful analysis techniques allow us to extract information on atmospheric mixing, temperatures, and temporal changes due to the solar and seasonal cycles from the variations in distribution and intensity of airglow emissions that result. We report on results of these efforts to date.

**Author(s): Christopher D. Parkinson5**, Tommi Koskinen3, Guillaume Gronoff4, Yuk L. Yung[1], Larry Esposito[2]
**Institution(s):** *1. California Institute of Technology, 2. LASP University of Colorado, 3. LPL, 4. SCIENCE SYSTEMS AND APPLICATIONS, INC., 5. Univ. of Michigan*

### 311.23 – Peeking into Saturn's atmosphere: the HST low-phase angle view

Recent Hubble Space Telescope WFC3 observations of Saturn have provided a low-phase angle view of the planet that nicely complements the higher phase angles and increased spatial resolution view from the Cassini spacecraft. HST orbits were perfectly timed for observing an atmospheric perturbation at polar latitudes, but they serendipitously captured other interesting features at the Equatorial Zone (EZ). In this presentation we will discuss how the synergy between the Cassini/ISS and HST/WFC3 observations provides an excellent way for peeking into Saturn's atmosphere and analyze the vertical distribution and properties of the particles and aerosols located in the lower stratosphere and upper troposphere of the planet. We first discuss how Cassini/ISS observations at a variety of phase angles constrain particle properties and phase function, in particular at the Equatorial Zone. This had not been investigated since the early 1980s (Tomasko & Doose, 1984), more than a Saturnian year before the current work. We will also discuss the sizes and shapes of particles in the troposphere, as constrained by the retrieved phase function . With this information, the HST/WFC3 observations at 10 filters from near-ultraviolet to the near-infrared provide substantial information on the vertical cloud structure and composition: the filters in and out of the intermediate and deep methane bands at the near infrared give information on particle number density around the tropopause level (5-10 part/cm3) and down to the ammonia condensation level, while near-ultraviolet and blue filters characterize the absorption of unknown chromophores in Saturn's atmosphere. We will further show observations and radiative transfer models of selected atmospheric features that have important dynamical implications for understanding Saturn's atmospheric dynamics at the EZ and the Northern polar atmosphere. In particular, fast-moving features in the EZ with Voyager-era speeds seem to be located deeper (≥ 2 bar) than the features used for cloud-tracking since the pre-Cassini era (0.1 - 1bar), thus simultaneously sounding for the first time three separate levels in the Equatorial region of the planet with substantially different wind speeds.

**Author(s): Santiago Perez-Hoyos[2]**, J.F. Sanz-Requena3, A. Sanchez-Lavega[2], R. Hueso[2], T. del Río-Gaztelurrutia[2], J.F. Rojas[2], A.A. Simon[1], M.H. Wong4, I. de Pater4, P.G.J. Irwin5, I. Irizar[2]
**Institution(s):** *1. Goddard Space Flight Center, 2. Universidad del Pais Vasco UPV/EHU, 3. Universidad Miguel de Cervantes, 4. University of California, 5. University of Oxford*

### 311.24 – The Colors of Saturn

Very little is known about the coloring agents, or chromophores, that color the clouds of Saturn's belts and zones. Although the clouds of Saturn are more muted in their coloration and do not exhibit the more striking variations seen among Jupiter's belts, zones, and cyclonic storm features, the physical processes that render Saturn's clouds a yellowish hue are likely similar to those at work on Jupiter. Thus, a comprehensive color study that includes both Jupiter and Saturn is warranted to advance our understanding of chromophores in the giant planet atmospheres. Here we report on our efforts to characterize the colors of Saturn's clouds.
This study involves the analysis of two imaging data sets: those from Cassini's Imaging Science Subsystem (ISS), and Wide Field Planetary Camera 2 images taken with the Hubble Space Telescope (HST). The HST data were acquired in 1994, 1998, 2002 and 2004 using eleven different filters spanning 255-973 nm. After the images were photometrically and geometrically calibrated, we used them to create low resolution spectra for six different latitude regions: the Equatorial Zone, the Equatorial Belt, the South Equatorial Belt, the South Temperate Zone, the South Temperate Belt and the South South Temperate Belt. The Cassini ISS images were acquired in 2004 and 2011 using twelve different filters spanning 258-938 nm, and corresponding low resolution spectra of the same latitude regions were generated using the ISS images. We compare these low resolution spectra to Saturn's full-disk spectrum (Karkoschka, E., 1994, Icarus 111, 174) to examine colors of discrete latitudes versus the full-disk spectrum of Saturn. The extensive temporal coverage afforded by the combination of the HST and ISS images will enable us to explore possible seasonal variations in Saturn's cloud colors. Finally, we examine the color evolution of the major 2011 storm on Saturn using the ISS data.
This work was supported by the Discovery Scholars Program in NMSU's College of Arts and Sciences and NASA's Outer Planets Research program through grant # NNX12AJ14G.

**Author(s): Kayla DeVogel[1]**, Nancy Chanover[1], Alexander Thelen[1]
**Institution(s):** *1. New Mexico State University*

### 311.25 – Photochemistry in Saturn's Ring-Shadowed Atmosphere: Modulation of Hydrocarbons and Aerosols

Cassini has been orbiting Saturn for over eleven years now. During this epoch, the ring shadow has moved from covering much of the northern hemisphere (the solar inclination was 24 degrees) to covering a large swath south of the equator and it continues to move southward. At Saturn Orbit Insertion in 2004, the projection of the A-ring onto Saturn reached as far as 40N along the central

meridian (52N at the terminator). At its maximum extent, the ring shadow can reach as far as 48N/S (58N/S at the terminator). The net effect is that the intensity of both ultraviolet and visible sunlight penetrating through the rings to any particular latitude will vary depending on both Saturn's axis relative to the Sun and the optical thickness of each ring system. In essence, the rings act like semi-transparent venetian blinds.
Our previous work, examined the variation of the solar flux as a function of solar inclination, i.e. for each 7.25-year season at Saturn. Here, we report on the impact of the oscillating ring shadow on the photolysis and production rates of hydrocarbons (acetylene, ethane, propane, and benzene) and phosphine in Saturn's stratosphere and upper troposphere. The impact of these production and loss rates on the abundance of long-lived photochemical products leading to haze formation are explored. Similarly, we assess their impact on phosphine abundance, a disequilibrium species whose presence in the upper troposphere can be used as a tracer of convective processes in the deeper atmosphere.
We will also present our ongoing analysis of Cassini's datasets that provide an estimate of the evolving haze content of the northern hemisphere and we will begin to assess the implications for dynamical mixing. In particular, we will examine how the now famous hexagonal jet stream acts like a barrier to transport, isolating Saturn's north polar region from outside transport of photochemically-generated molecules and haze.
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**Author(s): Scott G. Edgington[2]**, Sushil K. Atreya[3], Eric H. Wilson[3], Kevin H. Baines[2], Robert A. West[2], Gordon L. Bjoraker[1], Leigh N. Fletcher[4], Tom Momary[2]
**Institution(s):** *1. Goddard Space Flight Center, 2. Jet Propulsion Laboratory/CalTech, 3. University of Michigan, 4. University of Oxford*

### 311.26 – Comprehensive Optical Coverage of Jupiter for Spectral Comparison with $NH_4SH$

The distinct regions in Jupiter's atmosphere – comprised of belts, zones, storms, and the Great Red Spot – are thought to be colored by unidentified chemical compounds called chromophores. These molecules, created through Jupiter's complex atmospheric chemistry, may be responsible for the spectral slope and lack of features in the blue (shortwards of 500 nm) portion of Jupiter's optical spectrum. Though many candidate compounds have been proposed – such as ammonium hydrosulfide ($NH_4SH$) – the identity of the coloring agent (or agents) remains elusive due to the sparse history of laboratory experiments conducted at appropriate temperatures and pressures for Jovian conditions. To build on previous ground-based observations of Jupiter in the optical, we have obtained spectra with the Dual Imaging Spectrograph – mounted on the Astrophysical Research Consortium 3.5-meter telescope at Apache Point Observatory – over a wide portion of the visible spectrum (~380-880 nm) by utilizing multiple central wavelength settings. These observations, taken during February, 2013 and April, 2015, cover multiple latitudinal regions on Jupiter, including the Great Red Spot. In this study, we present the spectral comparison of various regions in the Jovian atmosphere with data taken at the Cosmic Ice Laboratory at NASA's Goddard Space Flight Center. By exposing thin films of $NH_4SH$ to varying amounts of ionizing radiation at Jovian temperature conditions, we can analyze the color and spectral changes of the ice. This enables us to evaluate $NH_4SH$ as a candidate chromophore through comparisons of spectral slope and features found in ground-based optical spectra of Jupiter. This work was supported by NASA's Outer Planets Research Program through grant number NNX12AJ14G.

**Author(s): Alexander E Thelen[2]**, Nancy Chanover[2], Mark Loeffler[1], Reggie Hudson[1], Amy Simon[1]
**Institution(s):** *1. NASA Goddard Space Flight Center, 2. New Mexico State University*

### 311.27 – Helium Rain and the Thermal Evolution of the Jovian Planets

The atmospheres of Jupiter and Saturn are observed to be depleted in helium relative to the protosolar nebula. Coupled with Saturn's drastic overluminosity compared to homogeneous thermal evolution models, this constitutes strong evidence that H/He phase separation is underway within the deep interiors of both planets. We compute thermal evolution models for Jupiter and Saturn, adopting a recent H/He phase diagram based on ab initio simulations. We find that if He settles efficiently despite convection, then differentiation contributes a significant amount of luminosity. It also establishes a composition gradient that tends to stabilize the fluid against convection between one and a few million bars. A steeper-than-adiabatic temperature gradient is thus required to deliver the planet's intrinsic flux, a feature which profoundly affects the thermal history and which has not been addressed in previous studies. In this quasistable region we consider two possibilities: (i) that overturning convection persists, but with decreased efficiency due to the added expense of mixing up heavier material; and (ii) that overturning convection gives way to overstable double-diffusive convection. We will judge the success of the adopted phase diagram along with these generalized theories of heat transport in matching the observed luminosities and atmospheric He abundances of Jupiter and Saturn simultaneously. The models we develop will be poised to incorporate the upcoming Juno and Cassini gravity field measurements.

**Author(s): Christopher Mankovich[1]**, Jonathan J. Fortney[1], Kevin L. Moore[1], Nadine Nettelmann[1]
**Institution(s):** *1. University of California Santa Cruz*

### 311.28 – Measurement Of The D/H Abundance On Jupiter And Saturn Using The CIRS Far-IR Interferometer

It is believed that the majority of the hydrogen on Jupiter and Saturn was obtained when the solar system formed about 4.6 Gyr ago. Consequently, knowing the D/H abundance on Jupiter and Saturn is essential to understanding stellar nucleosynthesis in our galaxy, and subsequently the composition of the primordial nebula. The Composite Infrared Spectrometer (CIRS) aboard the Cassini orbiter made observations of Jupiter in 2000-2001, and has been making continuous observations of Saturn since 2004 at a 0.5 $cm^{-1}$ spectral resolution and covering all latitudes. Utilizing this high spectral resolution, we have sought to model the HD rotational transitions (S0, S1, S2, S3 at 89.23, 177.84, 265.25, and 350.88 $cm^{-1}$ respectively) to retrieve the D/H ratios on Jupiter and Saturn, and show preliminary fitting to the far-IR spectral region using the CIRS FP1 far-IR interferometer. This work will provide a new measurement of D/H on the giant planets that will give improved constraint on formation and evolution models of the solar system and other planetary systems.

**Author(s): J D Roberts-Pierel[1]**, C A Nixon[2], G L Bjoraker[2], B E Hesman[4], R K Achterberg[4], P GJ Irwin[3], F M Flasar[2]
**Institution(s):** *1. CRESST/UMBC, 2. NASA GSFC, 3. Oxford University, 4. UMCP*

### 311.29 – Convective Origin of Long-Lived Spots on the Giant Planets

In an earlier paper (Chan and Mayr, 2013, Earth and Planetary Science Letters, 371-372: 212-219), we discussed the generation of long-lived cyclones and anticyclones in fast rotating convection zones. The mechnism was applied to explain phenomenon like the Great Red Spot on Jupiter. In those calculations only single compact vortices could be formed and generation of anticyclones could only be realized in high latitude. Similar problems exist in calculations by other authors (e.g. Kapyla et al. 2011, ApJ, 742: 34-41; Julien et al. 2012, Geophys. Astrophys. Fluid Dyn., 106: 392-428; Guervilly et al., 2014, JFM, 758: 407-435). Here we present new calculations with higher aspect ratio (width/depth = 8) showing that (i) anticyclones can be generated in low latitude (22.5 degree N in our case) (ii) multiple cyclones/anticyclones can form in a single computational domain. Besides demonstrating the prevalence of long-lived vortices in fast rotating convection zones, the result also shows that aspect ratio of the domain is an important factor in simulation, implying its effect also on laboratory experiments.

**Author(s): Kwing Lam Chan[2]**, Hans G Mayr[1]
**Institution(s):** *1. Applied Physics Laboratory, 2. Space Science Institute, Macau University of Science & Technology*

### 311.30 – Evaluation of Data Used for Modelling the Stratosphere of Saturn

Planetary atmospheres are modeled through the use of a photochemical and kinetic reaction scheme constructed from experimentally and theoretically determined rate coefficients, photoabsorption cross sections and branching ratios for the molecules described within them. The KINETICS architecture has previously been developed to model planetary atmospheres and is applied here to Saturn's stratosphere. We consider the pathways that comprise the reaction scheme of a current model, and update the reaction scheme according the to findings in a literature investigation. We evaluate contemporary photochemical literature, studying recent data sets of cross-sections and branching ratios for a number of hydrocarbons used in the photochemical scheme of Model C of KINETICS. In particular evaluation of new photodissociation branching ratios for $CH_4$, $C_2H_2$, $C_2H_4$, $C_3H_3$, $C_3H_5$ and $C_4H_2$, and new cross-sectional data for $C_2H_2$, $C_2H_4$, $C_2H_6$, $C_3H_3$, $C_4H_2$, $C_6H_2$ and $C_8H_2$ are considered. By evaluating the techniques used and data sets obtained, a new reaction scheme selection was drawn up. These data are then used within the preferred reaction scheme of the thesis and applied to the KINETICS atmospheric model to produce a model of the stratosphere of Saturn in a steady state. A total output of the preferred reaction scheme is presented, and the data is compared both with the previous reaction scheme and with data from the Cassini spacecraft in orbit around Saturn.
One of the key findings of this work is that there is significant change in the model's output as a result of temperature dependent data determination. Although only shown within the changes to the photochemical portion of the preferred reaction scheme, it is suggested that an equally important temperature dependence will be exhibited in the kinetic section of the reaction scheme. The photochemical model output is shown to be highly dependent on the preferred reaction scheme used within it by this thesis. The importance of correct and temperature-appropriate photochemical and kinetic data for the atmosphere under examination is emphasised as a consequence.

**Author(s): Eleanor Sophie Armstrong[2]**, Patrick G. J. Irwin [2], Julianne I. Moses[1]
**Institution(s):** *1. Space Science Institute, 2. University of Oxford*

### 311.31 – Distribution of alkali gases in Io's atmosphere

Thanks to high-sensitivity (sub)millimeter spectroscopic observations, KCl and NaCl in gas phase have been detected at low concentration levels in Io's atmosphere. These molecules are likely to be the main potassium and sodium carriers from the moon to its environment. Indeed, potassium and sodium are known to be present in Io's neutral clouds and plasma torus, which are believed to be fed from the moon itself.
The immediate sources of gaseous NaCl and KCl in Io's atmosphere are still unknown. Based on thermochemical arguments, both molecules could be present in volcanic plumes. Their lifetime in gaseous form is predicted to be rather low (a few hours), and a large portion of the emitted gas should quickly condense on the ground. Sputtering of surface condensates by high-energy particles may re-inject some of the condensates back in the atmosphere. The efficiency of this process is highly dependant on the local atmospheric column density.
We present maps of NaCl and KCl emission distribution, obtained in 2012 and 2015 with the Atacama Large Millimter Array (ALMA). The distribution maps will be compared to the distribution of volcanic centers and Io's bulk atmosphere ($SO_2$), in an attempt to characterize their immediate sources.

**Author(s): Arielle Moullet3**, Emmanuel Lellouch[2], Mark Gurwell5, Raphael Moreno[2], John Black[1], Bryan Butler4
**Institution(s):** *1. Chalmers University of Technology, 2. LESIA-Observatoire de Paris, 3. NRAO, 4. NRAO, 5. SAO-Center For Astrophysics*

### 311.32 – The effect of large-scale tropospheric storms on the ionospheres of giant planets

It is well recognized that large-scale storms in the Earth troposphere can leave observable signatures in the structure of the ionosphere in terms of local electron density distribution. Terrestrial numerical models indicate that thunderstorms can change the electron density by more than an order of magnitude (Shao et al. 2012). The atmospheres of Jupiter and Saturn are riddled by atmospheric storms of all scales. Lightning has been successfully detected in optical images in the tropospheres of both planets. Our work presents a theoretical study of the dynamical and electromagnetic effects of large thunderstorms on the vertical plasma distribution in the ionospheres of Jupiter and Saturn and compares the predicted signatures with the available electron density profiles from the Galileo and the Cassini missions.

**Author(s): Katia Matcheva[1]**
**Institution(s):** *1. University of Florida*

### 311.33 – Laboratory Measurements and Modeling of Molecular Photoabsorption Cross Sections in the Ultraviolet: Diatomic Sulfur ($S_2$) and Sulfur Monoxide (SO)

Our research program comprises the measurement and modeling of ultraviolet molecular photoabsorption cross sections with the highest practical resolution. It supports efforts to interpret and model observations of planetary atmospheres. Measurement and modeling efforts on diatomic sulfur ($S_2$) and sulfur monoxide (SO) are in progress.
$S_2$: Interpretations of atmospheric (Io, Jupiter, cometary comae) $S_2$ absorption features are hindered by a complete lack of laboratory cross section data in the ultraviolet. We are working to quantify the photoabsorption spectrum of $S_2$ from 240 to 300 nm based on laboratory measurements and theoretical calculations. We have constructed an experimental apparatus to produce a stable column of $S_2$ vapor at a temperature of 800 K. High-resolution measurements of the absorption spectrum of the strong B – X system of $S_2$ were completed using the NIST VUV-FTS at Gaithersburg, MD. These measurements are being incorporated into a coupled-channel model of the absorption spectrum of $S_2$ to quantify the contributions from individual bands and to establish the mechanisms responsible for the strong predissociation signature of the B – X system. A successful coupled channels model can then be used to calculate the B – X absorption spectrum at any temperature.
SO: There has been a long-standing need for high-resolution cross sections of SO radicals in the UV and VUV regions, where the molecule strongly predissociates, for modeling the atmospheres of Io and Venus, and for understanding sulfur isotope effects in the ancient (pre-$O_2$) atmosphere of Earth. We have produced a measurable column of SO in a continuous-flow DC discharge cell, using $SO_2$ as a parent molecule. Photoabsorption measurements were recently recorded with the high-resolution VUV-FTS on the DESIRS beamline of the SOLEIL synchrotron. A number of strong, predissociated SO bands were measured in the 140 to 200 nm region. Weaker features associated with the SO B – X system were simultaneously recorded, allowing for an approximate determination of the VUV SO band *f*-values.

**Author(s): Glenn Stark5**, James Lyons[1], Hannah Herde[2], Gillian Nave3, Nelson de Oliveira4
**Institution(s):** *1. Arizona State University, 2. Brandeis University, 3. N.I.S.T., 4. Synchrotron SOLEIL, 5. Wellesley College*

### 311.34 – Measurement and modeling of cold $^{13}CH_4$ spectra from 2.1 to 2.7 µm

A new study of $^{13}CH_4$ line intensities and positions in the Octad

region between 3600 and 4800 $cm^{-1}$ will be reported. Nine spectra were recorded with two Fourier transform spectrometers (the McMath-Pierce FTS at Kitt Peak Observatory and the Bruker 125 HR FTS at the Jet Propulsion Laboratory) using $^{13}C$-enriched samples at temperatures from 299 K to 80 K. Line positions and intensities were retrieved by non-linear least squares curve-fitting procedures and analyzed using the effective Hamiltonian and the effective Dipole moment expressed in terms of irreducible tensor operators adapted to spherical top molecules. Quantum assignments were found for all the 24 sub-vibrational states of the Octad (some as high as J=10). Over 4750 experimental line positions and 3300 line intensities were fitted with RMS standard deviations of 0.004 $cm^{-1}$ and 6.9%, respectively. A new linelist of over 9600 measured positions and intensities from 3607 to 4735 $cm^{-1}$ was produced, with known quantum assignments given for 45% of the features.[a] A manuscript and database has been submitted to J. Quant. Spectrosc. Radiat. Transfer.
[a] Part of the research described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, NASA Langley Research Center, and Connecticut College, under contracts and cooperative agreements with the National Aeronautics and Space Administration. The support of the Groupement de Recherche International SAMIA between CNRS (France) and RFBR (Russia) is acknowledged.

**Author(s): Linda R. Brown3**, Keeyoon Sung3, Timothy J. Crawford3, Andrei V. Nikitin4, Sergeri A. Tashkun4, Michael Rey2, Vladimir G. Tyuterev2, Mary Ann H. Smith5, Arlan Mantz1
**Institution(s):** *1. Dept. of Physics, Astronomy and Geophysics,Connecticutt College, 2. Groupe de Spectrométrie Moléculaire et Atmosphérique, Université de Reims, 3. Jet Propulsion Laboratory, California Institute of Technology, 4. Laboratory of Theoretical Spectroscopy, V.E. Zuev Institute of Atmospheric Optics, 5. Science Directorate, Nasa Langley*

### 311.35 – Probing the Depths of Jupiter and Saturn at Five-Microns

Both Jupiter and Saturn exhibit dramatic and dynamic changes at all levels of their atmospheres, as probed at various wavelengths, from the cloud tops to the deeper atmosphere and through their stratospheric changes. One common thread that is evident is that many changes observed in the clouds seem to be initiated in the deep atmospheres, via the five micron spectral window on both planets, based on the data acquired from the NASA/InfraRed Telescope Facility (IRTF). Jupiter exhibits traditional 5-micron hot spots; however their inventory varies with time. Similar features at other latitudes (e.g., SEB) may indicate a similar mechanism at play. Another region that underwent global change is recent fade of the northern component of the North Equatorial Belt (NEBn). It was characterized by visible brown barges along its northern boundary that are partially clear, but not as cloudless as 5-micron hot spots. On Saturn, long-term studies of thermal emission from its atmospheric window between 5.1 and 5.2 microns, revealed a detailed cloud structure representing variations of cloud opacity around Saturn's 2-3 bar pressure region that we have tracked since 1995. Since that time, the zonal-mean narrow, dark bands have remained constant and are correlated with variations of zonal jets. We have identified long-term variations in the cloud opacity that do appear to be correlated with seasonal changes, with a decrease of zonal-mean cloud opacity strongly correlated with seasonal changes in insolation. Substantial perturbations to the atmosphere in the northern hemisphere from the great storm of 2010-2011 have led to significant perturbations of the deep cloud field detected at 5.1 microns. The clouding over of the central storm track during early 2011 was followed by a central clearing and clouding over of regions to its north and south, making the storm latitude the clearest atmospheric region ever detected. We will discuss these trends and others over time, in particular, radiances, discrete features for Saturn and present a comparison of these trends with high quality images from the amateur community to identify correlation/anitcorrelations of the visible cloud field.

**Author(s): Padma A. Yanamandra-Fisher2**, Sara M. Gutierrez3, Anna Payne4, Glenn S Orton1, James Sinclair1
**Institution(s):** *1. CIT/Jet Propulsion Laboratory, 2. Space Science Institute, 3. University of California, Berkeley, 4. Wellesly College*

## 312 – Future Missions, Instruments and Facilities

### 312.01 – Historical trends of participation of women in robotic spacecraft missions

For many planetary scientists, being involved in a spacecraft mission is the highlight of a career. Many young scientists hope to one day be involved in such a mission. We will look at the science teams of several flagship-class spacecraft missions to look for trends in the representation of groups that are underrepresented in science. We will start with The Galileo, Cassini, and Europa missions to the outer solar system as representing missions that began in the 1980s, 1990s and 2010s respectively. We would also like to extend our analysis to smaller missions and those to targets other than the outer solar system.

**Author(s): Julie A. Rathbun8**, Luke Dones6, Pamela Gay5, Barbara Cohen4, Sarah Horst3, Emily Lakdawalla7, James Spickard8, Moses Milazzo9, Kunio M Sayanagi2, Joanna Schug1
**Institution(s):** *1. College of William and Mary, 2. Hampton University, 3. Johns Hopkins, 4. NASA Marshall, 5. SIUE, 6. southwest Research Institute, 7. The Planetary Society, 8. Univ. of Redlands, 9. USGS Flagstaff*

### 312.02 – NASA's Planetary Data System: Support for the Delivery of Derived Data Sets at the Atmospheres Node

NASA's Planetary Data System is charged with archiving electronic data products from NASA planetary missions that are sponsored by NASA's Science Mission Directorate. This archive, currently organized by science disciplines, uses standards for describing and storing data that are designed to enable future scientists who are unfamiliar with the original experiments to analyze the data, and to do this using a variety of computer platforms, with no additional support. These standards address the data structure, description contents, and media design. The new requirement in the NASA ROSES-2015 Research Announcement to include a Data Management Plan will result in an increase in the number of derived data sets that are being delivered to the PDS. These data sets may come from the Planetary Data Archiving, Restoration and Tools (PDART) program, other Data Analysis Programs (DAPs) or be volunteered by individuals who are publishing the results of their analysis. In response to this increase, the PDS Atmospheres Node is developing a set of guidelines and user tools to make the process of archiving these derived data products more efficient. Here we provide a description of Atmospheres Node resources, including a letter of support for the proposal stage, a communication schedule for the planned archive effort, product label samples and templates in extensible markup language (XML), documentation templates, and validation tools necessary for producing a PDS4-compliant derived data bundle(s) efficiently and accurately.

**Author(s): Nancy J. Chanover1**, Reta Beebe1, Lynn Neakrase1, Lyle Huber1, Shannon Rees1, Danae Hornung1
**Institution(s):** *1. New Mexico State Univ.*

### 312.03 – The Planetary Data System--preparing for a New Decade

In order to improve NASA's ability to serve the Planetary Science Community, the Planetary Data System (PDS) has been transformed. NASA has used the highly successful virtual institute model (e.g., for NASA's Astrobiology Program) to re-compete the Science Nodes within the PDS Structure. The new institute structure will facilitate our efforts within the PDS to improve both archive searchability and product discoverability. We will continue

the adaption of the new PDS4 Standard, and enhance our ability to work with other archive/curation activities within NASA and with the community of space faring nations (through the IPDA). PDS science nodes will continue to work with NASA missions from the initial Announcement of Opportunity through the end of mission to define, organize, and document the data. This process includes peer-review of data sets by members of the science community to ensure that the data sets are scientifically useful, effectively organized, and well documented.
The Science nodes were selected through a Cooperative Agreement Notice (NNH15ZDA006C) which specifically allowed the community to propose specific archive concepts. The selected nodes are: Cartography and Imaging Sciences, Rings-Moon Systems, Planetary Geosciences, Planetary Plasma Interactions, Atmospheres, and Small Bodies. Other elements of the PDS include an Engineering Node, the Navigation and Ancillary Information Facility, and a small project office.
The prime role of the PDS is unchanged. We archive and distribute scientific data from NASA planetary missions, astronomical observations, and laboratory measurements. NASA's Science Mission Directorate sponsors the PDS. Its purpose is to ensure the long-term usability of NASA data and to stimulate advanced research.
In this presentation we discuss recent changes in the PDS, and our future activities to build on the new Institute. Near term efforts include developing a PDS Roadmap for the next decade lead by PDS Chief Scientist, Dr. Ralph McNutt. We are actively seeking community involvement in this process. Please visit our User Support Area at the meeting if you have questions accessing our data sets or providing data to the PDS or about the new PDS structure.

**Author(s): Thomas H. Morgan[2]**, William P. Knopf[1], Edwin J. Grayzeck[2]
**Institution(s):** *1. NASA HQ, 2. NASA/GSFC*

### 312.04 – Metadata Design in the New PDS4 Standards - Something for Everybody

The Planetary Data System (PDS) archives, supports, and distributes data of diverse targets, from diverse sources, to diverse users. One of the core problems addressed by the PDS4 data standard redesign was that of metadata - how to accommodate the increasingly sophisticated demands of search interfaces, analytical software, and observational documentation into label standards without imposing limits and constraints that would impinge on the quality or quantity of metadata that any particular observer or team could supply. And yet, as an archive, PDS must have detailed documentation for the metadata in the labels it supports, or the institutional knowledge encoded into those attributes will be lost - putting the data at risk.
The PDS4 metadata solution is based on a three-step approach. First, it is built on two key ISO standards: ISO 11179 "Information Technology - Metadata Registries", which provides a common framework and vocabulary for defining metadata attributes; and ISO 14721 "Space Data and Information Transfer Systems - Open Archival Information System (OAIS) Reference Model", which provides the framework for the information architecture that enforces the object-oriented paradigm for metadata modeling. Second, PDS has defined a hierarchical system that allows it to divide its metadata universe into namespaces ("data dictionaries", conceptually), and more importantly to delegate stewardship for a single namespace to a local authority. This means that a mission can develop its own data model with a high degree of autonomy and effectively extend the PDS model to accommodate its own metadata needs within the common ISO 11179 framework. Finally, within a single namespace - even the core PDS namespace - existing metadata structures can be extended and new structures added to the model as new needs are identified
This poster illustrates the PDS4 approach to metadata management and highlights the expected return on the development investment for PDS, users and data preparers.

**Author(s): Anne C. Raugh[2]**, John S. Hughes[1]
**Institution(s):** *1. Jet Propulsion Laboratory, 2. University of Maryland*

### 312.05 – SPICE Supports Planetary Science Observation Geometry

"SPICE" is an information system, comprising both data and software, providing scientists with the observation geometry needed to plan observations from instruments aboard robotic spacecraft, and to subsequently help in analyzing the data returned from those observations. The SPICE system has been used on the majority of worldwide planetary exploration missions since the time of NASA's Galileo mission to Jupiter. Along with its "free" price tag, portability and the absence of licensing and export restrictions, its stable, enduring qualities help make it a popular choice. But stability does not imply rigidity–improvements and new capabilities are regularly added. This poster highlights recent additions that could be of interest to planetary scientists.
Geometry Finder allows one to find all the times or time intervals when a particular geometric condition exists (e.g. occultation) or when a particular geometric parameter is within a given range or has reached a maximum or minimum.
Digital Shape Kernel (DSK) provides means to compute observation geometry using accurately modeled target bodies: a tessellated plate model for irregular bodies and a digital elevation model for large, regular bodies.
WebGeocalc (WGC) provides a graphical user interface (GUI) to a SPICE "geometry engine" installed at a mission operations facility, such as the one operated by NAIF. A WGC user need have only a computer with a web browser to access this geometry engine. Using traditional GUI widgets–drop-down menus, check boxes, radio buttons and fill-in boxes–the user inputs the data to be used, the kind of calculation wanted, and the details of that calculation. The WGC server makes the specified calculations and returns results to the user's browser.
Cosmographia is a mission visualization program. This tool provides 3D visualization of solar system (target) bodies, spacecraft trajectory and orientation, instrument field-of-view "cones" and footprints, and more.
The research described in this publication was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

**Author(s): Charles Hall Acton[1]**, Nathaniel J Bachman[1], Boris V Semenov[1], Edward D Wright[1]
**Institution(s):** *1. Jet Propulsion Laboratory*

### 312.06 – NASA's Asteroid Redirect Mission (ARM)

The National Aeronautics and Space Administration (NASA) is developing a robotic mission to visit a large near-Earth asteroid (NEA), collect a multi-ton boulder from its surface, and redirect it into a stable orbit around the Moon. Once returned to cislunar space in the mid-2020s, astronauts will explore the boulder and return to Earth with samples. This Asteroid Redirect Mission (ARM) is part of NASA's plan to advance the technologies, capabilities, and spaceflight experience needed for a human mission to the Martian system in the 2030s. Subsequent human and robotic missions to the asteroidal material would also be facilitated by its return to cislunar space. Although ARM is primarily a capability demonstration mission (i.e., technologies and associated operations), there exist significant opportunities to advance our knowledge of small bodies in the synergistic areas of science, planetary defense, asteroidal resources and in-situ resource utilization (ISRU), and capability and technology demonstrations. In order to maximize the knowledge return from the mission, NASA is organizing an ARM Investigation Team, which is being preceded by the Formulation Assessment and Support Team. These teams will be comprised of scientists, technologists, and other qualified and interested individuals to help plan the implementation and execution of ARM. An overview of robotic and crewed segments of ARM, including the mission requirements, NEA targets, and mission operations, will be provided along with a discussion of the potential opportunities associated with the mission.

**Author(s): Paul Abell[2]**, Dan Mazanek3, David Reeves3, Bo Naasz[1], Benjamin Cichy[1]
**Institution(s):** *1. NASA Goddard Space Flight Center, 2. NASA Johnson Space Center, 3. NASA Langley Research Center*

### 312.07 – The Whipple Mission: Exploring the Kuiper Belt and the Oort Cloud

Whipple will characterize the small body populations of the Kuiper Belt and the Oort Cloud with a blind occultation survey, detecting objects when they briefly (~1 second) interrupt the light from background stars, allowing the detection of much more distant and/or smaller objects than can be seen in reflected sunlight. Whipple will reach much deeper into the unexplored frontier of the outer solar system than any other mission, current or proposed. Whipple will look back to the dawn of the solar system by discovering its most remote bodies where primordial processes left their imprint.
Specifically, Whipple will monitor large numbers of stars at high cadences (~12,000 stars at 20 Hz to examine Kuiper Belt events; as many as ~36,000 stars at 5 Hz to explore deep into the Oort Cloud, where events are less frequent). Analysis of the detected events will allow us to determine the size spectrum of bodies in the Kuiper Belt with radii as small as ~1 km. This will allow the testing of models of the growth and later collisional erosion of planetesimals in the early solar system. Whipple will explore the Oort Cloud, potentially detecting objects as far out as ~10,000 AU. This will be the first direct exploration of the Oort Cloud since the original hypothesis of 1950.
Whipple is a Discovery class mission that was proposed to NASA in response to the 2014 Announcement of Opportunity. The mission is being developed jointly by the Smithsonian Astrophysical Observatory, Jet Propulsion Laboratories, and Ball Aerospace & Technologies, with telescope optics from L-3 Integrated Optical Systems and imaging sensors from Teledyne Imaging Sensors.

**Author(s): Charles Alcock[2]**, Michael Brown[1], Tom Gauron[2], Cate Heneghan3, Matthew Holman[2], Almus Kenter[2], Ralph Kraft[2], John Livingstone3, Ruth Murray-Clay5, Paul Nulsen[2], Matthew Payne[2], Hilke Schlichting4, Amy Trangsrud3, Jan Vrtilek[2], Michael Werner3
**Institution(s):** *1. Caltech, 2. Harvard-Smithsonian, CfA, 3. JPL, 4. MIT, 5. UC Santa Barbara*

### 312.08 – Trojan Tour and Rendezvous (TTR): A New Frontiers Mission to Conduct the First Detailed Reconnaissance of the Jupiter Trojan Asteroids

Among the most potentially diagnostic but least explored populations of small bodies are the Jupiter Trojan asteroids, which orbit at ~5 AU in the L4 and L5 Lagrange points of Jupiter. The Trojans provide a unique perspective on solar system history, because their locations and physical, compositional, and mineralogic properties preserve evidence for important gravitational interactions among the giant planets. The locations and orbital properties of more than 6200 Jupiter Trojans are now known, but that is likely only a small fraction of a population of up to ~1e6 Trojans >1 km in size. The Trojans are hypothesized to be either former KBOs scattered into the inner solar system by early giant planet migration and then trapped in L4 and L5, or bodies formed near 5 AU in a more quiescent early solar system.
Important Planetary Decadal Survey questions that can be addressed by studying the Trojans include: (a) How did the giant planets and their satellite systems accrete, and is there evidence that they migrated to new orbital positions? (b) What is the relationship between large and small KBOs? Is the small population derived by impact disruption of the large one? (c) What kinds of surface evolution, radiation chemistry, and surface-atmosphere interactions occur on distant icy primitive bodies? And (d) What are the sources of asteroid groups (Trojans and Centaurs) that remain to be explored by spacecraft?
Here we describe the Trojan Tour and Rendezvous (TTR) New Frontiers mission concept, which is designed to answer these Decadal questions and to test hypotheses for early giant planet migration and solar system evolution. Via close flybys of many of these objects, and orbital characterization of at least one large Trojan, TTR will enable the initial up-close exploration of this population. Our primary mission goals are to characterize the overall surface geology, geochemistry and mineralogy of these worlds; to characterize their internal structure and dynamical properties; to investigate the nature, sources and history of activity on these bodies; and to explore the diversity of the broader Trojan asteroid population.

**Author(s): James F. Bell[1]**, Cathy Olkin3, Julie Castillo-Rogez[2]
**Institution(s):** *1. Arizona State Univ., 2. Jet Propulsion Laboratory / Caltech, 3. Southwest Research Inst.*

### 312.09 – REASON for Europa

The science goal of the Europa multiple flyby mission is to “explore Europa to investigate its habitability”. One of the primary instruments selected for the scientific payload is a multi-frequency, multi-channel ice penetrating radar system. This “Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON)” would revolutionize our understanding of Europa’s ice shell by providing the first direct measurements of its surface character and subsurface structure. REASON will address key questions regarding Europa’s habitability, including the existence of any liquid water, through the innovative use of radar sounding, altimetry, reflectometry, and plasma/particles analyses. These investigations require a dual-frequency radar (HF and VHF frequencies) instrument with simultaneous shallow and deep sounding that is designed for performance robustness in the challenging environment of Europa. The flyby-centric mission configuration is an opportunity to collect and transmit minimally processed data back to Earth and exploit advanced processing approaches developed for terrestrial airborne data sets. The observation and characterization of subsurface features beneath Europa’s chaotic surface requires discriminating abundant surface clutter from a relatively weak subsurface signal. Finally, the mission plan also includes using REASON as a nadir altimeter capable of measuring tides to test ice shell and ocean hypotheses as well as characterizing roughness across the surface statistically to identify potential follow-on landing sites. We will present a variety of measurement concepts for addressing these challenges.

**Author(s): Gerald Wesley Patterson[2]**, Don Blankenship3, Alina Moussessian[1], Jeffrey Plaut[1], Yonggyu Gim[1], Dustin Schroeder[1], Krista Soderlund3, Cyril Grima3, Elaine Chapin[1]
**Institution(s):** *1. Jet Propulsion Laboratory, California Institute of Technology, 2. Johns Hopkins University Applied Physics Laboratory, 3. University of Texas Institute for Geophysics*

### 312.10 – MarsCAT: Mars Array of ionospheric Research Satellites using the CubeSat Ambipolar Thruster

The MarsCAT (Mars Array of ionospheric Research Satellites using the CubeSat Ambipolar Thruster) Mission is a two 6U CubeSat mission to study the ionosphere of Mars proposed for the NASA SIMPLeX opportunity. The mission will investigate the plasma and magnetic structure of the Martian ionosphere, including transient plasma structures, magnetic field structure and dynamics, and energetic particle activity. The transit plan calls for a piggy back ride with Mars 2020 using a CAT burn for MOI, the first demonstration of CubeSat propulsion for interplanetary travel. MarsCAT will make correlated multipoint studies of the ionosphere and magnetic field of Mars. Specifically, the two spacecraft will make in situ observations of the plasma density, temperature, and convection in the ionosphere of Mars. They will also make total electron content measurements along the line of sight between the two spacecraft and simultaneous 3-axis local magnetic field measurements in two locations. Additionally, MarsCAT will demonstrate the performance of new CubeSat telemetry antennas designed at the University of Houston that are designed to be low profile, rugged, and with a higher gain than conventional monopole (whip) antennas. The two MarsCAT CubeSats will have five science instruments: a 3-axis DC magnetometer, adouble-Langmuir probe, a Faraday cup, a solid state energetic particle detector (Science Enhancement Option), and interspacecraft total electron content radio occulation experiment. The MarsCAT spacecraft will be solar powered and equipped with a CAT thruster that can provide up to 4.8 km/s of delta-V, which is sufficient to achieve Mars orbit using the Mars 2020 piggyback. They have an active attitude control system, using a sun sensor and flight-proven star tracker for determination, and momentum wheels for 3-axis attitude control.

**Author(s): Edgar Andrew Bering4**, Lawrence S Pinsky4, Liming Li4, David Jackson4, Ji Chen4, Helen Reed3, Mark Moldwin5, Justin Kasper5, J. P. Sheehan5, James Richard Forbes5, Thomas Heine5, Anthony Case[1], Michael Stevens[1], David G Sibeck[2]
**Institution(s):** *1. Harvard/Smithsonian Center for Astrophysics, 2. NASA/GSFC, 3. Texas A&M University, 4. University of Houston, 5. University of Michigan*

### 312.11 – Linear Ion Traps in Space: The Mars Organic Molecule Analyzer (MOMA) Instrument and Beyond

Historically, quadrupole mass spectrometer (QMS) instruments have been used to explore a wide survey of planetary targets in our solar system, from Venus (Pioneer Venus) to Saturn (Cassini-Huygens). However, linear ion trap (LIT) mass spectrometers have found a niche as smaller, versatile alternatives to traditional quadrupole analyzers.
The core astrobiological experiment of ESA's ExoMars Program is the Mars Organic Molecule Analyzer (MOMA) onboard the ExoMars 2018 rover. The MOMA instrument is centered on a linear (or 2-D) ion trap mass spectrometer. As opposed to 3-D traps, LIT-based instruments accommodate two symmetrical ion injection pathways, enabling two complementary ion sources to be used. In the case of MOMA, these two analytical approaches are laser desorption mass spectrometry (LDMS) at Mars ambient pressures, and traditional gas chromatography mass spectrometry (GCMS). The LIT analyzer employed by MOMA also offers: higher ion capacity compared to a 3-D trap of the same volume; redundant detection subassemblies for extended lifetime; and, a link to heritage QMS designs and assembly logistics. The MOMA engineering test unit (ETU) has demonstrated the detection of organics in the presence of wt.%-levels of perchlorate, effective ion enhancement via stored waveform inverse Fourier transform (SWIFT), and derivation of structural information through tandem mass spectrometry (MS/MS).
A more progressive linear ion trap mass spectrometer (LITMS), funded by the NASA ROSES MatISSE Program, is being developed at NASA GSFC and promises to augment the capabilities of the MOMA instrument by way of: an expanded mass range (i.e., 20 – 2000 Da); detection of both positive and negative ions; spatially resolved (<1 mm) characterization of individual rock core layers; and, evolved gas analysis and GCMS with pyrolysis up to 1300° C (enabling breakdown of refractory phases). The Advanced Resolution Organic Molecule Analyzer (AROMA) instrument, being developed through NASA PICASSO and ESA Research and Development Programs, combines a highly capable LIT front end (a la LITMS) with a high-resolution Orbitrap™ (a la CosmOrbitrap) mass analyzer to enable disambiguation of complex molecular signals in organic-rich targets.

**Author(s): Ricardo Arevalo[8]**, William Brinckerhoff[8], Paul Mahaffy[8], Friso van Amerom7, Ryan Danell3, Veronica Pinnick[1], Xiang Li[1], Lars Hovmand5, Stephanie Getty[8], Andrej Grubisic[2], Fred Goesmann[6], Hervé Cottin4
**Institution(s):** *1. CRESST, University of Maryland Baltimore County, 2. CRESST, University of Maryland College Park, 3. Danell Consulting, Inc., 4. Laboratoire Interuniversitaire des Systèmes Atmosphériques, 5. Linear Labs, LLC, 6. Max-Planck-Institut für Sonnensystemforschung, 7. Mini-Mass Consulting, 8. NASA Goddard Space Flight Center*

### 312.12 – Exploring near Earth object's activity with cubesats: low surface brightness

Ever smaller Near Earth Objects (NEOs) continue to be discovered, with most potentially hazardous ones already surveyed and ongoing plans for space missions to deflect and mine them in the near future. These transitional objects in relatively unstable orbits have recently experienced collisional or dynamical encounters that have sent them to Earth's vicinity. Finding comet-like activity (sublimation and ejected dust) is necessary to understand their origin, recent history, and evolution. Mommert et al (2014) have recently discovered cometary activity on the third largest NEO (3552) Don Quixote using near-Infrared imaging from Spitzer/IRAC they detect both a coma and tail as extended emission they identify as $CO_2$ ice sublimation. This activity has gone unnoticed due to either sporadic activity or the relatively low surface brightness in optical wavelengths of light reflecting off dust, 26 mag/arcsec$^2$ which necessarily imposes an extreme bias against detection. We propose to find this activity directly in the optical by going above the atmosphere.
We are developing a 6U Cubesat to carry a 20cm aperture telescope. The volume restrictions impose a deployment system design for the telescope. We will study the optimal mission and optical setup for our goals, including the feasibility of a novel coronagraph to increase the sensitivity. Detecting NEO activity requires stability and low instrumental noise over many hours. Atmosphere's varying point spread function (PSF), coupled with the extended PSF of reflective telescopes, lead us to propose to develop the concept and technology to manage a refractive telescope in space with the potential inclusion of a coronagraph, optimized for detecting faint features near bright targets. The experiment considers targeting nearby NEOs and optimizing observations for low surface brightness.

**Author(s): Cesar Fuentes[1]**, Marcos Diaz[1], Claudio Falcon[1], Marcel Clerc[1]
**Institution(s):** *1. Universidad de Chile*

### 312.13 – Fast Transit Access to the Outer Solar System

We explore the capability of a VASIMR® reusable probe "catapult" concept to send a 4000-5000 kg spacecraft to Jupiter on a Hohmann-like transfer orbit, arriving in just 36 months elapsed time. The VASIMR® performs a slingshot pass close to the Sun and uses the high level of available solar energy to produce a sustained burst of high thrust. Enough kinetic energy is provided to the probe to reach Jupiter orbit within 0.7-1.4 AU. The Catapult release the probe with enough speed to reach Jupiter in three years, and returns to Earth for another mission. This study identifies the important parameters in the probe ejector operation (power level, propellant mass, payload release point, distance of closest approach to the Sun), and scan these parameters to understand and optimize the capabilities of the proposed system. We assume that the Catapult and its payload begin at the Earth's sphere of influence (SOI), and are coasting in the Earth's orbit about the Sun. The VASIMR® engine's power rating must match the peak power available when the spacecraft is closest to the Sun. The solar array is assumed to be a planar array rather than a concentrator since it will have to operate near the Sun, where a concentrator would overheat photovoltaic cells. The feasibility of not releasing the payload and using the VASIMR® to provide thrust for the duration of the transfer orbit will also be examined. In this scenario, the VASIMR® RF generators could serve double duty as radar RF sources.

**Author(s): Jared Squire[1]**, Edgar Bering[2], Matthew Giambusso[2], Mark Carter[1], Andrew Ilin[1], Franklin R Chang Diaz[1]
**Institution(s):** *1. AdAstra Rocket Company, 2. University of Houston*

### 312.14 – Modeling momentum transfer by the DART spacecraft into the moon of Didymos

The Asteroid Impact and Deflection Assessment (AIDA) mission is a joint concept between NASA and ESA designed to test the effectiveness of a kinetic impactor in deflecting an asteroid. The mission is composed of two independent, but mutually supportive, components: the NASA-led Double Asteroid Redirect Test (DART), and the ESA-led Asteroid Impact Monitoring (AIM) mission. The spacecraft will be sent to the near-Earth binary asteroid 65803 Didymos, which makes unusually close approaches to Earth in 2022 and 2024. These close approaches make it an ideal target for a kinetic impactor asteroid deflection demonstration, as it will be easily observable from Earth-based observatories. The ~2 m3, 300

kg DART spacecraft will impact the moon of the binary system at 6.25 km/s. The deflection of the moon will then be determined by the orbiting AIM spacecraft and from ground-based observations by measuring the change in the moon's orbital period. A modeling study supporting this mission concept was performed to determine the expected momentum transfer to the moon following impact. The combination of CTH hydrocode models, analytical scaling predictions, and *N*-body *pkdgrav* simulations helps to constrain the expected results of the kinetic impactor experiment.
To better understand the large parameter space (including material strength, porosity, impact location and angle), simulations of the DART impact were performed using the CTH hydrocode. The resultant crater size, velocity imparted to the moon, and momentum transfer were calculated for all cases. For "realistic" asteroid types, simulated DART impacts produce craters with diameters on the order of 10 m, an imparted $\Delta v$ of 0.5–2 mm/s and a dimensionless momentum enhancement ("beta factor") of 1.07–5 for targets ranging from a highly porous aggregate to a fully dense rock. These results generally agree with predictions from theoretical and analytical studies. Following impact, *pkdgrav* simulations of the system evolution track changes in the orbital period of the moon and examine the effects of the shapes of Didymos and its moon on the deflection. These simulations indicate that the shapes of the bodies can influence the subsequent dynamics of the moon.

**Author(s): Angela M Stickle[1]**, Justin A Atchison[1], Olivier S Barnouin[1], Andy F Cheng[1], Carolyn M Ernst[2], Derek C Richardson[2], Andy S Rivkin[1]
**Institution(s):** *1. Johns Hopkins University Applied Physics Laboratory, 2. University of Maryland*

### 312.16 – Fourier transform spectroscopy for future planetary missions

Thermal-emission infrared spectroscopy is a powerful tool for exploring the composition, temperature structure, and dynamics of planetary atmospheres; and the temperature of solid surfaces. A host of Fourier transform spectrometers (FTS) such as Mariner IRIS, Voyager IRIS, and Cassini CIRS from NASA Goddard have made and continue to make important new discoveries throughout the solar system.
Future FTS instruments will have to be more sensitive (when we concentrate on the colder, outer reaches of the solar system), and less massive and less power-hungry as we cope with decreasing resource allotments for future planetary science instruments. With this in mind, NASA Goddard was funded via the Planetary Instrument Definition and Development Progrem (PIDDP) to develop CIRS-lite, a smaller version of the CIRS FTS for future planetary missions. Following the initial validation of CIRS-lite operation in the laboratory, we have been acquiring atmospheric data in the 8-12 micron window at the 1.2 m telescope at the Goddard Geophysical and Astronomical Observatory (GGAO) in Greenbelt, MD. Targets so far have included Earth's atmosphere (in emission, and in absorption against the moon), and Venus.
We will present the roadmap for making CIRS-lite a viable candidate for future planetary missions.

**Author(s): John C. Brasunas[1]**, Tilak Hewagama[2], John R Kolasinski[1], Theodor Kostiuk[1]
**Institution(s):** *1. NASA'S GSFC, 2. University of Maryland*

### 312.17 – Planetary Science with the Stratospheric Observatory for Infrared Astronomy (SOFIA)

The Stratospheric Observatory for Infrared Astronomy (SOFIA) is currently conducting the third annual Cycle of guest investigator observing programs. Programs selected for the fourth Cycle (2016) were announced in October. The planetary science community has made a significant showing in all proposal Cycles, comprising approximately 15% of the time awarded in Cycles 1-3. SOFIA offers observers access to the complete infrared spectrum, with much less atmospheric absorption than from even the finest ground-based telescope sites. New capabilities include high-resolution spectroscopy in the mid-infrared with the Echelon-Cross-Echelle Spectrograph (EXES) that allows spectroscopy of molecules from narrow stratospheric lines of planetary atmospheres, plus imaging spectroscopy with the Field Imaging Far-Infrared Line Spectrometer (FIFI-LS) capable, for example, of simultaneous observations in 9 spatial pixels in each of two far-infrared spectral lines. Also, the FLITECAM near-IR and FORCAST mid-IR cameras include grisms that allow moderate-resolution spectral imaging at wavelengths inaccessible from the ground, and HIPO and FPI+ high-speed photometric imagers are capable of high-S/N measurements of stellar occultations and exoplanet transits. Planetary science targets observed to date include comets ISON and PanSTARRS, main belt asteroids, Mars, Jupiter, Neptune, Pluto, Europa, exoplanets, and debris disks. This poster will showcase science highlights, give details regarding the SOFIA observatory and instrument capabilities, and present observing program statistics.

**Author(s): Dana E. Backman[1]**, William T. Reach[1]
**Institution(s):** *1. SOFIA*

### 312.18 – Capabilities of the Thirty-Meter Telescope (TMT) for Solar System Astronomy

The TMT will consist of a 30-m filled-aperture segmented primary mirror and will include non-sidereal rate tracking capabilities for observing Solar System objects. Its sensitivity will be 14 times larger than that of 8-m class telescopes for seeing-limited observations -up to 200 times larger for background limited adaptive optics (AO) observations- and will allow high angular/spatial resolution with diffraction-limited capability in the near infrared. AO guiding will accommodate faint, small angular size solar system objects to serve as natural guide stars for non-sidereal observations. For Kuiper belt objects (KBOs), on-instrument wavefront sensors can crawl the field-of-view to look for background natural stars that can be used for tip/tilt correction. We will describe the main characteristics of the Thirty Meter Telescope, its first light instrumentation suite, and the most relevant science-driven requirements for its design, emphasizing the strengths of the TMT for Solar System astronomical research. Some real-case scenarios of sensitivities for solar system targets will be presented for the first-light instruments.
Complementary information about TMT, and the opportunities it offers for planetary science research, will be presented at this meeting by Dumas et al., and at the TMT Solar System Town Hall event on Tuesday.
The international TMT partnership includes Canada, China, India, Japan, Caltech, the University of California, and Funding is also provided by the Gordon and Betty Moore Foundation. AURA is an Associate Member of TMT on behalf of the US national community. Through a cooperative agreement with the NSF, TMT and a US TMT Science Working Group are developing a model for potential US national partnership in the TMT.

**Author(s): Angel Otarola3**, Christophe Dumas3, Karen Meech[1], Tomohiko Sekiguchi[2], Warren Skidmore3, Feng Tian4, Tony Travouillon3, Michael H. Wong5, Brent Ellerbroek3, Luc Simard3
**Institution(s):** *1. Institute for Astronomy, University of Hawaii, 2. Hokkaido University of Education, 3. TMT International Observatory, 4. Tsinghua University, 5. University of California at Berkeley*

### 312.19 – The TMT International Observatory: A quick overview of future opportunities for planetary science exploration

The construction of the Thirty-Meter-Telescope International Observatory (TIO) is scheduled to take about eight years, with first-light currently planned for the horizon 2023/24, and start of science operations soon after. Its innovative design, the unequalled astronomical quality of its location, and the scientific capabilities that will be offered by its suite of instruments, all contribute to position TIO as a major ground-based facility of the next decade.
In this talk, we will review the expected observing performances of the facility, which will combine adaptive-optics corrected wavefronts with powerful imaging and spectroscopic capabilities. TMT will enable ground-based exploration of our solar system -

and planetary systems at large - at a dramatically enhanced sensitivity and spatial resolution across the visible and near-/thermal- infrared regimes. This sharpened vision, spanning the study of planetary atmospheres, ring systems, (cryo–)volcanic activity, small body populations (asteroids, comets, trans-Neptunian objects), and exoplanets, will shed new lights on the processes involved in the formation and evolution of our solar system, including the search for life outside the Earth, and will expand our understanding of the physical and chemical properties of extra-solar planets, complementing TIO's direct studies of planetary systems around other stars.
TIO operations will meet a wide range of observing needs. Observing support associated with "classical" and "queue" modes will be offered (including some flavors of remote observing). The TIO schedule will integrate observing programs so as to optimize scientific outputs and take into account the stringent observing time constraints often encountered for observations of our solar system such as, for instance, the scheduling of target-of-oportunity observations, the implementation of short observing runs, or the support of long-term "key-science" programmes.
Complementary information about TIO, and the opportunities it offers for planetary science research, will be presented at this meeting by Otarola et al., in addition to the TMT Solar System Town Hall event on Tuesday.

**Author(s): Christophe Dumas5**, Sandra Dawson5, Angel Otarola5, Warren Skidmore5, Gordon Squires5, Tony Travouillon5, Thomas K. Greathouse4, Jian-Yang Li2, Junjun Lu1, Frank Marchis3, Karen J. Meech7, Michael H. Wong6
**Institution(s):** *1. California Institute of Technology, 2. Planetary Science Institute, 3. SETI Institute, 4. Southwest Research Institute, 5. Thirty-Meter-Telescope International Observatory, 6. UC Berkeley, 7. University of Hawaii*

## 312.20 – The NASA Infrared Telescope Facility (IRTF): New Observational Capabilities

The NASA Infrared Telescope Facility (IRTF) is a 3.0-m infrared telescope located at an altitude of 4.2 km near the summit of Mauna Kea on the island of Hawaii. The IRTF was established by NASA to support planetary science missions. Current instruments include: (1) SpeX, a 0.7-5.3 µm moderate resolution spectrograph with a slit-viewing camera that is also an imager, (2) MORIS, a high-speed CCD imager attached to SpeX for simultaneous visible and near-infrared observations, and (3) CSHELL, a 1-5 µm high-resolution spectrograph. MORIS can also be used as a visible wavelength guider for SpeX. Detector upgrades have recently been made to SpeX. We discuss new observational capabilities resulting from completion of a new echelle spectrograph for 1-5 µm with resolving power of 70,000 with a 0.375 arcsec slit. This instrument will be commissioned starting in the spring of 2016. We also plan to restore to service our 8-25 µm camera, MIRSI. It will be upgraded with a closed-cycle cooler that will eliminate the need for liquid helium and allow continuous use of MIRSI on the telescope. This will enable thermal observations of NEOs on short notice. We also plan to upgrade MIRSI to have a simultaneous visible imager for guiding and for photometry. The IRTF supports remote observing from any site. This eliminates the need for travel to the observatory and short observing time slots can be supported. We also welcome onsite visiting astronomers. In the near future we plan to implement a low-order wave-front sensor to allow real-time focus and collimation of the telescope. This will greatly improve observational efficiency. For further information on the IRTF and its instruments including visitor instruments, see: http://irtfweb.ifa.hawaii.edu/. We gratefully acknowledge the support of NASA contract NNH14CK55B, NASA Science Mission Directorate.

**Author(s): Alan T. Tokunaga1**, S. J. Bus1, Michael S. Connelley1, John T. Rayner1
**Institution(s):** *1. Univ. of Hawaii*

## 312.21 – The (new) Mid-Infrared Spectrometer and Imager (MIRSI) for the NASA Infrared Telescope Facility

The Mid-Infrared Spectrometer and Imager (MIRSI) was developed at Boston University and has been in use since 2002 on the Infrared Telescope Facility (IRTF), making observations of asteroids, planets, and comets in the 2 - 25 µm wavelength range. Recently the instrument has been unavailable due to electronics issues and the high cost of supplying liquid helium on Maunakea. We have begun a project to upgrade MIRSI to a cryocooler-based system with new array readout electronics and a dichroic and optical camera to simultaneously image the science field for image acquisition and optical photometry. The mechanical cryocooler will enable MIRSI to be continuously mounted on the IRTF multiple instrument mount (MIM) along with the other facility instruments, making it available to the entire community for multi-wavelength imaging and spectral observations. We will propose to use the refurbished MIRSI to measure the 10 µm flux from Near Earth Objects (NEOs) and determine their diameters and albedos through the use of a thermal model. We plan to observe up to 750 NEOs over the course of a three year survey, most of whose diameters will be under 300 meters. Here we present an overview of the MIRSI upgrade and give the current status of the project. This work is funded by the NASA Solar System Observations/NEOO program.

**Author(s): Joseph L. Hora2**, David Trilling4, Michael Mommert4, Howard A. Smith2, Nicholas Moskovitz3, Alan P. Marscher1, Alan Tokunaga5, Lars Bergknut5, Morgan Bonnet5, Schelte J. Bus5, Michael Connelly5, John Rayner5, Darryl Watanabe5
**Institution(s):** *1. Boston University, 2. Harvard-Smithsonian, CfA, 3. Lowell Observatory, 4. Northern Arizona University, 5. University of Hawaii*

## 312.22 – Solar System science with the Large Synoptic Survey Telescope

The Large Synoptic Survey Telescope (LSST; http://lsst.org) will be a large-aperture, wide-field, ground-based telescope that will survey half the sky every few nights in six optical bands from 320 to 1050 nm. It will explore a wide range of astrophysical questions, ranging from performing a census of the Solar System, to examining the nature of dark energy. It is currently in construction, slated for first light in 2019 and full operations by 2022.
The LSST will survey over 20,000 square degrees with a rapid observational cadence, to typical limiting magnitudes of r~24.5 in each visit (9.6 square degree field of view). Automated software will link the individual detections into orbits; these orbits, as well as precisely calibrated astrometry (~50mas) and photometry (~0.01-0.02 mag) in multiple bandpasses will be available as LSST data products. The resulting data set will have tremendous potential for planetary astronomy; multi-color catalogs of hundreds of thousands of NEOs and Jupiter Trojans, millions of asteroids, tens of thousands of TNOs, as well as thousands of other objects such as comets and irregular satellites of the major planets. LSST catalogs will increase the sample size of objects with well-known orbits 10-100 times for small body populations throughout the Solar System, enabling a major increase in the completeness level of the inventory of most dynamical classes of small bodies and generating new insights into planetary formation and evolution. Precision multi-color photometry will allow determination of lightcurves and colors, as well as spin state and shape modeling through sparse lightcurve inversion. LSST is currently investigating survey strategies to optimize science return across a broad range of goals. To aid in this investigation, we are making a series of realistic simulated survey pointing histories available together with a Python software package to model and evaluate survey detections for a user-defined input population. Preliminary metrics from these simulations are shown here; the community is invited to provide further input.

**Author(s): Lynne Jones4**, Mike Brown1, Zeljko Ivezić4, Mario Jurić4, Renu Malhotra2, David Trilling3
**Institution(s):** *1. CalTech, 2. Lunar and Planetary Lab, 3. Northern Arizona University, 4. Univ. of Washington*

## 312.23 – The Space Launch System and Missions to

**the Outer Solar System**

**Introduction:** America's heavy lift launch vehicle, the Space Launch System, enables a variety of planetary science missions. The SLS can be used for most, if not all, of the National Research Council's Planetary Science Decadal Survey missions to the outer planets. The SLS performance enables larger payloads and faster travel times with reduced operational complexity.
**Europa Clipper:** Our analysis shows that a launch on the SLS would shorten the Clipper mission travel time by more than four years over earlier mission concept studies.
**Jupiter Trojan Tour and Rendezvous:** Our mission concept replaces Advanced Stirling Radioisotope Generators (ASRGs) in the original design with solar arrays. The SLS capability offers many more target opportunities.
**Comet Surface Sample Return:** Although in our mission concept, the SLS launches later than the NRC mission study (November 2022 instead of the original launch date of January 2021), it reduces the total mission time, including sample return, by two years.
**Saturn Apmospheric Entry Probe:** Though Saturn arrivial time remains the same in our concept as the arrival date in the NRC study (2034), launching on the SLS shortens the mission travel time by three years with a direct ballistic trajectory.
**Uranus Orbiter with Probes:** The SLS shortens travel time for an Uranus mission by four years with a Jupiter swing-by trajectory. It removes the need for a solar electric propulsion (SEP) stage used in the NRC mission concept study.
**Other SLS Science Mission Candidates:** Two other mission concepts we are investigating that may be of interest to this community are the Advanced Technology Large Aperature Space Telescope (ATLAST) and the Interstellar Explorer also referred to as the Interstellar Probe.
**Summary:** The first launch of the SLS is scheduled for 2018 followed by the first human launch in 2021. The SLS in its evolving configurations will enable a broad range of exploration missions which will serve to recapture the enthusiasm and commitment that permeated the planetary exploration community during the early years of robotic exploration.

**Author(s): Kurt K. Klaus[1]**, Kevin Post[1]
**Institution(s):** *1. The Boeing Company*

### 312.24 – THEO: Testing the Habitability of Enceladus's Ocean

Saturn's moon Enceladus offers a unique opportunity in the search for life and habitable environments beyond Earth, a key theme of the 2013 Decadal Survey as it informs our understanding of life and habitability on our own planet by addressing (1) the limits of life under colder, fainter sun conditions, (2) the importance of hydrothermal alteration in the origin of life, and (3) the distribution of molecules in the solar system that may have served as the precursors for life. Plumes of predominately water vapor and ice spew from the south pole of Enceladus. Cassini's data suggest these plumes are sourced by a liquid reservoir beneath the moon's icy crust that contains organics, salts, and water-rock interaction derivatives. Thus, the ingredients for life as we know it— liquid water, hydrocarbons, and energy sources— are available in Enceladus's subsurface ocean. We only have to sample the plumes to investigate this hidden ocean environment.
With the help of TeamX, the 2015 JPL Planetary Science Summer School student participants developed a proof of concept Enceladus New Frontiers-class solar-powered orbiter. The mission, Testing the Habitability of Enceladus's Ocean (THEO) conducts remote sensing and in-situ analyses with the following instrument suite: a mass spectrometer, a sub-mm radiometer-spectrometer, a camera, and two magnetometers. Measurements from these instruments can address four key questions for ascertaining Enceladean ocean habitability within the context of the moon's geological activity. How are the plumes and ocean connected? Is there evidence of biological processes? Are the abiotic conditions of the ocean suitable for habitability? What mechanisms maintain the liquid state of the ocean? By taking advantage of the opportunity Enceladus's plumes offer, THEO represents a viable, solar-powered option for exploring the potentially habitable ocean worlds of the outer solar system. This work was carried out at JPL/Caltech under a contract with NASA.

**Author(s): Shannon MacKenzie[12]**, Tess Caswell[1], Matteo Crismani[4], Kevin DeBruin[5], Jasmeet Dhaliwal[11], Jason Hofgartner[3], Akshata Krishnamurthy[6], Kristen John[7], Charity Phillips-Lander[15], Cecilia Leung[10], Joseph O'Rourke[2], Elaine Petro[13], Samson Phan[9], Kathryn Powell[16], E. Natasha Stavros[5], Casey Steuer[14], Vivian Sun[1], Jut Wynne[8], Charles Budney[5], Karl Mitchell[5]
**Institution(s):** *1. Brown University, 2. California Institute of Technology, 3. Cornell University, 4. CU Boulder, 5. Jet Propulsion Laboratory, California Institute of Technology, 6. Massachusetts Institute of Technology, 7. NASA, 8. Northern Arizona University, 9. Stanford University, 10. University of Arizona, 11. University of California San Diego, 12. University of Idaho, 13. University of Maryland, 14. University of Michigan, 15. University of Oklahoma, 16. Washington University*

### 312.25 – Deliverable water from small NEOs to DRLO

We have developed a simplified mission model to estimate the quantity of deliverable water from small NEOs to distant retrograde lunar orbit (DRLO) as a function of Earth-return trip time and $\Delta v$. Our model is designed to be analytically simple, computationally efficient, and close enough to optimal to provide a realistic but conservative assessment of the relevant parameters. The challenge stems from the fact that we are not considering a mission to a specific, known target, but rather missions to the ensemble of NEOs in a model population. To further simplify the analysis we treat Earth's heliocentric orbit as circular with a semi-major axis of 1 au and zero inclination.

**Author(s): Robert Jedicke[3]**, Joel Sercel[2], Karen Morenz[4], Leslie S. Gertsch[1]
**Institution(s):** *1. Missouri University of Science and Technology, 2. TransAstra Corp., 3. University of Hawaii, 4. University of Toronto*

### 312.26 – Laboratory Spacecraft Data Processing and Instrument Autonomy: AOSAT as Testbed

Recent advances in small spacecraft allow for their use as orbiting microgravity laboratories (e.g. Asphaug and Thangavelautham LPSC 2014) that will produce substantial amounts of data. Power, bandwidth and processing constraints impose limitations on the number of operations which can be performed on this data as well as the data volume the spacecraft can downlink. We show that instrument autonomy and machine learning techniques can intelligently conduct data reduction and downlink queueing to meet data storage and downlink limitations. As small spacecraft laboratory capabilities increase, we must find techniques to increase instrument autonomy and spacecraft scientific decision making. The Asteroid Origins Satellite (AOSAT) CubeSat centrifuge will act as a testbed for further proving these techniques. Lightweight algorithms, such as connected components analysis, centroid tracking, K-means clustering, edge detection, convex hull analysis and intelligent cropping routines can be coupled with the tradition packet compression routines to reduce data transfer per image as well as provide a first order filtering of what data is most relevant to downlink. This intelligent queueing provides timelier downlink of scientifically relevant data while reducing the amount of irrelevant downlinked data. Resulting algorithms allow for scientists to throttle the amount of data downlinked based on initial experimental results. The data downlink pipeline, prioritized for scientific relevance based on incorporated scientific objectives, can continue from the spacecraft until the data is no longer fruitful. Coupled with data compression and cropping strategies at the data packet level, bandwidth reductions exceeding 40% can be achieved while still downlinking data deemed to be most relevant in a double blind study between scientist and algorithm. Applications of this technology allow for the incorporation of instrumentation which produces significant data volumes on small spacecraft without comparable increases to power and bandwidth budgets.

**Author(s): Jack Lightholder[1]**, Erik Asphaug[1], Jekan Thangavelautham[1]
**Institution(s):** *1. Arizona State University*

## 400 – Jovian Planet Atmospheres: Storms and Upper Atmosphere

### 400.01 – Spectral analysis of Uranus' 2014 bright storm with VLT/SINFONI

Observations by amateur observers of an extremely bright storm system in Uranus' atmosphere in September 2014 triggered an international campaign to view this feature with many telescopes across the world. Near infrared observations of the storm system were acquired in October/November 2014 with SINFONI on ESO's Very Large Telescope (VLT) in Chile. SINFONI is an Integral Field Unit spectrometer, recording 64 × 64 pixel images with 2048 wavelengths/pixel using adaptive optics. H-band (1.43 – 1.87 μm) image 'cubes' were obtained at spatial resolutions of ~ 0.1″ per pixel. The observations show that the centre of the storm feature shifts markedly with increasing altitude, moving in the retrograde direction and slightly poleward with increasing altitude. A faint 'tail' of more reflective material was also seen to the immediate south of the storm, which again trails in the retrograde direction. The observed spectra were analysed with the radiative transfer and retrieval code, NEMESIS (Irwin et al., 2008). We find that the storm is well-modelled using either two main cloud layers of a 5-layer aerosol model based on Sromovsky et al. (2011) or employing the simpler two-cloud-layer model of Tice et al. (2013). The deep component appears to be caused by a brightening (i.e. an increase in reflectivity) and increase in altitude of the main tropospheric cloud deck at 2 – 3 bars for both models, while the upper component of the feature appears to be due to either a thickening of the tropospheric haze of the 2-layer model or a vertical extension of the upper tropospheric cloud of the 5-layer model, assumed to be composed of methane ice and based at the assumed methane condensation level at 1.23 bar. For the 5-layer model we also found this methane ice cloud to be responsible for the faint 'tail' seen to the feature's south and the brighter polar 'hood' seen in all observations polewards of ~ 45°N.
During the twelve days between our sets of observations the higher-altitude component of the feature was observed to have brightened significantly and moved to even higher altitudes, while the deeper component faded.

**Author(s): Patrick Gerard Joseph Irwin5**, Leigh N Fletcher5, Peter L Read5, Dane Tice5, Imke de Pater4, Glenn S Orton[1], Nicholas A Teanby3, Gary R Davis[2]
**Institution(s):** *1. Jet Propulsion Laboratory, 2. Square Kilometre Array Organisation, 3. University of Bristol, 4. University of California, Berkeley, 5. University of Oxford*

### 400.02 – Bright features in Neptune on 2013-2015 from ground-based observations with small (40 cm) and large telescopes (10 m)

Observations of Neptune over the last few years obtained with small telescopes (30-50 cm) have resulted in several detections of bright features on the planet. In 2013, 2014 and 2015, different observers have repeatedly observed features of high contrast at Neptune's mid-latitudes using long-pass red filters. This success at observing Neptune clouds with such small telescopes is due to the presence of strong methane absorption bands in Neptune's spectra at red and near infrared wavelengths; these bands provide good contrast for elevated cloud structures. In each case, the atmospheric features identified in the images survived at least a few weeks, but were essentially much more variable and apparently shorter-lived, than the large convective system recently reported on Uranus [de Pater et al. 2015]. The latest and brightest spot on Neptune was first detected on July 13th 2015 with the 2.2m telescope at Calar Alto observatory with the PlanetCam UPV/EHU instrument. The range of wavelengths covered by PlanetCam (from 350 nm to the H band including narrow-band and wide-band filters in and out of methane bands) allows the study of the vertical cloud structure of this bright spot. In particular, the spot is particularly well contrasted at the H band where it accounted to a 40% of the total planet brightness. Observations obtained with small telescopes a few days later provide a good comparison that can be used to scale similar structures in 2013 and 2014 that were observed with 30-50 cm telescopes and the Robo-AO instrument at Palomar observatory. Further high-resolution observations of the 2015 event were obtained in July 25th with the NIRC2 camera in the Keck 2 10-m telescope. These images show the bright spot as a compact bright feature in H band with a longitudinal size of 8,300 km and a latitudinal extension of 5,300 km, well separated from a nearby bright band. The ensemble of observations locate the structure at -41º latitude drifting at about +24.27º/day or -92.3 m/s consistently with the zonal winds. This work demonstrates excellent opportunities for pro-am collaboration in the study of Neptune and the value of nearly continuous monitoring of the planet by a broad network of amateur collaborators.

**Author(s): Ricardo Hueso9**, Marc Delcroix[8], Christoph Baranec[11], Agustín Sánchez-Lavega9, Josep María Gómez-Forrellad4, Jose Félix Rojas9, Statia Luszcz-Cook[1], Imke de Pater[10], Katherine de Kleer[10], François Colas[6], Joan Guarro7, Peter Goczynski7, Paul Jones7, Willem Kivits7, Paul Maxson7, Michael Phillips7, John Sussenbach7, Anthony Wesley7, Heidi B. Hammel[2], Santiago Pérez-Hoyos9, Iñigo Mendikoa9, Reed Riddle3, Nicholas M. Law[12], Kunio Sayanagi5
**Institution(s):** *1. American Museum of National History, 2. Association of Universities for Research in Astronomy, 3. California Institute of Technology, 4. Fundació Observatori Esteve Duran, 5. Hampton University, 6. IMCCE, Observatoire de Paris, 7. International Outer Planets Watch, Planetary Virtual Observatory Laboratory, 8. Sociéte Astronomique de France, 9. Universidad del País Vasco, 10. University of California, 11. University of Hawaii at Manoa, 12. University of North Carolina*

### 400.03 – An endurign rapidly moving storm as a guide to Saturn's equatorial jet complex structure

Saturn has an intense and broad eastward equatorial jet at cloud level whose variability and meridional and vertical structure are complex and actively debated. Due to its 27º rotation axis tilt and orbital eccentricity, Saturn is under a strong seasonal insolation cycle, enhanced at equator by the ring shadowing periods. These factors make it a good natural laboratory to test models of equatorial jet generation in giant planets. We report on a bright equatorial storm at 6 degrees North latitude observed in 2015 that moved rapidly but steadily at a high speed of 450 $ms^{-1}$, not reported since Voyagers times (Sanchez-Lavega et al., Icarus 147, 405-420, 2000). Imaging with the Hubble Space Telescope (HST) WFC3 showed detailed storm morphology at red wavelengths (689, 750 and 937 nm) confirming its high speed. Other equatorial clouds moved with lower velocities matching the Cassini ISS profile (García-Melendo et al., Icarus, 215, 62-74, 2011), while the storm matches the Voyager 1 and 2 profile. We interpret this result as the simultaneous detection of the wind profile at two separated altitude levels within the cloud layer. In addition, the HST methane band and ultraviolet images, allowed retrieving winds at a third altitude level of motion, in the haze layer above the cloud deck. Combining the current wind data with previous dates allowed us to construct a vertical – meridional section of the structure of Saturn's equatorial jet at cloud level. We discuss the implications of these results on the long-term stability of Saturn's equatorial jet.

**Author(s): Agustin Sanchez-Lavega3**, Mike H Wong5, Amy Simon[2], Ricardo Hueso3, Santiago Perez-Hoyos3, Arrate Antuñano3, Jose Felix Rojas3, Teresa del Rio-Gaztelurrutia3, Naiara Barrado-Izagirre3, Itziar Garate-Lopez3, Enrique Garcia-Melendo3, Jose Francisco Sanz-Requena4, Josep Maria Gomez-Forrellad[1], Imke de Pater5
**Institution(s):** *1. Fundació Observatori Esteve Duran, 2. NASA Goddard Space Flight Center, 3. Universidad del Pais Vasco UPV/EHU, 4. Universidad Europea Miguel de Cervantes, 5. University of California*

### 400.04 – The Clearing of Ammonia and Deeper Clouds in the Wake of Saturn's Great Storm of 2010-2011

Saturn's Great Storm of 2010-2011 produced a planet-encircling wake that slowly transitioned from a region that was mainly dark at 5 microns in February 2011 to a region that was almost entirely bright and remarkably uniform by January 2012 (Momary and Baines, 2014, AAS/DPS Meeting Abstracts). The uniformity and high emission levels suggested that the entire wake region had been cleared not only of the ammonia clouds that the storm had generated, but also of deep aerosols that normally provide significant blocking of the thermal emission from Saturn's warmer deep atmosphere. Measurements of 2.2-cm emission in May 2011 (Jannsen et al. 2013, Icarus 226, 522-535; Laraia et al. 2013, Icarus 226, 641-654) showed that the wake region was becoming "dried out" with respect to ammonia vapor, suggesting that a depletion of $NH_3$ clouds might be occurring. Our analysis of VIMS spectra from December 2012 confirmed a clearing of $NH_3$ particles but showed that two significant cloud layers remained behind: about 5 optical depths (at 2 microns) in a 120-530 mbar layer (needed to match levels of reflected sunlight), and an optically thick cloud near 3.5 bars (needed to limit 5-micron thermal emission). From spectra taken from the same latitude region upstream of the storm in February 2011 we inferred a similar cloud structure, with the main exception being that the deep thermal blocking layer, likely composed of $NH_4SH$ particles, was more spatially variable and at a lower effective pressure (2.9 bars vs. 3.5 bars), reducing 5-micron emission by a factor of 2 or more relative to the cleared region in the wake. While the storm head and early wake region displayed strong signatures of ammonia ice, these were not present prior to the storm, and disappeared completely as part of the wake clearing event. The main reason for the high 5-micron brightness of the cleared region is the removal of cloud particles in the region between about 500 mbar and 3.5 bars. Its exceptional horizontal uniformity remains to be explained.
This research was supported by a grant from NASA's CDAPS program.

**Author(s): Lawrence A. Sromovsky[1]**, Kevin H Baines[1], Patrick M Fry[1]
**Institution(s):** *1. Univ. of Wisconsin, Madison*

### 400.05 – The Evolution of Saturn's Storm-Perturbed Latitudinal Band Determined from Cassini/VIMS Daytime and Nighttime Spectra

Saturn's Great Storm of 2010-2011 was one of the most powerful convective events ever witnessed, as indicated, for example, by its ability to deliver spectrally-identifiable water ice to the top of its convective tower ~200 km above the water vapor condensation level near 20 bar (Sromovsky, L. A., et al., *Icarus* **226**, 402-418. 2013), and by its ability over ~ 6 months to encircle the planet with apparently anvil-like ammonia clouds sheared away from the top of its convective tower(s). Within a half-year after the storm subsided in mid-2011, these globe-encircling anvil-like clouds appeared to have largely disappeared, replaced by a 5-micron-bright band encircling the planet over nearly the same latitude region the storm generated clouds had been, indicating a dramatic decrease in the opacity of aerosols sensitive to 5-micron radiation (heat) emanating from the warm depths of the planet. Here we present quantitative results on the 5-year evolution of this storm-affected, 5-micron-bright region, from its initial appearance associated with a large anti-cyclone that formed in the Spring of 2011 through May 26-27, 2015, using both daytime and nighttime Cassini/VIMS spectral maps. Compared to the "normal", unperturbed regional cloud structure upstream of the storm as observed on Feb 24, 2011, we find that the initial 5-micron-bright region on May 11, 2011 had lost ~60% of its upper-cloud (100-500 mbar) opacity (i. e., nominally, 2.7 opacity post-storm at 2-microns vs 7.1 pre-storm) and that the pressure of an opaque, putatively $NH_4SH$, optically-thick "sheet" cloud dropped in altitude from a pre-storm level of 2.9 bar to the 3.2-bar level post-storm. Subsequently over the next 4 years, the upper-cloud region recovered half of its lost opacity, reaching ~5.6 on March 21, 2014 (and nearly recovered, to ~ 7 in our tentative May 26-27, 2015 data), corresponding to an e-folding time back to pre-storm opacity of 2.7 years, but the lower cloud has dropped down to the 3.3-bar level (rising to ~ 3.0 bar in our tentative analysis of the May 2015 data). Throughout, the region has remained 5-micron-bright, predominantly due to the deeper, warmer level of the opaque putative $NH_4SH$ cloud.

**Author(s): K.H. Baines5**, Larry A Sromovsky5, Patrick M Fry5, Thomas W Moimary3, Sarah Badman[2], Robert H Brown[6], Bonnie J Buratti3, Roger N Clark4, Philip D Nicholson[1], Christophe Sotin3
**Institution(s):** *1. Cornell University, 2. Lancaster University, 3. NASA/Jet Propulsion Laboratory, 4. Planetary Science Institute, 5. SSEC/University of Wisconsin-Madison, 6. University of Arizona*

### 400.06 – Shallow Water Simulations of the Three Last Saturn's Giant Storms

Shallow Water (SW) simulations are used to present a unified study of the polar (1960), equatorial (1990), and mid-latitude (2010) major storms in Saturn nicknamed as Great White Spots (GWS). The 2010 GWS appeared at +40, moved at -30 m s-1 where the Coriolis force is predominant producing an open anticyclone with a high speed peripheral circulation and a cloud front around the convective source; a long-lived anticyclone; and strong zonal advection on the south part of the storm forming a turbulent region. The 1990 GWS onset took place near the equator, between +12 and +5, on the broad prograde equatorial jet (450 m s-1) where equatorial dynamics dominated producing a storm nucleus, with rapid expansion to the west of a Kelvin-Helmholtz instability on the north side of the perturbation due to advection, and trapped equatorial waves which also expanded the storm to the east around the equator. The 1960 GWS appeared at high latitudes (+56) where Coriolis force is predominant in a region where zonal wind velocity is 0 m s-1. SW simulations predict a strong injection of relative vorticity which may produce large anticyclones on the anticyclonic side of the zonal profile, and a quick turbulent expansion on the background cyclonic regions at mid and high latitudes. In general, simulations indicate that negative relative vorticity injected by the storms also defines the natural interaction with the zonal winds at latitudes where the Coriolis force is dominant dictating its large scale dynamical behavior. Numerical experiments on the 1990 storm indicate that the onset of the storm can only be reproduced if the Voyager era background zonal flow is used, which suggests that it dominated the circulation dynamics at the storm's outbreak region at that time. They also reproduce its most important morphological features, and show the production of planetary waves and turbulence. We discuss possible mechanism for the observed equatorial jet alterations during the storm expansion.

**Author(s): Enrique Garcia-Melendo[2]**, Agustin Sanchez-Lavega[1]
**Institution(s):** *1. Fundacio Observatori Esteve Duran, 2. University of the Basque Country*

### 400.07D – Theoretical estimation of the radiative cooling rate in the Jovian troposphere

Jupiter exhibits characteristic cloud activities but their physical mechanism remains poorly understood. Recently, Sugiyama et al. (2014) demonstrated that the Jovian cloud convection may have a significant intermittency in the generation of cumulonimbus clouds with the typical interval length controlled by the radiative cooling rate in the upper troposphere. In spite of such importance as a controlling factor of cloud activity, the tropospheric radiative cooling rate profile has never been systematically quantified for the Jovian system. In the Jovian troposphere, condensable species ($NH_3$, $H_2S$, $H_2O$) and their condensates might significantly contribute to radiative transfer.
Here we show numerical estimates of radiative cooling rate profile under Jovian troposphere condition by using our non-gray radiative transfer model that contains optical properties of gas species ($H_2$, He, $H_2O$, $CH_4$, $NH_3$, $H_2S$, and $PH_3$) and cloud layers made of $H_2O$, $NH_4SH$, and $NH_3$ ice particles. The temperature profile is determined by the radiative-convective equilibrium state satisfying an observed potential temperature of Jovian troposphere. The mean vertical distributions of gas and cloud are given on the basis of the latest hydrodynamic simulation of Jovian cloud convection (Sugiyama et al., 2014) and cosmochemical consideration.
The modeled atmosphere has the tropopause at ~0.38 bar level.

The radiative cooling rate reaches the maximum 15 x $10^{-3}$ K/Jovian day at ~0.5 bar level, then decreases with depth and approaches zero below 5 bar level. This profile is largely determined by the thermal absorption and emission due to gaseous $NH_3$ and $H_2$ with a slight modification by solar heating due to $CH_4$. The cloud layers are found to have only a weak effect on either radiative cooling or heating because their opacities in the longwave radiation are estimated to be very small, which agrees with the observed 5-micron spectrum with high brightness temperatures. The uncertainty in $H_2O$ abundance in deep troposphere would not affect the radiative cooling because $H_2O$ mostly condenses out in the deep region with large optical depths for longwave radiation.

**Author(s): Yasuto Takahashi[1]**, George L Hashimoto[4], Masaki Ishiwatari[1], Yoshiyuki O Takahashi[3], Ko-ichiro Sugiyama[2], Masanori Onishi[3], Kiyoshi Kuramoto[1]
**Institution(s):** *1. Hokkaido University, 2. ISAS/JAXA, 3. Kobe University, 4. Okayama University*

### 400.08D – Seasonal evolution of Saturn's stratosphere

The exceptional duration of the Cassini-Huygens mission enables unprecedented study of Saturn's atmospheric dynamics and chemistry. In Saturn's stratosphere (from 20 hPa to $10^{-4}$ hPa), photochemical and radiative timescales are in the same order as Saturn's revolution period (29.5 years). Consequently, the large seasonal insolation variations experienced by this planet are expected to influence significantly temperatures and abundances of photochemical by-products in this region. We investigate the seasonal evolution of Saturn's stratosphere by measuring meridional and seasonal variations (from 2005 to 2012) of temperature and $C_2H_6$, $C_2H_2$, and $C_3H_8$ abundances using Cassini/CIRS limb observations. We complete this study with the development of a GCM (Global Climate Model), in order to understand the physical processes behind this seasonal evolution. The analysis of the CIRS limb observations show that the lower and upper stratospheres do not exhibit the same trends in their seasonal variations, especially for temperature. In the lower stratosphere, the seasonal temperature contrast is maximal (at 1 hPa) and can be explained by the radiative contributions included in our GCM. In contrast, upper stratospheric temperatures (at 0.01 hPa) are constant from northern winter to spring, at odds with our GCM predictions. This behavior indicates that other physical processes such as gravity waves breaking may be at play. At 1 hPa, $C_2H_6$, $C_2H_2$, and $C_3H_8$ abundances exhibit a striking seasonal stability, consistently with the predictions of the photochemical models of Moses and Greathouse, 2005 and Hue et al., 2015. However, the meridional distributions of these species do not follow the predicted trends, which gives insight on atmospheric dynamics. We perform numerical simulations with the GCM to better understand dynamical phenomena in Saturn's atmosphere. We investigate how the large insolation variations induced by the shadow of the rings influence temperatures and atmospheric dynamics. We also study the characteristics of atmospheric waves in the numerical simulations and compare them to existing observations (Achterberg and Flasar, 1996 ; Orton et al., 2013).

**Author(s): Melody Sylvestre[1]**, Thierry Fouchet[2], Aymeric Spiga[1], Sandrine Guerlet[1]
**Institution(s):** *1. Laboratoire de Météorologie Dynamique, Université Pierre et Marie Curie, 2. LESIA - Observatoire de Paris*

## 401 – Mars's Atmosphere and Surface

### 401.01 – Mars Science Laboratory's rover, Curiosity: Ongoing investigations into the habitability of Mars

NASA's Curiosity rover has the objective to determine whether Mars was habitable. The rover's science team has achieved that and more, including two major firsts in planetary science. First, Gale Crater was determined to once have an aqueous environment and able to support microbial life, evidenced by conglomerates and the detailed analyses of the drill samples [1]. Second, the age dating of rock on another planet – radiogenic and cosmogenic noble gases in a mudstone yielded a K-Ar age of 4.21 ± 0.35 Ga while 3He, 21Ne, and 36Ar yielded surface exposure ages of 78 ± 30 Ma [2], suggesting the potential to find rocks whose organic content has not yet been destroyed by cosmic rays. Indeed, organic compounds have been found in samples from the Sheepbed mudstone [3]. Reports of plumes of methane in the martian atmosphere have defied explanation to date. Curiosity measured a constant background level of atmospheric methane with a mean value of 0.69 ± 0.25 ppbv, consistent with methane released from the degradation of interplanetary dust and meteorites. However, in four consecutive measurements spanning two months, the rover measured a ten-fold increase (7.2 ± 2.1 ppbv), suggesting that methane was actively added from an unknown source [3]. Periodic measurements will continue, perhaps revealing the possible sources of high methane, whether biological or abiological. Enhancing our concept of Mars' capability to support life, the Curiosity rover has detected nitrogen-bearing compounds of 110–300 ppm of nitrate in scooped sand, and 70–1,100 ppm of nitrate in drilled mudstone. Discovery of martian nitrogen has important implications for a nitrogen cycle at some point in martian history [4]. More recent exploration has focused on the investigation of a mudstone-sandstone geologic contact, high Si and H abundances, and organics. These and the latest results from Curiosity will be discussed, exploring the transition of Mars from a habitable world to the desert planet it is today. [1] Grotzinger, et al. Science 343: 388 (2014), [2] Farley, et al. Science 343: 389 (2014), [3] Feissinet et al. JGR, 120: 495-514 (2015), [3] Webster, et al., Science, 347: 415-427 (2015), [4] Stern, et al., PNAS 112: 4245-4250 (2015).

**Author(s): Michael Meyer[2]**, Ashwin Vasavada[1]
**Institution(s):** *1. JPL, 2. NASA HQ*

### 401.02 – Liquid Water Lakes on Mars Under Present-Day Conditions: Sustainability and Effects on the Subsurface

Decades of Mars exploration have produced ample evidence that aqueous environments once existed on the surface. Much evidence supports groundwater emergence as the source of liquid water on Mars [1-4]. However, cases have also been made for rainfall [5] and snow pack melts [6].
Whatever the mechanism by which liquid water is emplaced on the surface of Mars, whether from groundwater seeps, atmospheric precipitation, or some combination of sources, this water would have collected in local topographic lows, and at least temporarily, would have created a local surface water system with dynamic thermal and hydrologic properties. Understanding the physical details of such aqueous systems is important for interpreting the past and present surface environments of Mars. It is also important for evaluating potential habitable zones on or near the surface.
In conjunction with analysis of surface and core samples, valuable insight into likely past aqueous sites on Mars can be gained through modeling their formation and evolution. Toward that end, we built a 1D numerical model to follow the evolution of small bodies of liquid water on the surface of Mars. In the model, liquid water at different temperatures is supplied to the surface at different rates while the system is subjected to diurnally and seasonally varying environmental conditions. We recently simulated cases of cold (275 K) and warm (350 K) water collecting in a small depression on the floor of a mid southern latitude impact crater. When inflows create an initial pool > 3 m deep and infiltration can be neglected, we find that the interior of the pool can remain liquid over a full Mars year under the present cold and dry climate as an ice cover slowly thickens [7]. Here we present new results for the thermal and hydrologic evolution of surface water and the associated subsurface region for present-day conditions when infiltration of surface water into the subsurface is considered.
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**Author(s): Jules M. Goldspiel[1]**
**Institution(s):** *1. Planetary Science Institute*

### 401.03 – $CO_2$-driven formation of gullies on Mars

Since their discovery by the Mars Observer Camera, Martian gullies have attracted considerable attention because they resemble terrestrial debris flows formed by the action of liquid water. This interpretation is now questioned by the discovery of ongoing gully formation occurring in conditions much too cold for liquid water, but with seasonal $CO_2$ frost present and defrosting. However, how a relatively thin seasonal dry ice cover could trigger the formation of decameter large debris flows exhibiting levees and sinuosities as if they were liquid-rich remained mysterious.
We have developed an innovative thermo-physical model of the Martian soil able to compute the seasonal evolution of a column composed of an underlying regolith, a $CO_2$ ice layer, and the atmosphere above. Below the surface, in the $CO_2$ ice layer (when present) and in the regolith, the model simultaneously solves the heat conduction, the radiative transfer through the ice as well as the diffusion, condensation and sublimation of $CO_2$ and the related latent heat exchanges.
We have found that, during the defrosting season, the pores below the ice layer can be filled with $CO_2$ ice, and subject to extreme pressure variations. The subsequent gas fluxes can destabilize the soil and create gas-lubricated debris flows with the observed geomorphological characteristics of the Martian gullies. In particular the viscosity of such flows can be estimated to range from a few tens to a few thousands of Pa.s, similar to water triggered debris flows and consistent with previous calculations on Martian gullies. Importantly, these gas fluidized debris flows can occur below the theoretical angle of repose, which has been a concern in the understanding of gully landforms formation. We also performed model calculations for a wide range of latitudes and slope orientations. These simulations reveal that high-pressure $CO_2$ gas trapping in the subsurface and the subsequent formation of ice within the regolith pores are predicted at latitudes and slope orientations where gullies are observed and not elsewhere. In particular the model explains why gullies are only observed on pole facing slopes between 30° and 45° latitude, and with no orientation preference above 45° latitude.

**Author(s): Cedric Pilorget[1]**, François Forget[2]
**Institution(s):** *1. Institut d'Astrophysique Spatiale, 2. Laboratoire de Meteorologie Dynamique*

### 401.04 – The Coupled Water-Dust Cycles on Mars: An Investigation of Cloud Formation Using MarsCAM-CARMA

Variability in the present day Martian climate is dominated by the impact of atmospheric dust. On Earth, mineral dust is a well known nucleation site for high altitude cirrus clouds. Similarly tenuous water ice and carbon dioxide clouds have been observed on Mars. Their impact is expected to be large, but is historically difficult to model accurately. Here, we present results from the NCAR Community Atmosphere Model for Mars (MarsCAM) coupled with a physically based, state-of-the-art cloud and dust physics package developed for Earth: the Community Aerosol and Radiation Model for Atmospheres (CARMA). Directly modeling heterogeneous nucleation on a time varying, fully interactive dust field provides a first step to better understanding the formation, distribution, and compostion of clouds on present day and early Mars.

**Author(s): Victoria Hartwick[1]**, O. Brian Toon[1]
**Institution(s):** *1. University of Colorado - Boulder*

### 401.05 – Reduced Baroclinicity During Martian Global Dust Storms

The eddy kinetic energy equation is applied to the Mars Analysis Correction Data Assimilation (MACDA) dataset during the pre-winter solstice period for the northern hemisphere of Mars. Traveling waves are triggered by geopotential flux convergence, grow baroclinically, and decay barotropically. Higher optical depth increases the static stability, which reduces vertical and meridional heat fluxes. Traveling waves during a global dust storm year develop a mixed baroclinic/barotropic growth phase before decaying barotropically. Baroclinic energy conversion is reduced during the global dust storm, but eddy intensity is undiminished. Instead, the frequency of storms is reduced due to a stabilized vertical profile.

**Author(s): Joseph Battalio[1]**, Istvan Szunyogh[1], Mark Lemmon[1]
**Institution(s):** *1. Texas A&M University*

### 401.06 – The effect of a temperature-dependent contact parameter on Mars cloud formation

Modeling the current water cycle on Mars is a complex problem that at present remains a scientific challenge. The water cycle is highly coupled to atmospheric temperature, dust, surface ice temperature, atmospheric transport and mixing (i.e. planetary boundary layer (PBL) processes, and radiation, just to name a few. One of the main features of Mars' water cycle is the formation of the aphelion cloud belt. Clouds are formed at altitude (10-40 km) within the subtropics during the aphelion season (Ls=60°-120°). In general the aphelion cloud belt forms at higher altitudes compared to the polar and high-latitude clouds, and therefore at colder temperatures (180 K and below). Laboratory experiments of nucleation under cold temperatures indicate that nucleation becomes more difficult at and below 180 K than expected. This can be modeled by using a temperature-dependent contact parameter, m(T). In this study we use the NASA Ames Mars Global Circulation Model (Mars GCM) to compare the constant contact parameter with the temperature-dependent contact parameterization described by Iraci et al. (2010). The simulations demonstrate that the contact parameter has a significant affect on the opacity of the aphelion clouds, as well as the clouds that form at the edge of the seasonal $CO_2$ ice caps. Both types of clouds tend to form near 180 K, supporting the importance of a temperature-dependent contact parameter.

**Author(s): Richard Atsuki Urata[1]**, Jeffery Hollingsworth[2], Melinda Kahre[2]
**Institution(s):** *1. Bay Area Environmental Research, 2. NASA Ames Research Center*

### 401.07 – CRISM Limb Observations of Coincident $CO_2$ Ice Clouds and $O_2$ Emission in the Mars Equatorial Mesosphere

Limb observations with the CRISM visible/near IR (0.4-4 µm) imaging spectrometer (Murchie et al., 2009) onboard the Mars Reconnaissance Orbiter have supported a broad range of atmospheric airglow (1.27 µm $O_2$, 1.45 and 2.9 µm OH) and aerosol (dust, $H_2O$ and $CO_2$ ice) vertical profile retrievals. Most recently, CRISM limb observations over $L_s$=62-137° in MY32 (Dec 2013-May 2014) have obtained the first visible-to-near IR scattering spectra of $CO_2$ ice clouds in the Mars equatorial mesosphere (i.e., 60-70 km altitudes, 10S-10N, over $L_s$=0-140°; Clancy et al, 2007, Montemessin et al, 2007). These spectra are highly diagnostic of both the $CO_2$ ice composition and cloud paritcle sizes ($R_{eff}$=1-2 µm). The current report regards May 27, 2014 ($L_s$=137°) CRISM limb imaging observations of $CO_2$ ice clouds centered near 10S,75W at an altitude of 60 km.
What is distinct about the May 2014 observation is the coincidence of striking mesospheric $O_2(^1\Delta_g)$ 1.27 µm dayglow, indicative of very low $H_2O$/temperature conditions, which lead to locally intense $O_3$ enhancements (and 1.27 µm $O_2$ emission associated with $O_3$ photolysis). In this respect, we have an unique temperature indicator in the presence of $CO_2$ ice clouds. Interestingly, LMD GCM photochemical simulations exhibit such localized $O_2$ dayglow at the same location/season, associated with a thermal tide temperature minimum (the current best explanation for mesospheric $CO_2$ ice cloud formation). We present $CO_2$ cloud optical depth and particle size determinations, and discuss observed and modeled $O_2$ mesospheric peak emissions in the context of very cold atmospheric temperatures implied by local $CO_2$ ice formation and $O_2$ emission.

**Author(s): R. T. Clancy[4]**, Michael Smith[3], Franck Lefvère[2], Brad Sandor[4], Michael Wolff[4], Tim McConnochie[5], Kim Seelos[1], Hari Nair[1], Anthony Toigo[1], Scott Murchie[1]
**Institution(s):** *1. JHU/APL, 2. LATMOS, UPMC Univ. Paris, 3. NASA/GSFC, 4. Space Science Inst., 5. Univ. Maryland*

### 401.08 – A Plume Tracing, Source Identifying Technique for Mars Rovers

We have developed and field-tested a technique to identify and characterize the source of an effluent plume (biogenic or otherwise) on Mars, using a slow-moving vehicle like a Mars Rover. The technique is based on terrestrial plume characterization methods (EPA Method 33a), and uses puff models of variable complexity to predict the plume behavior for a given source. The technique is developed assuming that a Mars Rover would be equipped with a high-performance eddy-sensing 3-D anemometer (e.g., a Martian Sonic Anemometer), as well as a fast-response tracer molecule-specific sensor (e.g., a TLS methane sensor). The platform is assumed to move only once a day, but have the ability to observe throughout the day and night. Data obtained from any one sol while the effluent plume meanders across the rover can be used to estimate the azimuth, range and strength of the source, but combining observations from multiple sols and locations is used to improve the estimate of the souce location and strength.
We have conducted preliminary field tests using a Sonic Anemometer (Gill and Campbell) and fast-response methane sensors (LICOR and Picarro) on mobile platforms using both controlled and existing methane releases to prove our algorithm in simple terrain, and with varying atmospheric stability. We will discuss our results and the efficacy of our algorithm in real world conditions.

**Author(s): Don Banfield[1]**, Brian Lamb[4], Chris Hovde[3], Tom Ferrara[2]
**Institution(s):** *1. Cornell Univ., 2. GHD Inc., 3. Southwest Sciences, 4. Washington State University*

### 401.09 – Martian upper atmospheric aerosol properties from Phobos eclipse observation

Solar occultation photometry is a useful method for probing upper atmospheric aerosols, using a long atmospheric path for direct extinction measurements. During April-June 2015, the Mars Science Laboratory's Mastcam was used for solar occultation photometry by proxy: 3 eclipse ingresses by Phobos into Mars' shadow were observed, as were 3 egresses from the shadow. The observations occurred in late Southern summer, at $L_S$ 331-352°. The observations of the moon's brightness sample the Martian atmosphere along the lines of site from the Sun to Phobos. The ingresses and egresses sampled longitudes up to 1000s of km west or east of the rover's position, respectively; sampled latitudes from 30° S to 7° S over time; and sampled local sunset or sunrise, respectively. Each eclipse was imaged with both Mastcam cameras, M-100 with an RGB filter (638, 551, and 493 nm) and M-34 with an 867-nm filter. Light-curves for the eclipses were derived from the images and interpreted via a geometric model of the event, accounting for the full range of lines of sight through the atmosphere. The altitude of 50% extinction was found to vary within the 40-60 km range. Extinction varied with wavelength: four events showed significantly higher extinction in the blue, with a monotonic decrease with wavelength, interpreted as a result of 0.3-0.4 µm dust aerosols. Two events (one of each type) showed no significant wavelength variation of extinction, interpreted as a result of large (>1 µm) aerosols. One of these, probing local sunrise conditions, may suggest a thin layer of $CO_2$ ice cloud. Future work may allow retrieval of vertical gradients in aerosol size near the mid-point of the sensitive region (i.e., altitudes near that of 50% transmission and/or path optical depth unity) and/or identification of discrete layers vs. well-mixed aerosols (for instance, clouds vs. dust)

**Author(s): Mark T. Lemmon[1]**
**Institution(s):** *1. Texas AandM University*

## 402 – Asteroid Spins, YORP, and Interiors: The Turning and Turning; The Centre Cannot Hold

### 402.01 – YORP: Its origin

It's all about photons and their behavior. Yarkovsky (1844-1902) did not have the knowledge we have today about photons and radiation pressure. Nevertheless, he published a pamphlet in 1901 that small rotating celestial bodies could absorb sunlight and reradiate it as heat after a delay, resulting in possible orbital changes, setting the stage for radiation effects in celestial mechanics. Yarkovsly's work remained obscure until Öpik recalled having read Yarkovsky's pamphlet. Öpik brought Yarkovsky's idea to the attention of John A. O'Keefe in the late 1960s. O'Keefe, the mentor for two aspiring PhD students, Paddack and Rubincam, told them about Yarkovsky. In 1968 Paddack postulated that the reflection of sunlight off of small, irregularly shaped celestial bodies could have a significant effect on their spin rates. He referred to this as a windmill effect. Paddack and O'Keefe tested the idea of windmill shapes causing spin by dropping crushed stones with irregular shapes into a swimming pool and watching them twirl. Paddack then mimicked the space environment by placing windmill-shaped artificial objects and tektites in a vacuum chamber on an almost frictionless bearing and spinning them up with a strong source of light, conclusively showing the relation of shape to spin. Earlier in 1954 Radzievskii wrote about the effects radiation pressure on variations in the albedo of small celestial bodies as a means of changing their spin rates. The uniform color of Paddack's test bodies ruled out Radzievskii's effect as the cause for the observed spin-up. The Yarkovsky effect was minimized because the test object had a coating of vapor-deposited aluminum with a very high albedo and consequently did not heat up. In 2000 Rubincam applied Paddack's idea to small asteroids and called it the YORP effect (YORP = Yarkovsky-O'Keefe-Radzievskii-Paddack), to give it a catchy name and sell the idea. In 2007 results were published in Science about the observed behavior of asteroid (54509) 2000 PH5 stating that its spin rate changes because of the YORP effect (Lowery et al and Taylor et al). Since 2000 there have been more than 400 papers and talks with "YORP" in the title or the abstract.

**Author(s): Stephen Paddack[2]**, David P. Rubincam[1]
**Institution(s):** *1. Goddard Space Flight Center, 2. Self*

### 402.02 – Challenging the wall of fast rotating asteroids – constraining internal cohesive strength for MBAs and NEAs

We report an observation of a 2 km size main belt asteroid (MBA), (60716) 2000 GD65, with a lightcurve indicating a rotation period of 1.9529±0.0002 hours, i.e. challenging the 'rubble pile spin barrier'. This adds to a handful of MBAs, recently observed by the Palomar Transient Factory (PTF) survey (Chang et al. 2014, 2015), with diameters between 0.5-1.5 km and lightcurves indicating rotation periods of 1.2-1.9 hours. These asteroids are relatively large compared to the population of small near-Earth asteroids (NEAs; D<300 m) that can reach rotation periods as fast as 15.797 seconds as is the case of NEA 2014 RC (Moskovitz and MANOS team).
We apply the Holsapple (2007) model to these two distinct populations in order to constrain the cohesion within these objects and to search for monolithic asteroids. We use the lightcurve's amplitude as indication of the triaxial shape ratio a/b, and assume b/c=1 (i.e. a>b=c). While the density is a free parameter, the given cohesion is the average of values for density ranges between 1.5 to 2.5 gr cm^-3, which are measured density values for asteroids (Carry 2012).
We find that the fast rotating MBAs must have internal cohesive strength of at least ~25 to ~250 Pa in order to prevent disruption against centrifugal acceleration. Similar cohesion values have been found within lunar soils (100-1000 Pa; Mitchell et al. 1974). However, since only a few MBAs rotate so quickly, such internal cohesive strength might be rare within the population of km-size MBAs. Among NEAs, about 25% have minimal constrained cohesion values similar to those found for the fast rotating MBAs.

Approximately 65% have no need for substantial cohesion values >25 Pa. Only ~10% of NEAs must have substantial internal cohesion of over 1000 Pa to prevent disruption, however none of them are rotating fast enough to require a fully monolithic body, i.e. cohesion >10 kPa.

**Author(s): David Polishook5**, Nicholas Moskovitz[1], Richard P Binzel[2], Francesca E. DeMeo[2], Oded Aharonson5, Cristina Thomas3, Matthew Lockhart[2], Audrey Thirouin[1], Michael Mommert4, David Trilling4, Brian Burt[2]
**Institution(s):** *1. Lowell Observatory, 2. MIT, 3. NASA Goddard Space Flight Center, 4. Northern Arizona University, 5. Weizmann Institute of Science*

### 402.03 – Effects of Earth Encounters on the Rotational Properties of Near-Earth Objects

The effects of Earth encounters on the physical properties of near-Earth objects (NEOs) have been shown to be significant factors in their evolution. Previous studies have examined the effects of these encounters on reflectance spectra, and effects such as spin state and shape changes have been studied for specific asteroids and through simulation. In this study, archive data from previous NEO surveys were used to investigate rotational frequencies as a function of minimum orbit intersection distance (MOID), which we use as a proxy for Earth encounter likelihood. When comparing objects of similar sizes, we find a highly significant difference in the dispersion of rotational frequency ($p < 0.01$; significant at a >99% confidence level) between NEO populations that were likely to have had an Earth encounter and those that are less likely to have had such an encounter. The encounter/non-encounter distinction is found at a dividing MOID value of 1 lunar distance (LD). These results were robust to changes in the size of the moving average window, as well as to removal of the smallest objects from the encounter population and the largest objects from the non-encounter population, which would be most strongly affected by a known size/spin period bias where smaller objects tend to have shorter periods. There was no statistically significant difference in the mean rotation rates of encounter and non-encounter objects, however, indicating that encounters cause greater dispersion, but do not preferentially spin objects up or down at a detectable level. Recent modeling work also lends credibility to the idea that NEO interactions with the Earth-Moon system as a whole may be leading to the dispersion difference boundary at 1 LD (Keane et al. 2015, DPS).

**Author(s): Ho Chit Siu[2]**, James T. Keane3, Nicholas Moskovitz[1], Richard P. Binzel[2]
**Institution(s):** *1. Lowell Observatory, 2. Massachusetts Institute of Technology, 3. University of Arizona*

### 402.04 – Failure modes and conditions of Itokawa

The YORP effect has been found to play a crucial role in the rotational evolution of small bodies. Recent studies have argued that the YORP effect is very sensitive to the shape of an asteroid (Statler, 2015, Icarus 202, 502) and, as the shape deforms, can possibly change (McMahon, 2015, DDA meeting #301.04). Such sensitivity has been considered to affect the orbital evolution of an asteroid (Bottke et al., 2015, Icarus 247, 191). As a result, this mysterious effect could make fast and slow rotators (personal communication with Bill Bottke, 2015). In addition, possible candidates of rotational disruption have also been discovered in the last decades (e.g., Jewitt et al., 2014, ApJ 784, L8). These studies gave rise to the following question: how does the shape of an asteroid change when subject to rotational variations from the YORP effect? Better understandings of asteroid deformation and failure at different spin periods will help us find clues of it. To do this we are surveying the failure modes and conditions of available shape models with detailed mass information. The main technique used is a plastic finite element model by Hirabayashi and Scheeres (2015, ApJ 798, L8). We have analyzed asteroid Itokawa, which is currently spinning at a spin period of 12.1 hours. Itokawa's failure conditions at different spin periods can be described by using the minimum cohesive strength that ensures stability of the structure. The results show that this minimum cohesive strength increases as the spin period becomes shorter. If the spin period is longer than 4.5 hours, a failure mode caused by a combination of compression and tension occurs at cohesive strength less than 6 Pa. At shorter spin periods, however, tension spreads out across the neck, causing the body to fail even at cohesive strength higher than it. Since Hill's stability condition is 5.2 hours, once the body fails at spin periods shorter than 4.5 hours, it breaks into two components that eventually escape from one another. In this presentation, we will discuss the detailed failure modes and conditions of four different shapes, including Itokawa: a top-like shape, an elongated shape, a contact binary and a strangely shaped asteroid.

**Author(s): Masatoshi Hirabayashi[1]**, Daniel J. Scheeres[1]
**Institution(s):** *1. University of Colorado at Boulder*

### 402.05 – Asteroids With Tensile Strength: The Case of 2015 HM10

Near-Earth asteroid 2015 HM10 was discovered on 2015 April 19 with the 4-m Blanco Telescope at Cerro Tololo (MPEC 2015-H90). HM10 made a 0.00295 AU / 1.14 lunar distance flyby of Earth on July 7. This was the asteroid's closest approach to Earth until at least 2419.
We observed HM10 with radar between July 5 and July 8 using Arecibo, the 70 m DSS-14 and 34 m DSS-13 antennas at Goldstone, Green Bank, and elements of the Very Long Baseline Array (VLBA). Bistatic observations were crucial to obtain high-resolution images of HM10 due to the short round-trip travel time of the radar signal, which was as low as 2.95 s on July 7. Our finest image resolution was 3.75 m/pixel in range, obtained on July 7 with the new 80 kW C-band (7190 MHz, 4.2 cm) transmitter on DSS-13 and receiving at Green Bank with the new radar backend. Optical lightcurves obtained prior to closest approach indicated that HM10 has a spin period of ~22.2 minutes and an elongated shape (W. Ryan, pers. comm). The delay-Doppler radar images confirm the rotation period estimated from photometry and reveal that HM10 has a long-axis extent of 80-100 m with an equatorial aspect ratio of about 2:1. Radar speckle tracking transmitting from Arecibo and receiving with the VLBA on July 6 rule out any non-principal axis 'wobble' with an amplitude greater than ~10°.
HM10's rapid rotation implies significant cohesion, with a minimum tensile strength of 25-150 Pa required at its center to prevent disruption, assuming overall bulk density between 0.7 and 3.9 g $cm^{-3}$. This is comparable to strength predictions for rubble-pile aggregates (e.g. Scheeres, Britt, Carry, & Holsapple 2015, Asteroids IV, *in press*). HM10 is not necessarily a 'monolith'. HM10's shape is complex and irregular. The radar images show angular features and 'facets' up to ~30 m across. There is also a cluster of radar-bright pixels that tracks with HM10's rotation, consistent with a high standing feature 15-20 m across. This feature is similar in appearance to radar images of decameter-scale boulders on other asteroids.

**Author(s): Michael W. Busch4**, Lance A.M. Benner[2], Shantanu P. Naidu[2], Marina Brozovic[2], James E. Richardson[1], Edgard G. Rivera-Valentin[1], Patrick A. Taylor[1], H. Alyson Ford3, Frank D. Ghigo3, Jon D. Giorgini[2], Joseph S. Jao[2], Lawrence Teitelbaum[2]
**Institution(s):** *1. Arecibo Observatory, 2. Jet Propulsion Laboratory, California Institute of Technology, 3. National Radio Astronomy Observatory, 4. SETI Institute*

### 402.06 – Size estimate of (99942) Apophis based on radar imaging

(99942) Apophis is one of the most important near-Earth asteroids ever discovered. It will make a very close Earth approach on Friday, April 13, 2029 when it will pass within only a few Earth radii above Earth's surface. This will be the closest approach by something this large currently known. Apophis approached within 0.1 au in January of 2013, and we organized an extensive radar campaign at Goldstone and Arecibo between December 2012 and March 2013. Our primary objective was to obtain ranging measurements to improve the orbit, characterize its physical properties, and facilitate detection of the Yarkovsky effect leading to estimation of the mass and bulk density. We obtained frequency-only data, and 150 m and

75 m ranging data. The signal-to-noise ratios (SNRs) were strong enough so that coarsely resolved delay-Doppler images revealed aspects of Apophis' shape. The visible extents varied from ~0.2 km to ~0.4 km and the bandwidths varied from 0.9 Hz to1.4 Hz. The object is clearly elongated, which is consistent with the large lightcurve amplitude of ~0.9 mag reported by Behrend et al. ( http://obswww.unige.ch/~behrend/r099942a.png) and Pravec et al. (*Icarus* 233, 48-60, 2014). The radar images suggest that Apophis could be a contact binary.
Pravec et al. have estimated the shape and spin of Apophis from lightcurves that were collected at similar times as our radar data. The radar data were not strong enough for 3D shape modeling, but we used the *Shape* software (Hudson, *Remote Sens. Rev.* 8, 195-203, 1993 and Magri et al., *Icarus* 186, 152-177, 2007) to scale the convex lightcurve-derived shape model to fit the radar data. We find that the best $\chi^2$ value corresponds to the model that has 0.43×0.30×0.26 (±0.04, ±0.03, ±0.03) km for long, intermediate, and short axis, and a dynamically equivalent, equal volume ellipsoid of 0.31±0.03 km.

**Author(s): Marina Brozovic[3]**, Lance Benner[3], Joseph McMichael[3], Petr Pravec[2], Petr Scheirich[2], Jon Giorgini[3], Chris Magri[6], Michael Busch[4], Joseph Jao[3], Clement Lee[3], Michael Nolan[5], Patrick Taylor[1], Ellen Howell[5], Martin Slade[3]
**Institution(s):** *1. Arecibo Observatory, 2. Astronomical Institute, Academy of Sciences of the Czech Republic, 3. Jet Propulsion Laboratory/Caltech, 4. SETI Institute, 5. University of Arizona, 6. University of Maine*

### 402.07 – Orbital and Physical Characteristics of Meter-sized Earth Impactors

We have analysed the orbits and ablation characteristics in the atmosphere of more than 60 earth-impacting meteoroids of one meter in diameter or larger. Using heights at peak luminosity as a proxy for strength, we find that there is roughly an order of magnitude spread in the apparent strength of the population of meter-sized impactors at the Earth. The orbits and physical strength of these objects are consistent with the majority being asteroidal bodies originating from the inner main asteroid belt. We find ~10-15% of our objects have a probable cometary (Jupiter-Family comet and/or Halley-type comet) origin based on orbital characteristics alone. Only half this number, however, show evidence for the expected weaker than average structure compared to asteroidal bodies. Almost all impactors show peak brightness between 20-40 km altitude. Several events have exceptionally high (relative to the remainder of the population) heights of peak brightness. These are physically most consistent with high microporosity objects, though all were on asteroidal-type orbits. We also find three events, including the Oct 8, 2009 airburst near Sulawesi, Indonesia, which display comparatively low heights of peak brightness, consistent with strong monolithic stones or iron meteoroids. Based on orbital similarity, we find a probable connection among several NEOs in our population with the Taurid meteoroid complex. No other major meteoroid streams show linkages with the pre-atmospheric orbits of our meter-class impactors. Our events cover almost four orders of magnitude in mass, but no trend in height of peak brightness is evident, suggesting no strong trend in strength with size for small NEOs, a finding consistent with the results of Popova et al (2011).

**Author(s): Peter G. Brown[2]**, Paul Wiegert[2], David Clark[2], Edward Tagliaferri[1]
**Institution(s):** *1. ET Space Systems, 2. Univ. of Western Ontario*

### 402.08 – Patterns of Failure in Heterogeneous Self-gravitating Aggregates

During the last 15 years or so, the Planetary Sciences community has been using DEM simulation codes to study small granular NEOs. In general these codes treat gravitational aggregates as conglomerates of spherical particles. Lately, Finite Element Method (FEM) codes and theoretical tools (Limit analysis) commonly used to study soil mechanics have also been employed to analyze the failure conditions and disruption patterns of granular asteroids as well as idealized simulation constructs. One general assumption has been that these granular systems have homogeneous interiors. In this research we change this and study the effect of stronger and weaker interiors in their disruption patterns and failure mechanisms.
Theory and simulations have shown that homogeneous aggregates spun at disruption rates fail initially at the centre and so, it is interesting to explore the influence of a stronger or weaker core in their disruption mechanisms. In our research we explore the failure mechanics of spherical aggregates with an angle of friction of 35$^\circ$ and systematically change the tensile strength and size of a spherical, concentric core. These aggregates are slowly spun up to disruption spin rates so that we can observe and analyze their disruption mechanics through our DEM code. At the same time, we use Limit analysis to provide the upper and lower bounds to find the actual conditions for failure.
What we observe is that simulations and theory point to surface shedding as the prevalent mechanism for aggregates with stronger cores. Also, a core of appropriate size produces a shape profile similar to 1999 KW4 alpha. Initial simulations of aggregates with weak cores continue to fail first a the centre, but if in homogeneous aggregates there was a smooth (cohesion dependent) change from shedding to fission, here this does not happen. When the size of the core is >0.5R, where R is the radius of the original body, material is shed from a now oblate body. For a core with a radius of 0.5R on the other hand, we observe that the break-up of the core leads to a severe fracturing, but not to fission. These and other scenarios will be explored in greater detail during the conference.

**Author(s): Paul Sánchez[1]**, Daniel Scheeres[1], Masatoshi Hirabayashi[1]
**Institution(s):** *1. University of Colorado at Boulder*

### 402.09 – Geodynamic stability of the primary in the binary asteroid system 65803 Didymos

The moon of the near-Earth binary asteroid 65803 Didymos is the target of the Asteroid Impact and Deflection Assessment (AIDA) mission. This mission is a joint concept between NASA and ESA to investigate the effectiveness of a kinetic impactor in deflecting an asteroid. The mission is composed of two components: the NASA-led Double Asteroid Redirect Test (DART) that will impact the Didymos moon, and the ESA-led Asteroid Impact Monitoring (AIM) mission that will characterize the Didymos system. In order to provide AIDA constraints on the physical character of the both objects in this binary system, we undertook preliminary numerical investigations to evaluate the stability of the shape of the primary using its rapid 2.26 h rotation. We modeled the primary as a rubble pile. Each model consisted of thousands of uniform rigid spheres collapsed together under their own gravity to form a spherical pile that was then carved to match the current radar-derived shape model of the primary, as well as other comparable shapes (e.g. asteroid 1999 KW4, spheres) that were scaled to match best estimates of the size of Didymos. Each model was given a starting rotation period of 6 h with the spin axis aligned to the pole. At each timestep the spin rate was increased by a small amount so that after about 1 million timesteps the spin would match the observed rotation of 2.26 h. We tested a range of bulk densities spanning the current observational uncertainty (mean 2.4 g/cc) using "gravel"-like material parameters that provide significant resistance to sliding and rolling. We find that at the upper range of the density uncertainty it is possible for Didymos to hold its shape and not lose mass at its nominal rotation period, without the need for cohesive forces. At lower densities or with smoother particles, significant shape change occurs and mass loss is possible. We conclude that based on the radar shape available at the time of this writing, Didymos is marginally stable as a rubble pile with bulk density close to 3 g/cc. Revisions to the radar shape in process may allow for stability at lower bulk densities without cohesion. These results suggest that the moon of Didymos may also not be heavily influenced by cohesion.

**Author(s): Olivier S Barnouin[2]**, Clara Maurel[1], Derek C Richardson[4], Ronald-Louis Ballouz[4], Stephen Schwartz[3], Patrick Michel[3]
**Institution(s):** *1. ISAE-Supaero, 2. JHUAPL, 3. Lagrange Lab., UCA, Côte d'Azur Observatory, CNRS, 4. Univ. of Maryland*

## 403 – Jovian Planet Interiors, Deep Atmosphere, and Structure

### 403.01 – Gravity and Zonal Flows of Giant Planets: From the Euler Equation to the Thermal Wind Equation

The nature of the east-west zonal flows observed on the cloud level of the solar system giant planets remains to be determined. The upcoming gravity and magnetic field measurements to be carried out by the Juno mission and the Cassini Grand Finale provide an opportunity to establish an observational fact about whether these flows are shallow atmospheric dynamics or surface expression of deep interior dynamics. It is currently debated whether the thermal wind equation (TWE) is applicable in forward calculating the gravity field associated with deep zonal flows. Here we will present a critical comparison between the Euler equation and the thermal wind equation (TWE). The TWE, which is a local diagnostic relation, captures the local density variations associated with the zonal flows while neglects the global shape change and density variations with non-local origins. Our analysis shows that the global corrections to the high degree gravity moments are small (less than a few tens of percent). Our analysis also shows that the applicability of the TWE in calculating the gravity moments does depend crucially on retaining the non-sphericity of the background density and gravity. Only when the background non-sphericity of the planet is taken into account, the TWE makes accurate enough prediction (with a few tens of percent errors) for the high-degree gravity moments associated with deep zonal flows.

**Author(s): Hao Cao[1]**, David J Stevenson[1]
**Institution(s):** *1. Caltech*

### 403.02 – The gravity signature of atmospheric dynamics on giant planets: comparing the potential-theory and thermal-wind approaches

The upcoming Juno and Cassini gravity experiments of Jupiter and Saturn, respectively, will allow us to probe the internal dynamics of these planets through accurate analysis of their gravity spectra. To date, two general approaches have been suggested for relating the flow velocities and gravity fields. In the first, potential-theory is invoked to calculate the gravity field due to internal dynamics in an oblate spheroid planet with full differential rotation. The second approach, calculated in the reference frame of the rotating planet, assumes that due to the large scale and rapid rotation of these planets, the winds are to leading order in geostrophic balance, and therefore thermal wind balance relates the wind shear to the density gradients. The first method allows accurate calculations of the gravity harmonics, but can take into account only the case of full differential rotation (completely barotropic flow), while the second method can take into account any internal flow structure, but is limited to only calculating the dynamical contribution and to spherical symmetry. This study comes to relate the two methods both from a theoretical perspective, showing that they are analytically identical in the barotropic limit, and numerically through systematically comparing the model solutions of the gravity harmonics. We find that despite the sphericity assumption the thermal wind solutions match well the potential-theory solutions.

**Author(s): Joseph E Davighi[2]**, Yohai Kaspi3, Eli Galanti3, William B Hubbard[1]
**Institution(s):** *1. University of Arizona, 2. University of Cambridge, 3. Weizmann Institute of Science*

### 403.03 – Tides in Giant Planets

The arrival of Juno at Jupiter in less than a year necessitates analysis of what we can learn from the gravitational signal due to tides raised on the planet by satellites (especially Io but also Europa). In the existing literature, there is extensive work on static tidal theory (the response of the planet to a tidal potential whose time dependence is ignored) and this is what is usually quoted when people refer to tidal Love numbers. If this were correct then there would be almost no new information content in the measurement of tidally induced gravity field, since the perturbation is of the same kind as the response to rotation (i.e., the measurement of $J_2$, a well-known quantity). However, tides are dynamic (that is, $k_2$ is frequency dependent) and so there is new information in the frequency dependent part. There is also (highly important) information in the imaginary part (more commonly expressed as tidal Q) but there is no prospect of direct detection of this by Juno since that quadrature signal is so small. The difference between what we expect to measure and what we can already calculate directly from $J_2$ is easily shown to be of order the square of tidal frequency over the lowest order normal mode frequency, and thus of order 10%. However, the governing equations are not simple (not separable) because of the Coriolis force. An approximate solution has been obtained for the n =1 polytrope showing that the correction to $k_2$ is even smaller, typically a few percent, because the tidal frequency is not very different from twice the rotation frequency. Moreover, it is not highly sensitive to structure in standard models. However, the deep interior of the planet may be stably stratified because of a compositional gradient and this modifies the tidal flow amplitude, changing the dynamic $k_2$ but not the static $k_2$. This raises the exciting possibility that we can use the determination of $k_2$ to set bounds on the extent of static stability, if any. There is also the slight possibility that the tidal frequency is coincidentally close to some resonance, as would be required if (as some have suggested) the tidal Q is currently small (e.g., a few thousand or less). Predictions and detectability for Juno will be presented.

**Author(s): David J. Stevenson[1]**
**Institution(s):** *1. Caltech*

### 403.04 – Laboratory Measurements of the 5-20 cm Wavelength Opacity of Ammonia and Water Vapor under High-Temperature Conditions charactyeristic of the Deep Jovian Atmosphere

In the past decade, several extensive laboratory studies have been conducted of the microwave opacity of ammonia and water vapor in preparation for interpretation of the precise measurements of Jovian microwave emission to be made with the Juno Microwave Radiometer (MWR) instrument. (See, e.g., Hanley et al. (Icarus, 202, 2009), Karpowicz and Steffes. (Icarus, 212, 2011), Karpowicz and Steffes. (Icarus, 214, 2011), and Devaraj et al. (Icarus, 241, 2014)). All of these works include models for the opacity of these constituents valid over the pressure and temperature ranges measured in their laboratory experiments (temperatures up to 500 K and pressures up to 100 bars). However, studies of the Jovian microwave emission indicate that significant contributions to the emission at the 24-cm and 50-cm wavelengths to be measured by the Juno MWR will be made by layers of the atmosphere with temperatures at or exceeding 600 K. While the ammonia opacity models described by Hanley et al. (Icarus, 202, 2009) and Devaraj et al. (Icarus, 241, 2014) give consistent results at temperatures up to 500 K (within 6%), they diverge significantly at temperatures and pressures exceeding 550 K and 50 bars, respectively. Similarly, at temperatures above 600 K, the model for water vapor opacity developed by Karpowicz and Steffes. (Icarus, 212, 2011; Icarus, 214, 2011) exhibits larger than expected microwave opacity. To resolve these ambiguities, we present results of laboratory measurements of the microwave opacity of ammonia in a hydrogen/helium atmosphere at temperatures up to 600 K and pressures up to 80 Bars, and that for water vapor at temperatures up to 600 K.

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**Author(s): Amadeo Bellotti[1]**, Paul G Steffes[1]
**Institution(s):** *1. Georgia Institute of Technology*

### 403.05 – The depths of clouds on Jupiter: Observational constraints on the O/H ratio

The oxygen abundance in Jupiter is an important constraint on planet formation and conditions in protoplanetary disks. Oxygen, in the form of water, is also dynamically significant in Jupiter's atmosphere: as a tracer of circulation and as a carrier of latent heat. We have developed a technique to spectroscopically measure the

depth of opaque cloud tops in Jupiter's atmosphere (Bjoraker et al. 2015, ApJ in press, arXiv:1508.04795). We measure resolved $CH_3D$ line shapes in the 5-micron window of Jupiter's spectrum to distinguish between cloud-top pressure levels of about 3 to 10 bars. We will use the retrieved cloud top pressure levels to place lower limits on the deep O/H ratio in Jupiter, based on Keck/NIRSPEC spectra acquired in January 2013. Since our spectra do not directly give the temperature/pressure profile in the cloud layer, constraining the O/H ratio requires independent atmospheric structure data. We will review observational and theoretical constraints on Jupiter's thermal structure, which lead to uncertainty bounds on the O/H ratio we derive. Preliminary work to date suggests that our technique may be able to determine whether or not the Galileo Probe Mass Spectrometer O/H measurement can be representative of the planet's bulk abundance, and whether O is supersolar in Jupiter like the other volatile elements C, N, and S. If we can distinguish between O/H lower limits of 10x and 3x solar, we will be able to test the hypothesis that Jupiter's volatiles must have been delivered via water ice clathrates.
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**Author(s): Michael H. Wong[2]**, Gordon L Bjoraker[1], Imke de Pater[2], Máté Ádámkovics[2]
**Institution(s):** *1. NASA Goddard Space Flight Center, 2. University of California*

## 403.06 – Variation in the Deep Gas Composition in Hot Spots on Jupiter

We used CSHELL on NASA's Infrared Telescope Facility and NIRSPEC on the Keck telescope in the last two years to spectrally resolve line profiles of $CH_3D$, $NH_3$, $PH_3$, and $H_2O$ in 5-micron Hot Spots on Jupiter. The profile of the $CH_3D$ lines at 4.66 microns is very broad in both NEB and SEB Hot Spots due to collisions with up to 8 bars of $H_2$, where unit optical depth occurs due to collision-induced $H_2$ opacity. The extreme width of these $CH_3D$ features implies that the Hot Spots that we observed do not have significant cloud opacity for P > 2 bars. We retrieved $NH_3$, $PH_3$, and gaseous $H_2O$ within Hot Spots in both the NEB and SEB. We had dry nights on Mauna Kea and a sufficient Doppler shift to detect $H_2O$. We will compare line wings to derive $H_2O$ profiles in the 2 to 6-bar region. NEB Hot Spots are depleted in $NH_3$ with respect to adjacent regions. Interestingly, SEB Hot Spots exhibit stronger $NH_3$ absorption than NEB Hot Spots. In addition, SEB Hot Spots have very similar 5-micron spectra as neighboring longitudes in the SEB, implying similar deep gas composition. The dynamical origin of SEB Hot Spots is much less studied than that of NEB Hot Spots, so our observations of gas composition in both regions may constrain mechanisms for forming Hot Spots.

**Author(s): Gordon Bjoraker[1]**, Imke de Pater[2], Michael H. Wong[2], Mate Adamkovics[2], Tilak Hewagama3, Brigette Hesman3
**Institution(s):** *1. NASA's GSFC, 2. Univ. of California-Berkeley, 3. Univ. of Maryland*

## 403.07 – Coupled Gas Giant Atmospheres: Solar Heating vs. Interior Heating

The weather layers of Jupiter and Saturn receive both solar radiation and heat from the deep interior. Currently, numerical models fall into two broad categories: deep, convecting interiors that lack an outer, solar-heated troposphere, or thin shells that represent only a troposphere, with parameterized heating from the lower boundary. Here we present results from a new coupled circulation model that allows deep convective plumes and columnar structures to interact with a stable troposphere that is heated by the sun. Equatorial superrotation, observed on Jupiter and Saturn, extends in axially-aligned columns from the deep interior through the troposphere. A tropospheric midlatitude baroclinic zone due to solar heating competes with the outer edges of the deep rotating columns to characterize midlatitude jet and temperature structure. We demonstrate this interplay between solar heating and interior heating in setting the strength and depth of the jets for a range of idealized gas giants. The relative impact of each is modulated by the static stability of the troposphere, which acts as a proxy for water abundance. We also show the impact of axial tilt, with respect to solar radiation, on asymmetries between the Northern and Southern hemispheres.

**Author(s): Morgan E O'Neill[1]**, Yohai Kaspi[1], Eli Galanti[1]
**Institution(s):** *1. Weizmann Institute of Science*

## 403.08 – Deciphering Jupiter's complex flow dynamics using the upcoming Juno gravity measurements and an adjoint based dynamical model

The nature of the large scale flow on Jupiter below the cloud level is still unknown. The observed surface wind might be confined to the upper layers, or be a manifestation of deep cylindrical flow. Moreover, it is possible that in the case where the observed wind is superficial, there exists deep flow that is completely separated from the surface. To date, all models linking the wind (via the induced density nomalies) to the gravity field to be measured by Juno, consider only wind flow related to the observed could level wind. Some assume full cylindrical flow while others allow for the wind to decay with depth.
Here we explore the possibility of complex wind dynamics that include both the upper-layer wind, and a deep flow that is completely detached from the flow above it. The surface flow is based on the observed cloud level flow and is set to decay with depth. The deep flow is constructed synthetically to produce cylindrical structures with variable width and magnitude, thus allowing for a wide range of possible setups of the unknown deep flow. This flow is also set to decay when approaching the surface flow in coordination with the exponential decay rate. The combined 3D flow is then related to the density anomalies via a dynamical model, taking into account oblateness effects as well, and the resulting density field is then used to calculate the gravitational moments. An adjoint inverse model is constructed for the dynamical model, thus allowing backward integration of the dynamical model, from the expected observations of the gravity moments to the parameters controlling the setup of the deep and surface flows. We show that the model can be used for examination of various scenarios, including cases in which the deep flow is dominating over the surface wind. The novelty of our adjoint based inversion approach is in the ability to identify complex dynamics including deep cylindrical flows that have no manifestation in the observed cloud-level wind. Furthermore, the flexibility of the adjoint method allows for a wide range of dynamical setups, so that when new observations and physical understanding will arise, these constraints could be easily implemented and used to better decipher Jupiter flow dynamics.

**Author(s): Eli Galanti[1]**, Yohai Kaspi[1]
**Institution(s):** *1. Weizmann Institute of Science*

## 403.09 – Jupiter's tropospheric composition and cloud structure from high-resolution ground-based spectroscopy

The CRIRES instrument on the Very Large Telescope was used to make high-resolution (R=100,000) observations of Jupiter in the 4.5-5.2 μm spectral range. At these wavelengths, Jupiter's atmosphere is optically thin and the spectra are sensitive to the 4-8 bar region. This enabled us to spectrally resolve the line shapes of four minor species in Jupiter's troposphere: $CH_3D$, $GeH_4$, $AsH_3$ and $PH_3$. The slit was aligned north-south along Jupiter's central meridian, allowing us to search for latitudinal variability in these line shapes. The spectra were analysed using the NEMESIS radiative transfer code and retrieval algorithm.
The $CH_3D$ line shape is narrower in the cool zones than in the warm belts. $CH_3D$ is chemically stable and does not condense in Jupiter's atmosphere, so this difference cannot be due to variations in the $CH_3D$ abundance. Instead, it can be modelled as variations in the opacity of a deep cloud located at around 4 bar. This deep cloud is opaque in the zones and transparent in the belts.
We also observe variability in the $GeH_4$ line shape, with stronger

absorption features in the belts than in the zones. As a disequilibrium species, $GeH_4$ is expected to vary with latitude, but we found that the variations in the line shape could be entirely explained by the variations in the cloud structure.
In contrast, there is clear evidence for spatial variability in the remaining two molecular species, $AsH_3$ and $PH_3$. Their absorption features are weak near the equator and significantly stronger at high latitudes. A full latitudinal retrieval leads to a broadly symmetric profile for both species, with a minimum at the equator and an enhancement towards the poles.

**Author(s): Rohini Sara Giles[2]**, Leigh N. Fletcher[1], Patrick G. J. Irwin[2]
**Institution(s):** *1. Leicester University, 2. Oxford University*

## 404 – Extrasolar Planets: Terrestrial and Neptunian Planets

### 404.01 – Cassini VIMS Spectra of the Earth from Saturn Orbit: an Extrasolar Planet Analog

Cassini VIMS has obtained spectra of the Earth while in Saturn orbit making observations of the Saturn system when the sun was behind Saturn. The observations, made in September 15, 2006 and July 19, 2013 are visible-near-infrared spectra (0.35 - 5.1 microns) of the Earth obtained at the furthest distance from the sun to date. The Earth was sub-pixel, 0.0088 milliradian in 2013 and 0.0085 milliradian in 2006, and the signal-to-noise ratio is low. A VIMS pixel IFOV is 0.25 x 0.5
milliradian. As such, these data are likely representative of the first spectra that might be obtained of extrasolar terrestrial-like planets. What information can be derived from such remote observations? The observation made in 2013 had a phase angle of 97 degrees with multiple
image cubes providing a higher S/N average. The 2006 observation was made at a phase angle of 33 degrees but is a single cube, 1 pixel. The 2006 observation has Africa dominant on the disk, while the 2013 observation is mostly ocean with part of South America in sunlight. The 2013 visible data show clear signatures of Rayleigh scattering but this blue coloring can be from both the atmosphere and/or ocean. The 2006 data show a flatter spectrum, a signature of land. Both observations include the Moon in the field of view. The 0.35-2.5 micron spectral range shows significant absorption due to H2O liquid + gas. The thermal signature is very strong with the highest S/N of the entire spectrum. The best fit preliminary temperatures are 280 K with a small 380 K component (from the Moon), putting at least some of the planet in the goldilocks zone. There is strong absorption by CO2 at 4.25 microns in both 2013 and 2006 data. There is possible detection of chlorophyll and oxygen emission but higher S/N would be required for a positive detection. The spectral profile of the thermal emission could be used to constrain the diameter of the planet. If such spectra were obtained of an extrasolar planet, we could conclude that the planet had large regions of liquid water and exposed land at temperatures excellent for life in a habitable zone. If the chlorophyll signature could be confirmed, it would be a positive identification of life from a remote distance

**Author(s): Roger Nelson Clark3**, Matthew M. Hedman5, Robert H. Brown4, Gianrico Filacchione[2], Philip D. Nicholson[1], Jason W. Barnes5
**Institution(s):** *1. Cornel U., 2. INAF, 3. Planetary Science Institute, 4. U. Arizona, 5. U. Idaho*

### 404.02 – Under an Orange Sky: The Many Implications of Organic Haze for Earthlike Planets

Geochemical evidence suggests Archean Earth was intermittently enshrouded in an organic haze resulting from methane photolysis. Hazy exoplanets may be common, and hazes can significantly impact the environment of habitable planets. Earth is frequently studied as an analog for habitable exoplanets, and Archean Earth is the most alien planet we have geochemical data for. We have used 1D photochemical-climate and radiative transfer simulations to examine the climate, surface radiation environment, and spectra of Archean Earth with fractal hydrocarbon haze. We find that haze would have strongly impacted Earth's climate, lowering the planetary surface temperature by 20-30 K. However, this cooling can be countered by concentrations of greenhouses gases consistent with geochemical constraints. For example, an atmosphere with 2% $CO_2$, 0.37% $CH_4$ and a self-consistent hydrocarbon haze has a globally averaged surface temperature of 274 K, which GCM models have shown is consistent with a large open ocean fraction (Charnay et al 2013). The cooling from haze means that there exists a "hazy habitable zone" closer to the star than the traditional habitable zone boundaries. Our results suggest that the hazy habitable zone can extend to the distance of Venus. An organic haze produces strong, remotely detectable spectral features, especially at wavelengths $< 0.5$ μm, reddening the planet's color. The strong absorption of UV radiation by this haze means it could have provided a UV shield for the Archean Earth prior to the rise of oxygen when there was no ozone layer: we show that an organic haze can block 97% of the surface-incident UVC ($\lambda < 0.28$ μm) radiation compared to a haze-free planet. UVC radiation directly dissociates DNA, and it is blocked by ozone in the modern atmosphere. Organic hazes may therefore benefit surface biospheres on Earth and similar exoplanets. Finally, assuming geochemical constraints on the Archean atmospheric composition, we show that abiotic levels of methane flux to the atmosphere are insufficient to form an organic haze. For Earthlike exoplanets, organic haze may therefore be a novel type of spectral biosignature.

**Author(s): Giada Arney4**, Shawn D Domagal-Goldman[1], Victoria S Meadows4, Eric Wolf[2], Edward W Schwieterman4, Benjamin Charnay4, Mark Claire3, Eric Hebrard[1]
**Institution(s):** *1. NASA Goddard Space Flight Center, 2. University of Colorado, 3. University of St. Andrews, 4. University of Washington*

### 404.03 – C/O: Effects on Habitability of Stellar Exoplanet Systems

We assess how differences in the composition of exoplanet host stars might affect the availability of water in their systems, particularly the role of carbon and oxygen abundances. Water, one of the key chemical ingredients for habitability, may be in short supply in carbon-rich, oxygen-poor systems even if planets exist in the 'habitable zone'. For the solar system, C/O = 0.55 is particularly important in determining the refractory (silicate and metal) to volatile ice ratio expected in material condensed beyond the snow line **(**Gaidos E. J. *Icarus* 145, 637, 2000; Wong M. H. et al. in Oxygen in the Solar System, G.J. MacPherson, Ed., 2008). Our analysis of published compositions for a set of exoplanet host stars (Johnson T. V. et al. *ApJ*. 757(2), 192, 2012) showed that the amount of condensed water ice in those systems might range from as much as 50% by mass for sub-solar C/O = 0.35 to less than a few percent for super-solar C/O = 0.7. A recent analysis using similar techniques (Pekmezci G. S., Dottorato di Ricerca in Astronomia, Università Degli Studi di Roma "Tor Vergata", 2014) of a much larger stellar composition data set for 974 FGK stars (Petigura E. and Marcy G. *Journal of Astrophysics* 735, 2011), allows us to assess the possible range of water ice abundance in the circumstellar accretion disks of these 'solar-type' stars (of which 72 were known to have one or more planets as of 2011). Stellar C/O in a subset (457 stars) of this stellar database with reported C, O, Ni, and Fe abundances ranges from 0.3 to 1.4. The resulting computed water ice fractions and refractory (silicate + metal) fractions range from ~0 to 0.6 and 0.3 to 0.9 respectively. These results have implications for assessing the habitability of exoplanets since they constrain the amount of water available beyond the snow line for dynamical delivery to inner planets, depending on the host stars' C/O in the circumstellar nebula. TVJ acknowledges government support at JPL/Caltech, under a contract with NASA. JIL was supported by the JWST Project through NASA. O.M. acknowledges support from CNES.

**Author(s): Torrence V. Johnson[4]**, Gül Sevin Peckmezci[5], Olivier Mousis[1], Jonathan I Lunine[2], Nikku Madhusudhan[3]
**Institution(s):** *1. Aix Marseille Université, CNRS, LAM (Laboratoire d'Astrophysique de Marseille), 2. Center for Radiophysics and Space Research, 3. Institute of Astronomy, University of Cambridge, 4. Jet Propulsion Laboratory, 5. Università Degli Studi di Roma "Tor Vergata"*

### 404.04 – Spectral identification of abiotic $O_2$ buildup from early runaways and rarefied atmospheres

The spectral detection of oxygen ($O_2$) in a planetary atmosphere has been considered a robust signature of life because $O_2$ is highly reactive on planets with Earth-like redox buffers and because significant continuous abiotic sources were thought to be implausible. However, recent work has revealed the possibility that significant $O_2$ may build-up in terrestrial planet atmospheres through (1) photochemical channels or (2) through massive hydrogen escape. We focus on the latter category here. Significant amounts of abiotic $O_2$ could remain in the atmospheres of planets in the habitable zones of late type stars, where an early runaway greenhouse and massive hydrogen escape during the pre-main-sequence phase could have irreversibly oxidized the crust and mantle (Luger & Barnes 2015). Additionally, it has been hypothesized that $O_2$ could accumulate in the atmospheres of planets with sufficiently low abundances of noncondensable gases such as $N_2$ where water would not be cold trapped in the troposphere, leading to H-escape from UV photolysis in a wet stratosphere (Wordsworth & Pierrehumbert 2014). We self-consistently model the climate, photochemistry, and spectra of both rarefied and post-runaway, high-$O_2$ atmospheres. Because an early runaway might not have lasted long enough for the entire water inventory to have escaped, we explore both completely desiccated scenarios and cases where a surface ocean remains. We find "habitable" surface conditions for a wide variety of oxygen abundances, atmospheric masses, and $CO_2$ mixing ratios. If $O_2$ builds up from H escape, the $O_2$ abundance should be very high, and could be spectrally indicated by the presence of $O_2$ collisionally-induced absorption (CIA) features. We generate synthetic direct-imaging and transit transmission spectra of these atmospheres and calculate the strength of the UV/Visible and NIR $O_2$ CIA features. We find that while both the UV/Visible and NIR $O_2$ CIA features are strong in the direct-imaging spectra of very high-$O_2$ atmospheres, only the NIR $O_2$ CIA features are significant in transmission spectra. We also conclude that detection of $N_2$-$N_2$ CIA in transmission or direct-imaging spectra could rule out $O_2$ origination from H-escape from thin atmospheres.

**Author(s): Edward Schwieterman[2]**, Victoria Meadows[2], Shawn Domagal-Goldman[1], Giada Arney[2], Rodrigo Luger[2], Rory Barnes[2]
**Institution(s):** *1. NASA Goddard Space Flight Center, 2. University of Washington*

### 404.05 – Exoplanet Magma Ocean Magnetic Fields may be Common

Kepler data suggest that many exoplanets have low densities for their mass, and therefore probably have hydrogen-rich atmospheres. For all but very thin atmospheres, these have a convective zone beneath the radiative outer region, and as a consequence have high temperatures at the assumed silicate surface, usually above the liquidus, implying a magma ocean. In many cases, the resulting high internal temperatures are sufficient to allow for dynamo action in the magma. There, the electrical conductivities are high enough to support such a dynamo but not so high that the thermal conductivity favors conduction over convection. High conductivity is bad for a dynamo so this lower thermal conductivity makes such magma ocean dynamos preferable to a putative iron core dynamo.
In our simple models, the atmospheres of exoplanets will contain a convective zone beneath a radiative zone if sufficiently thick. We develop a simple model for the surface temperature of a rocky exoplanet with atmosphere-to-planet mass ratios 0.001% to 10%, planet masses 1-10 $M_\oplus$, and effective temperatures 150-1000 K. In most models with atmosphere mass ratios greater than 0.1% the rocky surface is above 1500 K, above the liquidus for silicate magma. Assuming a fully molten silicate magma ocean planet of Earthlike composition, the primary mode of heat transport is convection except at the high-temperature, high atmosphere mass ratio end. From that, even with conservative estimates of the electrical conductivity of the liquid silicate magma, the nominal magnetic Reynolds number at the surface seldom falls below 10. Thus the tentative conclusion is that rocky exoplanets with sufficiently thick atmospheric envelopes to melt the surface can generate magnetic fields irrespective of their putative cores. Estimates of the magnetic field were done following Christensen, yielding surface values in the range of 0.1 to 0.5 Gauss.

**Author(s): Alexander Bourzutschky[1]**, David Stevenson[1]
**Institution(s):** *1. California Instiute of Technology*

### 404.06 – Understanding the Early Evolution of M dwarf Extreme Ultraviolet Radiation

The chemistry and evolution of planetary atmospheres depends on the evolution of high-energy radiation emitted by its host star. High levels of extreme ultraviolet (EUV) radiation can drastically alter the atmospheres of terrestrial planets through ionizing, heating, expanding, chemically modifying and eroding them during the first few billion years of a planetary lifetime. While there is evidence that stars emit their highest levels of far and near ultraviolet (FUV; NUV) radiation in the earliest stages of their evolution, we are currently unable to directly measure the EUV radiation. Most previous stellar atmosphere models under-predict FUV and EUV emission from M dwarfs; here we present new models for M stars that include prescriptions for the hot, lowest density atmospheric layers (chromosphere, transition region and corona), from which this radiation is emitted. By comparing our model spectra to GALEX near and far ultraviolet fluxes, we are able to predict the evolution of EUV radiation for M dwarfs from 10 Myr to a few Gyr. This research is the next major step in the HAZMAT (HAbitable Zones and M dwarf Activity across Time) project to analyze how the habitable zone evolves with the evolving properties of stellar and planetary atmospheres.

**Author(s): Sarah Peacock[2]**, Travis Barman[2], Evgenya Shkolnik[1]
**Institution(s):** *1. Arizona State University, 2. University of Arizona, LPL*

### 404.07 – A Statistical Characterization of Reflection and Refraction in the Atmospheres of sub-Saturn *Kepler* Planet Candidates

We present the results of our method to detect small atmospheric signals in *Kepler*'s close-in, sub-Saturn planet candidate light curves. We detect an average secondary eclipse for groups of super-Earth, Neptune-like, and other sub-Saturn-sized candidates by scaling and combining photometric data of the groups of candidates such that the eclipses add constructively. This greatly increases the signal-to-noise compared to combining eclipses for individual planets. We have modified our method for averaging short cadence light curves of multiple planet candidates (2014, ApJ, 794, 133), and have applied it to long cadence data, accounting for the broadening of the eclipse due to the 30 minute cadence. We then use the secondary eclipse depth to determine the average albedo for the group. In the short cadence data, we found that a group of close-in sub-Saturn candidates (1 to 6 Earth radii) was more reflective (geometric A ~ 0.22) than typical hot Jupiters (geometric A ~ 0.06 to 0.11: Demory 2014, ApJL, 789, L20). With the larger number of candidates available in long cadence, we improve the resolution in radius and consider groups of candidates with radii between 1 and 2, 2 and 4, and 4 and 6 Earth radii. We also modify our averaging technique to search for refracted light just before and after transit in the *Kepler* candidate light curves, as modelled by Misra and Meadows (2014, ApJL, 795, L14).

**Author(s): Holly A. Sheets[2]**, Drake Deming[2], Giada Arney[1], Victoria Meadows[1]
**Institution(s):** *1. Astronomy Department, University of Washington, 2. Department of Astronomy, University of Maryland*

### 404.08 – Mechanisms controlling the number and latitudinal spacing of jets-streams on multiple jet planets: from terrestrial planets to gas giants

Zonal jets dominate the atmospheric dynamics of a wide range of planetary systems as observed in all Solar System planetary atmospheres and even observed on exoplanets. Specifically, when the ratio between the eddy length scale and the planetary scale becomes small these planetary atmospheres develop multiple jets. In this study we use an idealized general circulation model to demonstrate how such multiple-jets are formed and what controls their latitudinal width and spacing. We find that for each latitude, over a wide range of parameters, the jet spacing scales with the Rhines scale. The simulations show the presence of a critical latitude, where poleward (equatorward) of this latitude the Rhines scale is larger (smaller) than the Rossby deformation radius. Poleward of this latitude, a classic geostrophic turbulence picture appears with a -5/3 spectral slope of inverse energy cascade from the deformation radius up to the Rhines scale. A shallower slope than the classic -3 slope of forward cascade is found from the deformation radius down to the viscosity scale, due to the broad input of baroclinic eddy kinetic energy. At these latitudes, eddy-eddy interactions transfer barotropic eddy kinetic energy from the input scales of baroclinic eddy kinetic energy up to the jet scale and down to smaller scales. We provide scaling laws for the number of eddy driven jets, their latitudinal width and speed as a function of a broad range of planetary parameters.

**Author(s): Yohai Kaspi[1]**, Rei Chemke[1]
**Institution(s):** *1. Weizmann Institute of Science*

### 404.09 – Equilibrium and Disequilibrium Chemistry in Evolved Exoplanet Atmospheres

It has been found that sub-Neptune-sized planets, although not existing in our Solar System, are ubiquitous in our interstellar neighborhood. This revelation is profound because, due to their special sizes and proximity to their host stars, Neptune- and sub-Neptune-sized exoplanets may have highly evolved atmospheres. I will discuss helium-dominated atmospheres as one of the outcomes of extensive atmospheric evolution on warm Neptune- and sub-Neptune-sized exoplanets. Due to depleted hydrogen abundance, the dominant carbon and oxygen species may not be methane or water on these evolved planets. Equilibrium and disequilibrium chemistry models are used to compute the molecular compositions of the atmospheres and their spectral features. Applications to GJ 436 b and other Neptune- and sub-Neptune-sized exoplanets will be discussed. As the observations to obtain the spectra of these planets continue to flourish, we will have the opportunity to study unconventional atmospheric chemical processes and test atmosphere evolution theories

**Author(s): Renyu Hu[1]**
**Institution(s):** *1. Jet Propulsion Laboratory*

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## 405 – Galilean Satellites

### 405.01D – The spatial structure and temporal variability of Ganymede’s auroral ovals from Hubble Space Telescope observations

We analyze spectrally and spatially resolved images of Ganymede’s FUV-auroral ovals obtained during the past two decades by Hubble’s Space Telescope Imaging Spectrograph (HST/STIS). We find both, spatial inhomogeneities of the brightness-distribution on the observed disk as well as temporal variation as a function of Ganymede’s position relative to the Jovian current sheet. The brightness of the ovals is not equally distributed along the ovals, i.e., the Jupiter-facing side is always brighter than the anti-Jupiter side at least by ~60%. When Ganymede moves from high elevated magnetic latitudes towards the center region of the Jovian current sheet, the brightness of the aurora on the leading side increases by over 30% from ~80 Rayleigh up to ~108 Rayleigh. Simultaneously, inside the current sheet center the auroral ovals are displaced by an average of ~6° of planetographic latitude, i.e., the ovals shift furthermore down towards the planetographic equator on the leading side, and up towards the poles on the trailing side. Both effects, the increase of brightness and the moving of the ovals, are correlated to increased plasma interaction inside the current sheet. Ganymede’s electron-impact-excited auroral emissions are thought to be driven by electron acceleration by strong field-aligned currents at the boundary area between open and closed magnetic field lines of Ganymede’s mini-magnetosphere. The change of the auroral morphology is a direct response to the changing plasma environment, i.e., changing ram and thermal pressures. Thus, the investigation of the aurora proves to be a suitable diagnostic tool of the various processes that contribute to Ganymede’s complex plasma and magnetic field environment.

**Author(s): Fabrizio Musacchio[5]**, Joachim Saur[5], Lorenz Roth[2], Kurt D. Retherford[4], Melissa A. McGrath[3], Paul D. Feldman[1], Darrel F. Strobel[1]
**Institution(s):** *1. Department of Physics and Astronomy, Johns Hopkins University, 2. School of Electrical Engineering, KTH Royal Institute of Technology, 3. SETI Institute, 4. Southwest Research Institute, 5. University of Cologne*

### 405.02 – Jupiter's Satellite Europa: Evidence for an Extremely Fine-Grained, High Porosity Surface

We have measured the polarization phase curves of highly reflective, fine-grained, particulate materials that simulate Europa’s predominately water ice regolith. Our laboratory measurements exhibit polarization phase curves that are remarkably similar to results reported by experienced astronomers (Rosenbush et al., 1997, 2015). Our previous reflectance phase curve measurements of the same materials were in agreement with the same astronomical observers. In addition, we found that these materials exhibit an increase in circular polarization ratio with decreasing phase angle. This is consistent with coherent backscattering (CB) of photons in the regolith (Nelson et al., 2000, 2002). Shkuratov et al. (2002) report that the polarization properties of these particulate media are also consistent with the CB enhancement process (Shkuratov, 1989; Muinonen, 1990).
We have reconfigured a goniometric photopolarimeter (Nelson et al., 2000, 2002) to undertake measurements of the polarization phase curves of these particulate materials. Our reconfiguration applies the Helmholtz Reciprocity Principle (Hapke, 2012, p264) - i.e. we present our samples with linearly polarized light and measure the intensity of the reflected component. These laboratory measurements are physically equivalent to the astronomical polarization measurements. We report here the polarization phase curves of high albedo Aluminium Oxide particulates of size $0.1<D<30$ μm, five of which are 1.5 μm or smaller in diameter. The phase angle varied from 0.05 to 15 degrees. We find for particles less than or equal to 1.5 μm that the depth and position of the polarization phase curve minimum, the crossover point, and the slope at the crossover point all correlate with particle size and porosity. We find zero polarization for the particle sizes greater than 2 μm.
Our results replicate the astronomical data and are consistent with a Europan regolith that is extremely fine-grained, with remarkably high porosity, probably with void space exceeding 90%. The Europa Clipper Mission science value would be strongly enhanced by measuring the polarization phase angle data of the Galilean satellites.
This work is supported by NASA’s Cassini Saturn Orbiter mission.

**Author(s): Robert M. Nelson[4]**, Mark D. Boryta[3], Bruce W. Hapke[6], Ken S. Manatt[1], Adaeze Nebedum[3], Desiree Kroner[5], Yuriy Shkuratov[2], Vladimir Psarev[2], William D. Smythe[1]
**Institution(s):** *1. Jet Propulsion Laboratory, 2. Karazin University, 3. Mount San Antonio College, 4. Planetary Science Institute, 5. University of California at Los Angeles, 6. University of Pittsburgh*

### 405.03 – Using Lava Tube Skylights To Derive Lava Eruption Temperatures on Io

The eruption temperature of Io's silicate lavas constrains Io's interior state and composition [1]. We have examined the theoretical thermal emission from lava tube skylights above basaltic and ultramafic lava channels. Assuming that tube-fed lava flows are common on Io, skylights could also be common. Skylights present steady thermal emission on a scale of days to months. We find that the thermal emission from such a target, measured at multiple visible and NIR wavelengths, can provide a highly accurate diagnostic of eruption temperature. However, the small size of skylights means that close flybys of Io are necessary, requiring a dedicated Io mission [2]. Observations would ideally be at night or in eclipse. We have modelled the thermal emission spectrum for different skylight sizes, lava flow stream velocities, end-member lava compositions, and skylight radiation shape factors, determining the resulting flow surface cooling rates. We calculate the resulting thermal emission spectrum as a function of viewing geometry. From the resulting 0.7:0.9 µm ratios, we see a clear distinction between basaltic and ultramafic compositions for skylights smaller than 20 m across, even if sub-pixel. Our analysis will be further refined as accurate high-temperature short-wavelength emissivity values become available [3]. This work was performed at the Jet Propulsion Laboratory-California Institute of Technology, under contract to NASA. We thank the NASA OPR Program for support. References: [1] Keszthelyi et al. (2007) Icarus 192, 491-502 [2] McEwen et al. (2015) The *Io Volcano Observer* (IVO) LPSC-46 abstract 1627 [3] Ramsey and Harris (2015) IAVCEI-2015, Prague, Cz. Rep., abstract IUGG-3519.

**Author(s): Ashley Gerard Davies[1]**, Laszlo P Keszthelyi3, Alfred S McEwen[2]
**Institution(s):** *1. JPL, 2. University of Arizona, 3. USGS Astrogeology Division*

### 405.04 – The Spatial Distribution of Volcanic Events on Io in 2013-2015

The spatial distribution of heat flow on Io is a key prediction of tidal heat dissipation models, and therefore provides an important constraint for understanding Io's interior. However, the majority of our knowledge about eruption locations is derived from geological features tracing long time periods (e.g. Hamilton et al., 2013), and from activity during the Galileo era (e.g. Davies et al., 2015; Veeder et al., 2015).
We report on new results from a campaign to image Io in the near-infrared with adaptive optics on the Keck and Gemini N telescopes. We observed Io on 93 nights between August 2013 and June 2015, detecting volcanic activity at dozens of hot spot locations. We present the spatial distribution of the observed eruption sites during this period, and compare this with the distributions inferred from past hot spot and patera locations by previous authors. We discuss the locations of eruptions of different magnitudes, including a preponderance of bright activity at latitudes polewards of 45 degrees in both hemispheres and an apparent spatial clustering of activity in the months following large eruptions. Finally, we address the durations of the detected eruptions, as well as connecting our findings to the EXCEED Mission's observations of the Io plasma torus during the same time period.

**Author(s): Katherine R. de Kleer[1]**, Imke de Pater[1]
**Institution(s):** *1. UC Berkeley*

### 405.05 – Insights into Io's volcanoes by combining ground-based and spacecraft data

Active volcanoes dominate Io's surface. They dominate Io's infrared flux, they add to the composition of the atmosphere, and are the origin of material in the Io Plasma torus. Understanding when, how, and why they erupt is the key to understanding material input into the Jovian system. They are also key to understanding the dominant heating process in the solar system: tidal heating, because Io is where that process has the greatest and most obvious effect.
The Galileo spacecraft obtained data from Io during periods less than a few days on more than 30 occasions between mid 1996 and late 2001. The New Horizons spacecraft observed Io for a 2-week period in early 2007. Other spacecraft, while not as useful for volcano observations, observed the Jupiter system in recent decades. The Cassini spacecraft flew by the Jupiter system in 2001 and the JAXA Hisaki (SPRINT-A) spacecraft observed the Jovian magnetosphere in 2014. The Juno spacecraft will reach Jupiter in a year. An mission specifically to Io has been submitted to the Discovery Program and will be allowed to the New Frontiers Program starting with call number 5.
NASA's Infrared Telescope Facility (IRTF) has been used to observe Io's volcanoes for more than two decades. Data consist of images in 3 wavelengths (2.2, 3.5, and 4.8 microns), with short exposures for shift-and-add processing to increase spatial resolution. In addition, Jupiter occultations of Io while it is in eclipse enable the accurate determination of the intensity and 1-D location of active volcanoes on the Jupiter-facing hemisphere of Io, but only in a single wavelength. IRTF observations were obtained on more than 100 nights, concentrated at times when a spacecraft is also observing Io.
Combining data from multiple instruments and facilities has allowed us to determine length of eruption events, such as Loki and Tvashtar, as well as temperatures of the erupted lavas. We will show how IRTF and New Horizons data, specifically, have been combined to yield greater information into the nature of Io's volcanism and we will discuss how ground-based observations during future missions can be optimized for the greatest scientific output.

**Author(s): Julie A. Rathbun3**, John R Spencer[2], Robert Howell4, Rosaly Lopes[1]
**Institution(s):** *1. JPL, 2. Southwest Research Institute, 3. Univ. of Redlands, 4. University of Wyoming*

### 405.06 – Sea salt irradiation experiments relevant to the surface conditions of ocean worlds such as Europa and Enceladus

We have conducted a set of laboratory experiments to measure changes in NaCl, KCl, $MgCl_2$, and mixtures of these salts, as a function of exposure to the temperature, pressure, and radiation conditions relevant to ice covered ocean worlds in our solar system. Reagent grade salts were placed onto a diffuse aluminum target at the end of a cryostat coldfinger and loaded into an ultra-high vacuum chamber. The samples were then cooled to 100 K and the chamber pumped down to ~$10^{-8}$ Torr, achieving conditions comparable to the surface of several moons of the outer solar system. Samples were subsequently irradiated with 10 keV electrons at an average current of 1 µA.
We examined a range of conditions for NaCl including pure salts grains (~300 µm diameter), salt grains with water ice deposited on top, and evaporites. For the evaporites saturated salt water was loaded onto the cryostat target, the chamber closed, and then slowly pumped down to remove the water, leaving behind a salt evaporate for irradiation.
The electron bombardment resulted in the trapping of electrons in halogen vacancies, yielding the the F- and M- color centers. After irraditiation we observed yellow-brown discoloration in NaCl. KCl was observed to turn a distinct violet. In NaCl these centers have strong absorptions at 450 nm and 720 nm, respectively, providing a highly diagnostic signature of otherwise transparent alkali halides, making it possible to remotely characterize and quantify the composition and salinity of ocean worlds.

**Author(s): Kevin P. Hand[1]**, Robert W Carlson[1]
**Institution(s):** *1. JPL*

### 405.07 – Linear spectral modeling of ground-based observations of Europa (ESO/VLT/SINFONI)

Jupiter's moon Europa may harbor a global salty subsurface liquid water ocean (Kivelson et al. 2000), and its surface should contain important clues about its composition. However, debate still persists about the nature of the surface chemistry and the relative roles of exogenous versus endogenous processing. Recently, Roth et al. (2014) reported the presence of activity by the detection of

plumes reinforcing Europa as a major target of interests of upcoming space missions such as the ESA L-class mission JUICE. To continue the investigation of the composition of the surface of Europa, a global mapping campaign of the satellite was performed between October 2011 and January 2012 with the integral field spectrograph SINFONI on the Very Large Telescope (VLT) in Chile. The high spectral binning of this instrument (0.5 nm) is suitable to detect any narrow signature in the wavelength range 1.45-2.45 µm. The spatially resolved spectra we obtained over five epochs nearly cover the entire surface of Europa with a pixel scale of 12.5 by 25 m.a.s (~35 by 70 km on Europa's surface).
We perform linear spectral modeling using 4 types of species : water-ice (both crystalline and amorphous), sulfuric acid hydrate, sulfate salts and Cl-rich salts. At first order, spectra on the leading side are, as expected, dominated by water-ice distorted and asymmetric absorption features, whereas sulfuric acid hydrate thought to originate from Iogenic sulfur ion bombardment is clearly predominant on the trailing side (Carlson et al. 2005).Salts are also required to fit any SINFONI spectrum with the following notable result: when Na/K-bearing chlorines instead of Mg-sulfates are used, the fits are improved whatever the region. The feature centered at ~2.07 µm previously associated to the magnesium sulfates (Brown et al. 2013) is also observed in the SINFONI spectra and can be reproduced by some chlorine salts. Global abundance maps will be presented, regional variations of abundances will be discussed and the question of the endogenic or exogenic origin of salts will be addressed. Finally, a preliminary comparison with similar SINFONI data of Ganymede and Callisto will be presented.

**Author(s): Nicolas Ligier[2]**, François Poulet[2], John Carter[2], Yves Langevin[2], Christophe Dumas[1], Florian Gourgeot[3]
**Institution(s):** *1. European Southern Observatory (ESO), 2. Institut d'Astrophysique Spatiale (IAS), 3. Observatorio Nacional (ON)*

### 405.08 – Thermal Coupling Between the Ocean and Mantle of Europa: Implications for Ocean Convection

Magnetic induction signatures at Europa indicate the presence of a subsurface ocean beneath the cold icy crust. The underlying mantle is heated by radioactive decay and tidal dissipation, leading to a thermal contrast sufficient to drive convection and active dynamics within the ocean. Radiogenic heat sources may be distributed uniformly in the interior, while tidal heating varies spatially with a pattern that depends on whether eccentricity or obliquity tides are dominant. The distribution of mantle heat flow along the seafloor may therefore be heterogeneous and impact the regional vigor of ocean convection. Here, we use numerical simulations of thermal convection in a global, Europa-like ocean to test the sensitivity of ocean dynamics to variations in mantle heat flow patterns. Towards this end, three end-member cases are considered: an isothermal seafloor associated with dominant radiogenic heating, enhanced seafloor temperatures at high latitudes associated with eccentricity tides, and enhanced equatorial seafloor temperatures associated with obliquity tides. Our analyses will focus on convective heat transfer since the heat flux pattern along the ice-ocean interface can directly impact the ice shell and the potential for geologic activity within it.

**Author(s): Krista M. Soderlund[3]**, Britney E. Schmidt[1], Johannes Wicht[2], Donald D. Blankenship[3]
**Institution(s):** *1. Georgia Institute of Technology, 2. Max Planck Institute for Solar System Research, 3. University of Texas Institute for Geophysics*

## 406 – Harold Masursky Award: The CSWA Survey on Workplace Climate and Anti-Harassment Policies, Christina Richey (NASA HQ)

### 406.01 – The CSWA Survey on Workplace Climate and Anti-Harassment Policies

Workplace climate can promote, or hinder, scientific productivity and innovation. The Committee on the Status of Women in Astronomy (CSWA) Survey on Workplace Climate sought to discover whether scientists in the astronomical and planetary science communities experienced a hostile work environment. The survey investigated the extent to which negative experiences 1) were motivated by the target's identity (e.g., gender, gender identity, sexual orientation, ability status, religion, neurodiversity, or race and ethnicity) and 2) affected the extent to which respondents felt safe in their workplaces. 426 participants were recruited for an online survey. This presentation will include the preliminary results from respondents' experiences in the last five years. Notable conclusions include: 1. Scientists in the astronomical and planetary science communities experience and witness inappropriate language, verbal harassment, and physical assault. 2. Abuses that relate to gender are those that appear in the greatest proportion in this sample. 3. Inappropriate comments, harassment, and assault lead to a number of scientists feeling unsafe in their workplaces, and pursuing fewer scholarly opportunities as a direct result of these experiences. This presentation, in addition to highlighting results from the recent CSWA Survey, will also include a definition for harassment and highlight the types of harassment that are frequently encountered by scientists, as well as highlight techniques for dealing with harassment, both in the workplace and at conferences.

**Author(s): Christina Richey[1]**
**Institution(s):** *1. NASA HQ*

## 407 – Rosetta at Perihelion: The Journey Continues, Paul Weissman (Planetary Science Institute)

### 407.01 – Rosetta at Perihelion: The Journey Continues

ESA's Rosetta spacecraft, with participation by NASA, has been in orbit around the nucleus of comet 67P/Churyumov-Gerasimenko for over one year. It has been a year of great discoveries and accomplishments, including the first successful spacecraft landing on the surface of a cometary nucleus (and the second and the third landings). The discoveries include 1) the unusual shape of the bi-lobed nucleus, 2) the substantial change of the nucleus rotation period (which continues to evolve), 3) the high dust-to-gas ratio, 4 ± 1 (by mass), 4) the low bulk density of the nucleus, 0.50 g/cm3, 5) the high deuterium/hydrogen ratio of the coma water molecules, $5.3 \times 10^{-4}$, more than 3 times the terrestrial value, 6) the highly complex and different terrains on the nucleus surface, 7) the lack of any intrinsic magnetic field, 8) the existence of cylindrical pits in the nucleus surface, typically ~200 m in diameter and ~180 m deep, 9) the existence of "goose bump" terrain, which may provide clues to the accretion of the comet nucleus, 10) the existence of many similarly-sized boulders on the nucleus surface, and much more. The spacecraft and comet passed through perihelion on August 13, 2015, which has been marked by substantial, volatile-rich outbursts from the cometary nucleus. The Rosetta mission has now been extended to September, 2016, when the comet and spacecraft will be approaching 4 AU, outbound from the Sun. This talk is dedicated to the memory of Dr. Claudia J. Alexander, U.S. Rosetta Project Scientist, who passed away in July of this year. Her tireless efforts and tremendous enthusiasm on behalf of Rosetta contributed greatly to the success of the mission.

**Author(s): Paul R. Weissman[3]**, Matthew Taylor[1], Claudia J. Alexander[2]
**Institution(s):** *1. European Space Agency, 2. Jet Propulsion Laboratory, 3. Planetary Science Institute*

## 408 – 20 Years of Exoplanets: From Surveys Towards Characterization, Emily Rauscher (University of Michigan)

### 408.01 – 20 Years of Exoplanets: From Surveys Towards Characterization

Twenty years ago the discovery of the first planet outside of our solar system ushered in a new subfield of exoplanet study. In the years since, the number of known planets has skyrocketed into the thousands, due to an ever-expanding pool of detection methods, projects and missions, and substantial improvements in technique. These remarkable discoveries have revealed an exoplanet population that is highly diverse, in many cases breaking expectations set by the single example of our own solar system, and providing us with the opportunity to study planets under a wide range of physical conditions. Equally as exciting as the increasing number of known exoplanets, within the last dozen years we have seen the move from exoplanet *discovery* to *characterization*; we are currently able to measure atmospheric properties of many of the brightest exoplanets. We are now in an era where we can study the diversity of atmospheric conditions for dozens of exoplanets, including measurements of their temperatures, albedos, compositions, and in some cases even more detailed information about their two- or three-dimensional atmospheric structures and circulation patterns. In this talk I will review the current state of theory and observations, the lessons we have learned, and the questions and techniques that direct future work.

**Author(s): Emily Rauscher[1]**
**Institution(s):** *1. University of Michigan*

## 409 – Galilean Satellites

### 409.01 – Mutual Occultation Observations of Volcanic Hot Spots on Io in 2015

During spring 2015 we observed a series of mutual occultations and eclipses of Io using the SpeX instrument on the NASA Infrared Telescope Facility (IRTF). Mutual event lightcurves were obtained on 4 Feb., 18 Feb., 15 Mar., and 22 Mar. in the Lp (3.8 micron) filter, with observations on 11 Feb. and on 8 and 10 Mar. lost to weather. Such lightcurves can potentially provide the highest spatial resolution observations of Io's volcanic hotspots possible from ground-based observations. The geometry of the recent events was particularly favorable for studies of the Loki Patera region, but unfortunately Loki remained relatively faint during the 2015 series. An eruption of Pillan was observed on 18 Feb., and is discussed in more detail by de Pater et al. (2015) at this meeting. While the relative faintness of Loki during the recent series limits the value of the new observations for studying that source, recent improvements to the Galilean satellite ephemerides also allow us to significantly improve the analysis of previous Loki occultations from 1985, 1991, 1997, and 2003. In that earlier work it was necessary to allow adjustable offsets in the relative position of the satellites to accommodate ephemeris uncertainty. That in turn limited the accuracy with which hot regions within Loki Patera could be fixed, and limited the ability to test different models for Patera activity. Initial analysis of the most recent event series indicates that such arbitrary adjustments are no longer necessary. We will present the occultation lightcurves for the most recent series and the constraints on the location of Loki activity provided by those observations and from earlier occultation series.

**Author(s): Robert R. Howell4**, John R Spencer3, Julie A. Rathbun[2], Jay D. Goguen[1]
**Institution(s):** *1. JPL, 2. Planetary Science Institute, 3. SwRI, 4. Univ. of Wyoming*

### 409.02 – Large Binocular Telescope Observations of Europa Occulting Io's Volcanoes at 4.8 µm

On 8 March 2015 Europa passed nearly centrally in front of Io. The Large Binocular Telescope observed this event in dual-aperture AO-corrected Fizeau interferometric imaging mode using the mid-infrared imager LMIRcam operating behind the Large Binocular Telescope Interferometer (LBTI) at a broadband wavelength of 4.8 µm (M-band). Occultation light curves generated from frames recorded every 123 milliseconds show that both Loki and Pele/Pillan were well resolved. Europa's center shifted by 2 kilometers relative to Io from frame-to-frame. The derived light curve for Loki is consistent with the double-lobed structure reported by Conrad et al. (2015) using direct interferometric imaging with LBTI.

**Author(s): Michael F. Skrutskie[6]**, Albert Conrad[2], Aaron Resnick[1], Jarron Leisenring7, Phil Hinz7, Imke de Pater[8], Katherine de Kleer[8], John Spencer4, Andrew Skemer7, Charles E Woodward5, Ashley Gerard Davies3, Denis Defrére7
**Institution(s):** *1. Amherst College, 2. Large Binocular Telescope Observatory, 3. NASA/JPL, 4. Southwest Research Institute, 5. Univ. of Minnesota, 6. Univ. Of Virginia, 7. University of Arizona, 8. University of California, Berkeley*

### 409.04 – Search for Trace Species at Europa

Understanding the present surface composition of Europa provides critical information about its potential habitability. From Earth we currently have very few tools at our disposal to measure Europa's composition. Two notable exceptions are Keck NIR spectroscopy (cf Brown and Hand 2013) and Hubble Space Telescope UV spectroscopy (cf Cunningham et al. 2015). In March 2015 we obtained 5 orbits of deep UV spectroscopy of Europa using the Cosmic Origins Spectrograph covering wavelength range 1170–1760 Å. The purpose of the observations was to detect trace species in Europa's exosphere, which is generated by charged particle sputtering of Europa's water ice surface. The composition of the exosphere therefore provides an indirect measurement of surface composition. Furthermore, if active plumes are present, the composition of the exosphere may also reflect the composition of Europa's subsurface water reservoir. Of particular interest in the observed wavelength range are multiplets of atomic chlorine, because chlorine is predicted to be a major constituent of Europa's ocean (Kargel et al. 2000), and Na and K chlorides are expected to be major constituents of the icy shell (Zolotov and Shock 2001; Zolotov and Kargel 2009). The present situation at Europa is analogous to that at Io in the late 1990s, when chlorine ions were first detected in the plasma near Io (Kuppers and Schneider 2000), motivating searches for atomic chlorine and chlorine-bearing species that were subsequently detected in Io's atmosphere (Lellouch et al. 2003, Feaga et al. 2004). Galileo plasma measurements have detected chlorine ions near Europa (Volwerk et al. 2001), which has motivated the present search for chlorine in Europa's exosphere. We will present the new COS spectra of Europa and discuss the implications of the trace species that have been detected in these data.

**Author(s): Melissa McGrath[1]**, William Sparks[2], John Spencer3
**Institution(s):** *1. SETI Institute, 2. STScI, 3. SWRI*

### 409.05 – The distinct spectrum of large-scale chaos on Europa from 1-4 micron

We present new, spatially-resolved reflectance spectra of the surface of Europa obtained with Keck NIRSPEC and adaptive optics. These include the first spatially-resolved, high-quality, 3-4 micron spectra on Europa. In recent work (Fischer et al. 2015, in review), we show that Europa's surface consists of three major compositional units at the ~100 km scale, one of which is geographically associated with large-scale chaos and therefore endogenous processes. We focus on this region; we will present the first moderate-resolution spectrum of large-scale chaos from 1.4-2.5 and 3.1-4.0 micron. We will also present cryogenic laboratory spectra of candidate materials from 1-4 micron and discuss the implications for identifying Europa's native composition.

**Author(s): Patrick D. Fischer[1]**, Michael E. Brown[1], Kevin P. Hand[2]
**Institution(s):** *1. Caltech, 2. JPL*

### 409.06 – Time Evolution of Io's volcanoes Pele and Pillan from 1996 – 2015, as derived from *Galileo* NIMS, Keck, Gemini, IRTF, and LBTI observations

We present highlights of our observations of Pele and Pillan on Io, and a multi-decade timeline of thermal emission intensities in both regions. Io was regularly observed by *Galileo* NIMS during 1996-2001. Since 2001 the satellite has been imaged semi-regularly with NIRC2, coupled to an adaptive optics system, on the 10-m Keck telescope. In 1997, *Galileo* NIMS observed a large and highly-variable eruption close to Pillan Mons; this eruption lasted several months [1]. Since that time no eruptions had been seen (but time coverage was scarce), until our Keck images on 14 August 2007 revealed an active and highly-energetic eruption at a location close to that of the 1997 eruptions. A one-temperature blackbody fit to the data revealed a (blackbody) temperature of 840 ± 40 K over an area of 17 $km^2$, with a total power output of ~500 GW. Using Davies' (1996) Io Flow Model [2] we find that the oldest lava present is less than 1-2 hours old, having cooled down from the eruption temperature of >1400 K to ~710 K. This young, hot lava suggests that an episode of lava fountaining was underway. Since 2007, several eruptions have been seen in the Pillan region. The 18 February 2015 eruption was discovered during a mutual occultation event with the NASA IRTF. This event was (serendipitously) subsequently imaged with the Large Binocular Telescope Interferometer (LBTI) on 8 March 2015 during a mutual event occultation, and again with the IRTF on 15 March. The site was imaged with the Keck and Gemini-N telescopes between 27 March and May 5, during which time the intensity gradually decreased. Interestingly, the precise location of the eruption had shifted to the north-west from Pillan Patera, where the initial (18 Feb) eruption had taken place. In contrast to the episodicity of Pillan, Pele has been remarkably consistent in its thermal emission during the *Galileo* era [1] through February 2002, when a blackbody temperature of 940 ± 40 K and an area of 6.5 $km^2$ was measured. Since that time, however, the radiant flux from this large overturning lava lake has gradually subsided over the next decade by a factor of ~4. [1] Davies et al. (2001) JGR, 106, 33079-33103. [2] Davies (1996) Icarus, 124, 45-61.

**Author(s): Imke de Pater[1]**
**Institution(s):** *1. UC, Berkeley*

## 410 – Enceladus

### 410.01 – Resolving Enceladus thermal emission at the 10s of meters scale along Baghdad Sulcus using Cassini CIRS

On 14th April 2012 Cassini executed one of its closest flyby to the South Pole of Enceladus with the primary goal to study the moon's gravity. During this flyby the Composite InfraRed Spectrometer (CIRS) was orientated such that its three focal planes were dragged across Baghdad sulcus. The instrument was specifically configured to record interferograms with 52 seconds duration. CIRS focal plane 1 (17 to 1000 μm) single circular detector provided a spatial resolution of about 300 meters. CIRS focal plane 3 and 4 (9 to 17 μm and 7 to 9 μm) are 2 1x10 detectors arrays. Both arrays were used in pair mode leading to 5 elements per focal plane and a resolution of about 43 meters across track.
The ground-track speed was so fast during this observation that this was enough time to observe the entire South Polar Region in a single integration. The thermal sources were passed over so rapidly that it is not possible to reconstruct a spectrum from the resulting interferogram, instead features were created in the interferogram whenever the scene temperature changed. The signature of these features was also altered by bit trimming and band-pass filter convolution. To enable interpretation of the interferograms we developed an innovative new approach that included the development of new instrument models, modification of the flight software and multiple in flight validation experiments. Our preliminary results show temperature variability of the tiger stripes at 10s meters scale along track, providing a constraint on the distribution and temperature profile of Enceladus' endogenic sources.
A similar methodology will be used for the penultimate targeted Enceladus flyby in Oct 28th 2015 and we aim to also present our preliminary analysis of the results from this encounter

**Author(s): Nicolas Gorius[1]**, Carly Howett3, John Spencer3, Shane Albright4, Don Jennings[2], Terry Hurford[2], Paul Romani[2], Marcia Segura5, Anne Verbiscer[6]
**Institution(s):** *1. Catholic University of America, 2. Goddard Space Flight Center, 3. Southwest Research Institute, 4. System and Software Design, 5. University of Maryland, 6. University of Virginia*

### 410.02 – Drawing the Curtain on Enceladus' South-Polar Eruptions

For a comprehensive description of Enceladus' south-polar eruptions observed at high resolution, they must be represented as broad curtains rather than discrete jets. Meanders in the fractures from which the curtains of material erupt give rise to optical illusions that look like discrete jets, even along fractures with no local variations in eruptive activity, implying that many features previously identified as "jets" are in fact phantoms. By comparing Cassini images with model curtain eruptions, we are able to obtain maps of eruptive activity that are not biased by the presence of those phantom jets. The average of our activity maps over all times agrees well with thermal maps produced by Cassini CIRS. We can best explain the observed curtains by assuming spreading angles with altitude of up to 14° and zenith angles of up to 8°, for curtains observed in geometries that are sensitive to those quantities.

**Author(s): Joseph N. Spitale3**, Terry A Hurford[2], Alyssa R Rhoden[1], Emily E Berkson4, Symeon S Platts5
**Institution(s):** *1. Arizona State University, 2. NASA Goddard Space Flight Center, 3. Planetary Science Institute, 4. Rochester Institute of Technology, 5. University of Arizona*

### 410.03 – Venting of $CO^2$ at Enceladus' Surface

Enceladus has $CO_2$ surface deposits in its South Polar Region that have been recently mapped by J.-P. Combe et al. (2015 AGU Fall Meeting). Assuming that these are $CO_2$ frost, we show how they can be formed. We use an ocean-water circulation model [1] that specifies pressure gradients that drive water to the surface from a relatively gas-rich, subsurface ocean. We now examine the movement of $CO_2$ to the surface; formation of shallow $CO_2$ gas pockets in the ice; and the venting of $CO_2$, when at least some of the gas freezes to form frost. If the local heat flow is known (cf. [2]), then the depths of the corresponding gas pockets can be calculated. References: [1] Matson et al. (2012) Icarus, 221, 53-62. [2] Howett et al. (2011) J. Geophys. Res. 116, E03003. Acknowledgements: AGD thanks the NASA OPR Program for support.

**Author(s): Dennis L. Matson[1]**, Ashley G. Davies3, Torrence V. Johnson[1], Jean-Philippe Combe3, Tom B. McCord3, Jani Radebaugh[2]
**Institution(s):** *1. Bear Fight Institute, 2. Brigham Young University, 3. Jet Propulsion Laboratory-California Institute of Technology*

### 410.04 – Inside Enceladus' plumes: the view from Cassini's mass spectrometer

Between early 2008 and late 2012, the Ion and Neutral Mass Spectrometer (INMS) on Cassini measured particles deep inside the plumes of Enceladus seven times from varying altitudes and locations. From these measurements and the models that use them, we have extracted information that can be used to constrain the physical processes that create the plumes and govern their source.
Neutral densities are high only when INMS is within view of the tiger stripes. Inside the plumes, INMS measures spatial variations that are consistent with Mach-4 jets superimposed on more-diffuse vapor. INMS measured vapor velocity directly during a portion of one encounter, finding a Mach-4 distribution centered on 1.2 km/s. Modeling of vapor sources distributed along the tiger stripes show they contribute 20% to 75% of the total density, depending on the encounter and assumptions on the discrete sources. Model-fitted velocities range from 500 to 1300 m/s. The INMS data also show 3x variations in total density that are consistent with the orbit-phase variations detected in visual and IR remote

observations of dust plumes. Only $H_3O^+$ ions are observed clearly inside the plumes.
An ice grain entering INMS increases the counts for one measurement. These spikes are the largest source of uncertainty (40%) in vapor measurements, but also provide independent measurements of ice grains. The frequency of these ice grains matches the Cosmic Dust Analyzer counts for grains larger than 0.2 µm. Their orbit-phase variability as seen by INMS is also consistent with VIMS data.
Water vapor comprises at least 90% of the plumes, with $CO_2$, $NH_3$, and $CH_4$ positively identified and less than 1%, each. $H_2$ is likely 5-10%, but its abundance is uncertain due to fractionation of $H_2O$ in the instrument. A species (CO or $N_2$) with a mass of 28 u is as abundant as $CO_2$. The $C_2$ group totals < 0.5%, and the $C_3$ group < 0.01%. The high-velocity encounters show carbon fractions of organic molecules with masses > 100 u. During individual encounters, $CO_2$ and the 28-u species show differences that are due at least in part to mass-dependent thermal spreading in high-velocity jets. There has been no significant variation in total composition between encounters.

**Author(s): Mark E. Perry[1]**, Dana M. Hurley[1], Ben D. Teolis[2], J. Hunter Waite[2], Brian A. Magee[2], H. Todd Smith[1], Valeriy Tenishev3, Joe H. Westlake[1], Ralph L. McNutt[1]
**Institution(s):** *1. Johns Hopkins Applied Physics Lab, 2. Southwest Research Institute, 3. University of Michigan*

### 410.05 – Modeling of the Enceladus water vapor jets for interpreting UVIS star and solar occultation observations

One of the most spectacular discoveries of the Cassini mission is jets emitting from the southern pole of Saturn's moon Enceladus. The composition of the jets is water vapor and salty ice grains with traces of organic compounds. Jets, merging into a wide plume at a distance, are observed by multiple instruments on Cassini. Recent observations of the visible dust plume by the Cassini Imaging Science Subsystem (ISS) identified as many as 98 jet sources located along "tiger stripes" [Porco et al. 2014]. There is a recent controversy on the question if some of these jets are "optical illusion" caused by geometrical overlap of continuous source eruptions along the "tiger stripes" in the field of view of ISS [Spitale et al. 2015]. The Cassini's Ultraviolet Imaging Spectrograph (UVIS) observed occultations of several stars and the Sun by the water vapor plume of Enceladus. During the solar occultation separate collimated gas jets were detected inside the background plume [Hansen et al., 2006 and 2011]. These observations directly provide data about water vapor column densities along the line of sight of the UVIS instrument and could help distinguish between the presence of only localized or also continuous sources. We use Monte Carlo simulations and Direct Simulation Monte Carlo (DSMC) to model the plume of Enceladus with multiple (or continuous) jet sources. The models account for molecular collisions, gravitational and Coriolis forces. The models result in the 3-D distribution of water vapor density and surface deposition patterns. Comparison between the simulation results and column densities derived from UVIS observations provide constraints on the physical characteristics of the plume and jets. The specific geometry of the UVIS observations helps to estimate the production rates and velocity distribution of the water molecules emitted by the individual jets.
Hansen, C. J. et al., Science 311:1422-1425 (2006); Hansen, C. J. et al, GRL 38:L11202 (2011); Porco, C.C. et al. Astron. J. 148, 45 (2014); Spitale, J.N. et al. Nature 521, 57-60 (2015)

**Author(s): Ganna Portyankina[1]**, Larry W Esposito[1], Klaus-Michael Aye[1], Candice J. Hansen[2]
**Institution(s):** *1. Laboratory for Atmospheric and Space Physics, University of Colorado, 2. Planetary Science Institute*

### 410.06 – Modeling of the spatial profile of neutrals in the plume of Enceladus observed by Cassini INMS

Monte Carlo modeling of the vapor erupting from Enceladus' South polar region is presented to demonstrate the influence of physical characteristics of the emitted vapor on the distribution of particles at altitude. The modeled sources include both localized jets and eruptions distributed along the surface features called "tiger stripes." The modeling reveals that density enhancements at altitude can be displaced from the source location. The displacement can be produced by the angle of emission. However, in some cases it is caused by superposition of material from adjacent sources. Assuming different molecules are emitted at the same bulk velocity and the same temperature, differences in the amount of spreading for the different species emerges owing to the dependence of thermal velocity on mass. The altitude of the superposition is mass dependent and contributes to differences observed in the mass 28 and mass 44 channels of the Cassini INMS during Enceladus encounters.
We present comparisons of INMS data with the model for four Cassini Enceladus flybys. INMS data are modeled using only the tiger stripe sources to reproduce the broad structure of the plume. The difference between the data and the model is attributed to the presence of stronger, more-localized sources, which are identified by their excess. In particular, an additional source is required for mass 44 u on the Saturn-facing hemisphere of Baghdad Sulcus. It is apparent in 3 parallel Cassini flybys. A relative decrease in the source rate is observed for mass 28 u for E14. The lack of small-scale spatial structure of high-density regions in the 28 u INMS observations compared to the more collimated structure of the 44 u INMS observations is consistent with increased thermal spreading for low-mass constituents of the plume. This indicates that even less spatial structure should be expected for the dominant species in the plume--water.

**Author(s): Dana Hurley[1]**, Mark Perry[1], Hunter Waite[2]
**Institution(s):** *1. JHU/APL, 2. SwRI*

## 411 – Icy Satellites

### 411.01 – Searching for Thermal Anomalies on Icy Satellites: Step 1- Validation of the Three Dimensional Volatile-Transport (VT3D)

In the last few decades, thermal data from the Galileo and Cassini spacecraft have detected various anomalies on Jovian and Saturnian satellites, including the thermally anomalous "PacMan" regions on Mimas and Tethys and the Pwyll anomaly on Europa (Howett et al. 2011, Howett et al. 2012, Spencer et al. 1999). Yet, the peculiarities of some of these anomalies, like the weak detection of the "PacMan" anomalies on Rhea and Dione and the low thermal inertia values of the widespread anomalies on equatorial Europa, are subjects for on-going research (Howett et al. 2014, Rathbun et al. 2010). Further, analysis and review of all the data both Galileo and Cassini took of these worlds will provide information of the thermal inertia and albedos of their surfaces, perhaps highlighting potential targets of interest for future Jovian and Saturnian system missions. Many previous works have used a thermophysical model for airless planets developed by Spencer (1990). However, the Three Dimensional Volatile-Transport (VT3D) model proposed by Young (2012) is able to predict surface temperatures in significantly faster computation time, incorporating seasonal and diurnal insolation variations. This work is the first step in an ongoing investigation, which will use VT3D's capabilities to reanalyze Galileo and Cassini data. VT3D, which has already been used to analyze volatile transport on Pluto, is validated by comparing its results to that of the Spencer thermal model. We will also present our initial results using VT3D to reanalyze the thermophysical properties of the PacMan anomaly previous discovered on Mimas by Howett et al. (2011), using temperature constraints of diurnal data from Cassini/CIRS. VT3D is expected to be an efficient tool in identifying new thermal anomalies in future Saturnian and Jovian missions.
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**Author(s): Gary G. Simmons[2]**, Carly J.A. Howett[1], Leslie A. Young[1], John R. Spencer[1]
**Institution(s):** *1. Southwest Research Institute, 2. University of Colorado-Boulder*

### 411.02 – Dark material on the classical Uranian satellites: What is it and where did it come from?

During Voyager 2's flyby of Uranus, its Imaging Science Subsystem (ISS) camera captured tantalizing images of the icy, gray-toned surfaces of the classical Uranian satellites. Additionally, ground-based near-infrared (NIR) observations of these moons have detected a mixture of $H_2O$ ice and a low albedo, and potentially carbonaceous, constituent on their surfaces. Analysis of ISS color maps demonstrated that the leading hemispheres of these moons are spectrally redder than their trailing hemispheres, and both the degree of reddening and the correlation between low albedo and spectrally red regions increases with distance from Uranus. However, ISS almost exclusively observed the southern hemispheres of these moons (subsolar point ~81° S), and we have collected new observations of their northern hemispheres (current subsolar point ~29° N). By characterizing the distribution of the dark material, we will be able to constrain the primary production mechanism for this low albedo constituent. Our preferred hypothesis is that the dark material represents accumulated intraplanetary dust that originated on Uranus' retrograde irregular satellites.
To characterize the distribution of the spectrally red, low albedo material on these moons, we are measuring their spectral slopes using visible wavelength (VIS) spectra and photometry gathered over similar wavelengths to those sensed by ISS (~0.4 – 0.6 μm). Additionally, we have collected NIR spectra of these satellites in order to characterize the relative strengths of 1.52 and 2.02 μm $H_2O$ ice bands, which are modified by the presence of low albedo contaminants. Our results indicate that the 1.52 and 2.02 μm $H_2O$ bands are stronger on the leading hemispheres of these moons, and the hemispherical asymmetry in $H_2O$ band strengths decreases with distance from Uranus. Spectral modeling of these NIR spectra will help discern between contaminant mixing and grain size effects on the relative strength of the $H_2O$ bands. We will present our interpretation of the $H_2O$ band strength results, and our ongoing analysis of VIS spectral slopes for the classical Uranian satellites.

**Author(s): Richard J. Cartwright3**, Joshua P. Emery3, Michael P. Lucas3, Noemi Pinilla-Alonso3, David E. Trilling[2], Andy S. Rivkin[1]
**Institution(s):** *1. John Hopkins University Applied Physics Laboratory, 2. Northern Arizona University, 3. University of Tennessee*

### 411.03 – Structural diversity of the 3-micron absorption band in Enceladus' plume from Cassini VIMS: Insights into subsurface environmental conditions

Water ice particles in Enceladus' plume display their diagnostic 3-micron absorption band in Cassini VIMS data. These near infrared measurements of the plume also exhibit noticeable variations in the character of this band. Mie theory calculations reveal that the shape and location of the 3-micron band are controlled by a number of environmental and structural parameters. Hence, this band provides important insights into the properties of the water ice grains and about the subsurface environmental conditions under which they formed. For example, the position of the 3-micron absorption band minimum can be used to distinguish between crystalline and amorphous forms of water ice and to constrain the formation temperature of the ice grains. VIMS data indicates that the water ice grains in the plume are dominantly crystalline which could indicate formation temperatures above 113 K [e.g. 1, 2]. However, there are slight (but observable) variations in the band minimum position and band shape that may hint at the possibility of varying abundance of amorphous ice particles within the plume. The modeling results further indicate that there are systematic shifts in band minimum position with temperature for any given form of ice but the crystalline and amorphous forms of water ice are still distinguishable at VIMS spectral resolution. Analysis of the eruptions from individual source fissures (tiger stripes) using selected VIMS observations reveal differences in the 3-micron band shape that may reflect differences in the size distributions of the water ice particles along individual fissures. Mie theory models suggest that big ice particles (>3 micron) may be an important component of the plume.
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**Author(s): Deepak Dhingra[2]**, Matthew M. Hedman[2], Roger N. Clark[1]
**Institution(s):** *1. Planetary Science Institute, 2. University of Idaho*

### 411.04 – Deriving the Structure and Composition of Enceladus' Plume from Cassini UVIS Observations

Cassini's Ultraviolet Imaging Spectrograph (UVIS) has observed 4 stellar and one solar occultation by Enceladus' water vapor plume. The July 2005 occultation observation established that water is the primary constituent of the plume [1], and allowed us to calculate the flux of water coming from the plume; the 2007 occultation showed super-sonic jets of gas imbedded within the plume [2]. The solar occultation observation set upper limits for $N_2$ as a constituent of the plume and provided higher resolution data on the jets [3]. On 19 October 2011, epsilon and zeta Orionis were simultaneously occulted by the plume. The stars were in separate pixels on the detector, separated by 24 mrad, or ~20 km, with the lower altitude star (epsilon Orionis) 18 km above the limb at its closest point. The profile at two altitudes shows evidence for a new gas jet location, possibly between dust jet #50 and #51 identified in [4].
Results from the assemblage of these data sets, with implications for the composition and vertical structure of the plume and jets, will be described. Gas being expelled from the "tiger stripe" fissures is largely on a vertical escape trajectory away from Enceladus. Upper limits are set for water vapor near the limb at latitudes well away from the south pole at 3 x $10^{15}$ $cm^{-2}$. Upper limits are set for the amount of ethylene and $H_2$ in the plume, two species of interest to the chemistry of the plume [5]. No hydrogen or oxygen emission features have been observed from Enceladus' water vapor plume, in contrast to the purported plumes at Europa, probably due to the very different plasma environment at Saturn. Data have now been processed consistently for all occultations with slightly different results for water vapor supply to the Saturn magnetosphere than previously reported. Overall, eruptive activity has been steady to within ~20% from 2005 to 2011.
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**Author(s): Candice Hansen[2]**, Larry Esposito5, Josh Colwell4, Amanda Hendrix[2], Ganna Portyankina5, Don Shemansky3, Robert West[1]
**Institution(s):** *1. JPL / CIT, 2. PSI, 3. Space Environment Technologies, 4. University of Central Florida, 5. University of Colorado*

### 411.05 – The 'Excess' Emission from the Warm Surface Adjacent to Active Fissures on Enceladus from Combined VIMS and CIRS Spectra

The exciting discovery of thermal emission from the tiger stripe fissures at the S. pole of Enceladus is a major highlight of the Cassini mission. Both VIMS (Visible and Infrared Mapping Spectrometer) and CIRS (Composite InfraRed Spectrometer) detect the thermal 'blackbody' spectrum emitted from the warm fissure areas. The VIMS instrument is uniquely suited to measuring the hottest active locations because VIMS covers the 3 to 5 micron wavelength range where the rising edge of the Planck function for these T~200 K areas dominates the emission

spectrum. At longer wavelengths, the spectrum is more complicated because contributions from small hot areas and larger cooler areas combine to form the broad emission spectrum that is detected by the CIRS instrument at wavelengths >6.7 microns. It is the combination of VIMS and CIRS spectra that paint a more complete portrait of the fissure heat transfer processes. Using spectra that span both the VIMS and CIRS wavelengths places a stronger constraint on the T distribution near the fissures than consideration of the spectra from either instrument alone.
We show that when the best (= highest spatial resolution, 800 m/pixel and smaller) VIMS and CIRS spectra of the fissure thermal emission are considered together, there is a large (up to 400%) component of 'excess' emission spanning 7 to 17 microns that requires explanation. New analysis of ~2 km spatial resolution VIMS spectra of the Damascus hot spot on 8/13/2010 are similar to the highest resolution 4/14/2012 VIMS Baghdad spectra, confirming that differences in location or time between the best VIMS and CIRS spectra do not explain away the excess. The obvious interpretation is that there are processes that transfer heat from the fissure eruption to the surface within 400 m of the fissure center in addition to heat conduction through the fissure walls. Candidate heat transfer processes include fallback of large warm low velocity ice particles from the edges of the plume, and condensation of the low velocity component of water vapor expanding outward from the edge of the plume.
This research was conducted at the Jet Propulsion Laboratory, California Institute of Technolgy, Pasadena, CA.

**Author(s): Jay D. Goguen[1]**, Bonnie J Buratti[1], Robert R. Howell[2]
**Institution(s):** *1. JPL, 2. University of Wyoming*

### 411.06 – A 1-D evolutionary model for icy satellites, applied to Enceladus

A 1-D long-term evolution code for icy satellites is presented, which couples multiple processes: water migration, geochemical reactions, water and silicate phase transitions, crystallization, compaction by self-gravity, and ablation. The code takes into account various energy sources: tidal heating, radiogenic heating, geochemical energy released by serpentinization or absorbed by mineral dehydration, gravitational energy, and insolation. It includes heat transport by conduction, convection, and advection. The code is applied to Enceladus, by guessing the initial conditions that would render a structure compatible with present-day observations, and adopting a homogeneous initial structure. Assuming that the satellite has been losing water continually along its evolution, it follows that it was formed as a more massive, more ice-rich and more porous object, and gradually transformed into its present day state, due to sustained tidal heating. Several initial compositions and evolution scenarios are considered, and the evolution is simulated for the age of the Solar System. The results corresponding to the present configuration are confronted with the available observational constraints. The present configuration is shown to be differentiated into a pure icy mantle, several tens of km thick, overlying a rocky core, composed of dehydrated rock in the central part and hydrated rock in the outer part. Such a differentiated structure is obtained not only for Enceladus, but for other medium size ice-rich bodies as well.
Predictions for Enceladus are a higher rock/ice mass ratio than previously assumed, and a thinner ice mantle, compatible with recent estimates based on gravity field measurements. Although, obviously, the 1-D model cannot be used to explain local phenomena, it sheds light on the internal structure invoked in explanations of localized features and activities.

**Author(s): Dina Prialnik[1]**, Uri Malamud[1]
**Institution(s):** *1. Tel Aviv University*

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## 412 – Irregular Satellites

### 412.01 – The Himalia Satellite Group: A Case Study on the Dynamical Self-spreading of Families of Irregular Satellites and Asteroids

Many of the outer planets' irregular satellites are grouped into families, thought to originate from collisional fragmentation (Nesvorný et al 2004, AJ). Interestingly, families associated with the largest irregulars are either more dispersed than expected (e.g. J6 Himalia; Nesvorný et al 2003, AJ), or do not exist at all (e.g. S9 Phoebe; Ćuk et al 2003, DDA meeting #34). Christou (2005, Icarus) found that gravitational scattering by Himalia of its own group could explain the large velocity dispersion found by Nesvorný et al (2003, AJ). At the same time, Christou identified a new type of dynamical mechanism that intermittently locks the node of the satellite J10 Lysithea to that of Himalia. The same mechanism, but due to Ceres, was recently found to operate within the Hoffmeister family, dispersing its members and allowing an estimate of its age (Novaković et al 2015, ApJ).
Here we revisit the issue of family self-dispersion, aiming to better understand it by studying its effects on the Himalia group. For this we utilise (a) intensive test particle simulations on a larger scale than those by Christou (2005, Icarus) (b) a semi-analytical treatment of the new resonance based on the secular theory of coorbital motion by Namouni (1999, Icarus). This has allowed us to obtain firmer constraints on the rate of dispersion over time and on how the resonance affects the long-term evolution of the orbital elements. A principal result of this work is that particles near the resonance evolve differently than those away from it. During the meeting, we will present a new estimate of the family's age as well as an analysis of the resonant structure and how it affects Himalia family members. We will also discuss the broader implications for the long-term evolution of orbital concentrations of small bodies in the solar system.
Astronomical research at the Armagh Observatory is funded by the Northern Ireland Department of Culture, Arts and Leisure (DCAL).

**Author(s): Daohai Li[1]**, Apostolos A Christou[1]
**Institution(s):** *1. Armagh Observatory*

### 412.02 – Lightcurves for 25 Irregular Satellites of Saturn

This abstract reports rotational-lightcurve observations of irregular moons of Saturn based on disk-integrated observations with the Narrow-Angle Camera of the Cassini spacecraft. For 16 objects, synodic rotation periods have been derived at <1% accuracy, for 6 others at lower accuracy or with an ambiguity with respect to the amount of maxima and minima. The average of all 22 measured periods lies between 16 and 19 h. For the 19 objects with periods faster than 24 h, the average is ~12.5 h.
The objects were observed at phase angles between 2° and 143°. Among the lightcurves obtained at low phases (< ~45°), ~85% exhibit 2 maxima and 2 minima, while only ~15% show 3max/3min. For mid-phase lightcurves (~45° to ~90°), the ratio between 2max/2min and 3max/3min lightcurves is almost equal. At high phases (> ~90°), only ~1/3 of the lightcurves display 2max/2min, while ~2/3 show 3max/3min or even 4max/4min. For low- and mid-phase angles, the lightcurve amplitudes clearly increase with increasing phase. While ~50% of the objects show lightcurves with amplitudes below ~0.4 mag at low phases, we found almost no such small amplitudes for mid and high phases. Between mid- and high-phase angles, the trend of magnitude increase lessens. The most extreme measured amplitudes were ~2.5 mag.
No object with a period close to the spin barrier for Main Belt asteroids (~2.3 h) was detected. By assuming a bulk density of the Saturnian irregulars of ~1 g $cm^{-3}$, the fastest measured period of 5.5 h would be close to the spin barrier for these objects.
A comparison of the irregular moons' rotation periods with five orbit parameters indicates possible weak correlations with two of them: Periapses and co-latitude of the orbit pole ($i'$; with $i' = i$ for prograde, $i' = 180°-i$ for retrograde moons; $i$ is the object's orbit inclination). For moons with orbits of high $i' >$ ~27°, no fast rotator ($P$ < 10 h) has been found, and their average rotation period is ~1.7x longer than for the low-$i'$ objects. The five fastest rotators are all members of the "low-$i'$ group". A null hypothesis claiming that objects of the two inclination bins come from the same population is rejected at the 95% confidence level.

**Author(s): Tilmann Denk[2]**, Stefano Mottola[1]
**Institution(s):** *1. DLR, 2. Freie Universität*

### 412.04 – Radial Profiles of Saturn's Phoebe Ring

In 2009, the Spitzer observatory discovered a vast circumplanetary dust ring around Saturn, sourced by its swarm of irregular satellites. This material had been hypothesized to exist, in order to blanket Iapetus' leading face and create its stark hemispherical dichotomy. Unfortunately, observations from near-Earth space cannot probe how far inward the Phoebe ring extends, as they are overwhelmed by scattered light from the planet. Additionally, to date, such measurements have only been achieved of thermal emission in the mid-infrared.
By contrast, we present results from recent observations with the Cassini spacecraft (in orbit about Saturn) at optical wavelengths. Using a novel observational technique that exploits the moving shadow cast by Saturn, we mitigate the scattered light and background, and have been able to clearly extract the exceedingly faint Phoebe ring signal (line-of-sight optical depth of 10e-9, surface brightness of roughly 27 mag/arcsec^2).
Our extracted albedos are consistent with dark material liberated from the irregular satellites. Additionally, we present reconstructed radial profiles over the broad range of distances from Saturn spanned by our observations. We also connect these results to theoretical models of the size-dependent dynamics of Phoebe ring dust grains under the action of the relevant perturbations.

**Author(s): Daniel Tamayo3**, Stephen Markham[1], Matthew M Hedman[2], Joseph A Burns[1]
**Institution(s):** *1. Cornell University, 2. University of Idaho, 3. University of Toronto at Scarborough*

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## 413 – 67P/Churyumov-Gerasimenko

### 413.01 – The nucleus of comet 67P through the eyes of the OSIRIS cameras

The Rosetta spacecraft is studying comet 67P/Churyumov-Gerasimenko from a close distance since August 2014. Onboard the spacecraft, the two scientific cameras, the OSIRIS narrow- and the wide-angle camera, are observing the cometary nucleus, its activity, as well as the dust and gas environment.
This overview paper will cover OSIRIS science from the early arrival and mapping phase, the PHILAE landing, and the escort phase including the two close fly-bys. With a first characterization of global physical parameters of the nucleus, the OSIRIS cameras also provided the data to reconstruct a 3D shape model of the comet and a division into morphologic sub-units. From observations of near-surface activity, jet-like features can be projected onto the surface and active sources can be correlated with surface features like cliffs, pits, or flat planes. The increase of activity during and after perihelion in August 2015 showed several outbursts, which were seen as strong, collimated jets originating from the southern hemisphere.
A comparison of results between different Rosetta instruments will give further inside into the physics of the comet's nucleus and its coma. The OSIRIS and VIRTIS instruments are particularly well suited to support and complement each other. With an overlap in spectral range, one instrument can provide the best spatial resolution while the other is strong in the spectral resolution. A summary on collaborative efforts will be given.

**Author(s): Carsten Guettler5**, Holger Sierks5, Cesare Barbieri7, Philippe Lamy4, Rafael Rodrigo[1], Detlef Koschny[2], Hans Rickman[8], The OSIRIS Team5, Fabrizio Capaccioni3, Gianrico Filacchione3, Mauro Ciarniello3, Stephane Erard[6], Giovanna Rinaldi3, Federico Tosi3
**Institution(s):** *1. Centro de Astrobiología, CSIC-INTA, 2. European Space Research and Technology Centre/ESA, 3. INAF, 4. LAM (Laboratoire d'Astrophysique de Marseille), 5. Max Planck Institute for Solar System Research, 6. Observatoire de Paris, 7. University of Padova, 8. Uppsala University*

### 413.02 – Interpretation of spectrophotometric surface properties of comet 67P/Churyumov-Gerasimenko by laboratory simulations of cometary analogs

The OSIRIS imaging system [1] onboard European Space Agency's Rosetta mission has been orbiting the comet 67P/Churyumov-Gerasimenko (67P) since August 2014. It provides an enormous quantity of high resolution images of the nucleus in the visible spectral range. 67P revealed an unexpected diversity of complex surface structures and spectral properties have also been measured [2].
To better interpret this data, a profound knowledge of laboratory analogs of cometary surfaces is essential. For this reason we have set up the LOSSy laboratory (Laboratory for Outflow Studies of Sublimating Materials) to study the spectrophotometric properties of ice-bearing cometary nucleus analogs. The main focus lies on the characterization of the surface evolution under simulated space conditions. The laboratory is equipped with two facilities: the PHIRE-2 radio-goniometer [3], designed to measure the bidirectional visible reflectance of samples under a wide range of geometries and the SCITEAS simulation chamber [4], designed to study the evolution of icy samples subliming under low pressure/temperature conditions by hyperspectral imaging in the VIS-NIR range. Different microscopes complement the two facilities.
We present laboratory data of different types of fine grained ice particles mixed with non-volatile components (complex organic matter and minerals). As the ice sublimes, a deposition lag of non-volatile constituents is built-up on top of the ice, possibly mimic a cometary surface. The bidirectional reflectance of the samples have been characterized before and after the sublimation process.
A comparison of our laboratory findings with recent OSIRIS data [5] will be presented.

[1] Keller, H. U., et al., 2007, Space Sci. Rev., 128, 26
[2] Thomas, N. , 2015, Science, 347, Issue 6220, aaa0440
[3] Jost, B., submitted, Icarus
[4] Pommerol, A., et al., 2015. Planet Space Sci 109:106-122.
[5] Fornasier, S., et al., in press. Icarus, arXiv:1505.06888

**Author(s): Bernhard Jost3**, Antoine Pommerol3, Olivier Poch[1], Nathalie Carrasco[2], Cyril Szopa[2], Nicolas Thomas3
**Institution(s):** *1. Center for Space and Habitability, University of Bern, 2. LATMOS-IPSL, Université Versailles St-Quentin, 3. Physics Institute, University of Bern*

### 413.03 – Photometric properties of the nucleus of 67P/Churyumov-Gerasimenko from OSIRIS/Rosetta, space telescope, and ground-based observations

In-situ imaging of the nucleus of comet 67P/Churyumov-Gerasimenko by the OSIRIS Narrow Angle Camera (NAC) allows an in depth characterization of its photometric properties that can be compared with remote observations thus helping in the interpretation of other nuclei. We performed a photometric analysis of both unresolved and resolved NAC images of the nucleus obtained during twenty five observational campaigns spreading from 23 March to 6 August 2014 with up to twelve filters whose spectral coverage extended from 271 to 986 nm. An accurate photometric calibration was obtained from the observations of a solar analog star, 16 Cyg B. We further combined this analysis with previous observations obtained with the Hubble and Spitzer space telescopes and ground-based telescopes. The analysis further incorporates the shape model and the rotational state the nucleus of \67P independently determined from the NAC images. We will present results on the geometric albedo, phase function, color and thermal properties and put them in the broader context of properties of cometary nuclei.

**Author(s): Philippe L. Lamy3**, Guillaume Faury[1], Imre Toth[2], Laurent Jorda3, Robert Gaskell4, Olivier Groussin3, Claire Capanna3
**Institution(s):** *1. AKKA Technologies, 2. Konkoly Observatory, 3. Laboratoire d'Astrophysique de Marseille, 4. Planetary Science Institute*

### 413.04 – The Nucleus and Coma of Comet 67P/C-G as

**Seen at Millimeter and Submillimeter Wavelengths by the MIRO Instrument**

The Microwave Instrument for the Rosetta Orbiter (MIRO) is a U.S. instrument on the European Space Agency's Rosetta spacecraft, currently flying along side comet 67P/Churyumov-Gerasimenko. MIRO is designed to study the nucleus and coma of the comet as a coupled system. It makes broad-band continuum measurements of the thermal emission of the nucleus at 190 and 563 GHz (1.6 and 0.5 mm) which probe the thermal and dielectric properties of the nucleus as a function of depth from ~1 mm to ~10 cm. When looking off the nucleus, continuum emission from dust can be used to constrain the abundance and size distribution of particles. In addition to its continuum channels, MIRO has a high resolution (44 kHz) spectrometer fixed tuned to submillimeter lines of $H_2O$, $H_2{}^{17}O$, $H_2{}^{18}O$, CO, $NH_3$, and three $CH_3OH$ transitions. All 8 lines have been observed, yielding estimates of the abundance, velocity, and temperature of these species in the coma. This talk will provide an overview of the instrument and our results to date.

**Author(s): Mark D. Hofstadter[1]**, Samuel Gulkis[1], Mark Allen[1], Paul von Allmen[1], Gerard Beaudin4, Nicolas Biver4, Dominique Bockelee-Morvan4, Mathieu Choukroun[1], Jacques Crovisier4, Pierre Encrenaz4, Therese Encrenaz4, Margaret Frerking[1], Paul Hartogh[2], Wing Ip3, Michael Janssen[1], Christopher Jarchow[2], Stephen Keihm[1], Seungwon Lee[1], Emmanuel Lellouch4, Cedric Leyrat4, Ladislav Rezac[2], Frederick Peter Schloerb[6], Thomas Spilker5

**Institution(s):** *1. JPL, 2. Max Planck, 3. National Central University, 4. Observatoire de Paris, 5. Solar System Science and Exploration, 6. University of Massachusetts*

## 413.05 – Search for regional variations of thermal and electrical properties of comet 67P/CG probed by MIRO/Rosetta

Since June 2014, The MIRO (Microwave Instrument for Rosetta Orbiter) on board the Rosetta (ESA) spacecraft observes comet 67P-CG along its heliocentric orbit from 3.25 AU to 1.24 AU. MIRO operates in millimeter and submillimeter wavelengths respectively at 190 GHz (1.56 mm) and 562 GHz (0.5 mm). While the submillimeter channel is coupled to a Chirp Transform Spectrometer (CTS) for spectroscopic analysis of the coma, both bands provide a broad-band continuum channel for sensing the thermal emission of the nucleus itself.
Continuum measurements of the nucleus probe the subsurface thermal emission from two different depths. The first analysis (Schloerb et al., 2015) of data already obtained essentially in the Northern hemisphere have revealed large temperature variations with latitude, as well as distinct diurnal curves, most prominent in the 0.5 mm channel, indicating that the electric penetration depth for this channel is comparable to the diurnal thermal skin depth. Initial modelling of these data have indicated a low surface thermal inertia, in the range 10-30 J K-1 m-2 s-1/2 and probed depths of order 1-4 cm. We here investigate potential spatial variations of thermal and electrical properties by analysing separately the geomorphological regions described by Thomas et al. (2015). For each region, we select measurements corresponding to those areas, obtained at different local times and effective latitudes. We model the thermal profiles with depth and the outgoing mm and submm radiation for different values of the thermal inertia and of the ratio of the electrical to the thermal skin depth. We will present the best estimates of thermal inertia and electric/thermal depth ratios for each region selected. Additional information on subsurface temperature gradients may be inferred by using observations at varying emergence angles.
The thermal emission from southern regions has been analysed by Choukroun et al (2015) during the polar night. Now that the comet has reached perihelion, the South Pole is fully illuminated, allowing extension of this study to these regions.

**Author(s): Cedric Leyrat[2]**, Doriann Blain[2], Emmanuel Lellouch[2], Paul von Allmen[1], Stephen Keihm[1], Matthieu Choukroun[1], Pete Schloerb3, Nicolas Biver[2], Samuel Gulkis[1], Mark Hofstadter[1]

**Institution(s):** *1. Jet Propulsion Laboratory, 2. LESIA - Observatoire de Paris, 3. University of Massachusetts*

## 413.06 – Modeling of the VIRTIS-M Observations of the Coma of Comet 67P/Churyumov-Gerasimenko

The recent images of the inner coma of 67P/Churyumov-Gerasimenko (CG) made by the infrared channel of the VIRTIS-M instrument on board the Rosetta spacecraft show the gas distribution as it expands in the coma (Migliorini et al. 2015, DPS abstract).
Since VIRTIS is a remote sensing instrument, a proper modeling of these observations requires the computation of the full coma of comet CG, which necessitates the use of a kinetic approach due to the rather low gas densities. Hence, we apply a Direct Simulation Monde Carlo (DSMC) method to solve the Boltzmann equation and describe CG's coma from the nucleus surface up to a few hundreds of kilometers. The model uses the SHAP5 nucleus shape model from the OSIRIS team. The gas flux distribution takes into account solar illumination, including self-shadowing. The local activity at the surface of the nucleus is given by spherical harmonics expansion reproducing best the ROSINA-DFMS data. The densities from the DSMC model outputs are then integrated along the line-of-sight to create synthetic images that are directly comparable with the VIRTIS-M column density measurements. The good agreement between the observations and the model illustrates our continuously improving understanding of the physics of the coma of comet CG.

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**Author(s): Nicolas Fougere9**, Michael R Combi9, Valeriy Tenishev9, Andre Bieler9, Alessandra Migliorini[2], Giuseppe Piccioni[2], Fabrizio Capaccioni[2], Gianrico Filacchione[2], Gabor Toth9, Zhenguang Huang9, Tamas Gombosi9, Kenneth Hansen9, Dominique Bockelee-Morvan 3, Vincent Debout3, Stephane Erard3, Cedric Leyrat3, Uwe Fink7, Martin Rubin[8], Kathrin Altwegg[8], Chia-Yu Tzou[8], Lena Le Roy[8], Ursina Calmonte[8], Jean-Jacques Berthelier3, Henri Reme[6], Myrtha Hassig4, Stephen Fuselier4, Bjorn Fiethe5, Johan De Keyser[1]

**Institution(s):** *1. Belgian Institute for Space Aeronomy, 2. Istituto Nazionale di Astrofisica , 3. Laboratoire d'Etudes Spatiales et d'Instrumentation en Astrophysique, Observatoire de Paris/CNRS/Université Pierre et Marie Curie/Université Paris-Diderot, 4. Southwest Research Institute, 5. TU Braunschweig, 6. Universite de Toulouse, 7. University of Arizona, 8. University of Bern, 9. University of Michigan*

## 413.07 – Activity and jets of comet 67P, as observed by OSIRIS since August 2014

Dust jets, i.e. fuzzy collimated streams of cometary material arising from the nucleus, have been observed in-situ on all comets since the Giotto mission flew by comet 1P/Halley in 1986. Yet their formation mechanism remains unknown. Several solutions have been proposed, from localized physical mechanisms on the surface/sub-surface to purely dynamical processes involving the focusing of gas flows by the local topography. While the latter seems to be responsible for

the larger features, high resolution imagery has shown that broad streams are composed of many smaller features (a few meters wide) that connect directly to the nucleus surface.
The OSIRIS cameras on board Rosetta are monitoring these jets in high resolution images since August 2014. We followed this type of activity from 3.6 AU to perihelion (1.23 AU). We have traced the jets back to their sources on the surface and noticed a good correlation with sub-solar latitude, surface morphologies, and color variations. As the comet receives more insolation, we observed different type of jets, some of them sustained beyond the local sunset, and an increasing number of transient events with sudden release of gas and dust.
We will present here how activity changes with local seasons and how it contributes to the erosion of the surface.
Acknowledgements: OSIRIS was built by a consortium led by the Max-Planck-Institut für Sonnensystemforschung, Göttingen, Germany, in collaboration with CISAS, University of Padova, Italy, the Laboratoire d'Astrophysique de Marseille, France, the Instituto de Astrofisica de Andalucia, CSIC, Granada, Spain, the Scientific Support Office of the European Space Agency, Noordwijk, The Netherlands, the Instituto Nacional de Tecnica Aeroespacial, Madrid, Spain, the Universidad Politechnica de Madrid, Spain, the Department of Physics and Astronomy of Uppsala University, Sweden, and the Institut für Datentechnik und Kommunikationsnetze der Technischen Universität Braunschweig, Germany. We thank the Rosetta Science Ground Segment at ESAC, the Rosetta Mission Operations Centre at ESOC and the Rosetta Project at ESTEC for their outstanding work enabling the science return of the Rosetta Mission.

**Author(s): Jean-Baptiste Vincent5**, Nilda Oklay5, Maurizio Pajola1, Sebastian Höfner5, Holger Sierks5, Cesare Barbieri1, Philippe Lamy4, Rafael Rodrigo3, Hans Rickman6, Detlef Koschny2
**Institution(s):** *1. CISAS, 2. ESTEC, 3. INTA-CSIC, 4. LAM, 5. MPS, 6. Uppsala University*

## 413.08 – Dust Outbursts From Comet 67P/Churyumov-Gerasimenko Observed by Rosetta-Alice

The comet 67P/Churyumov-Gerasimenko, passed through perihelion on 13 August 2015. In the weeks surrounding the perihelion passage, several dramatic outbursts of dust have been observed by instruments aboard ESA’s Rosetta spacecraft. These outbursts are typically intense and short-lived, with timescales on the order of several tens of minutes to a few hours. We report on the two largest of these dusty outbursts observed by the Alice far-ultraviolet (700-2050Å) spectrograph, which occurred on 10 July 2015 and 22 August 2015. On 10 July 2015 02:06 UTC, Alice spectra of the sunward limb, nucleus and anti-sunward limb show typical levels of dust-scattered sunlight, with the sunward limb 3-4x brighter than the anti-sunward limb. Beginning around 02:10 UTC, the dust on the anti-sunward side of the nucleus brightened rapidly, increasing by a factor of 21 over pre-outburst levels, when integrated over a 10-minute exposure. A 40s exposure beginning at 02:20 showed an additional factor of two increase in brightness. During the outburst, the dust became significantly brighter than the sunlit nucleus. Concurrent NAVCAM images show a large dust cloud expanding out from the night side of the nucleus. Despite this forty-fold increase in dust brightness, the Alice data show no evidence of enhancements of $H_2O$, CO, $CO_2$, $O_2$, O, or H in the post-outburst spectra. By 04:24 UTC, after a 2-hour data gap, the comet had returned to pre-event levels. Although complicated by the scanning motion of the spacecraft, the start of Alice observations on 22 August 2015 revealed a major dust outburst in progress, this time confined to the sunward side of the nucleus. Between 07:03 and 07:54, the brightness of dust on the sunward side faded by a factor of 7. NAVCAM images from this period also show a dramatic fan-shaped cloud of dust. Unlike the 10 July event, the 22 August event shows some evidence of increased gas emissions.

**Author(s): Andrew J. Steffl5**, Paul D. Feldman1, Michael F. A'Hearn7, Jean-Loup Bertaux3, Lori M. Feaga7, Brian A. Keeney6, Matthew M. Knight4, John Noonan5, Joel Wm. Parker5, Eric R. Schindhelm5, S. Alan Stern5, Ronald J. Vervack2, Harold A. Weaver2
**Institution(s):** *1. Johns Hopkins University, 2. Johns Hopkins University Applied Physics Lab, 3. LATMOS, 4. Lowell Observatory, 5. Southwest Research Institute, 6. Univeristy of Colorado, 7. Univeristy of Maryland*

## 413.09 – Evidence for a precession of the nucleus of comet 67P/C-G from ROSETTA/OSIRIS images

The retrieval of the rotational parameters of comet 67P/C-G is part of the shape reconstruction process conducted from data collected by the OSIRIS imaging system aboard ROSETTA. Among other parameters, this includes the reconstruction of the (RA,Dec) direction of the Z axis of the body-fixed frame and that of the angular momentum vector. The stereophotogrammetric solution (Preusker et al., A&A 2015, in press) obtained in Aug-Sep 2014 already showed evidence for a complex rotation of comet 67P/C-G. A subsequent analysis of the rotational data obtained using the stereophotoclinometry method (Gaskell et al., MP&S 43, 1049, 2008) up to April 2015 also revealed a precession with a likelihood greater than 99.99 %. The amplitude and period of the (RA,Dec) variations measured with both methods are fully compatible.
We propose an interpretation of the measured period as a combination of torque free motions: a rotation combined with a precession of small amplitude. The modeling of this motion has implications on the value of the moments of inertia, from which it is possible to constrain the internal density distribution of comet 67P/C-G.

**Author(s): Laurent Jorda4**, Pedro Gutierrez3, Bjoern Davidsson7, Robert Gaskell5, Stubbe Hviid2, Horst Uwe Keller6, Lucie Maquet1, Stefano Mottola2, Frank Preusker2, Frank Scholten2
**Institution(s):** *1. European Space Agency, 2. German Aerospace Center (DLR), 3. Instituto de Astrofisica de Andalucia, 4. Laboratoire d'Astrophysique de Marseille, 5. Planetary Science Institute, 6. Technical University of Braunschweig, 7. University of Uppsala*

## 413.10 – The interior of 67P/C-G nucleus revealed by CONSERT measurements and simulations

The CONSERT bistatic radar onboard the Rosetta spacecraft and the Philae lander has begun to reveal the internal structure of Comet 67P/Churyumov-Gerasimenko, through radio tomographic mapping between the lander and main spacecraft. The small lobe was found to be structurally homogeneous, at the spatial scale of ten meters, corresponding to a few wavelengths of CONSERT instrument [1]. The real part of the relative permittivity has been derived from the travel time of the strongest signals obtained on 12-13 November 2014, from Philae final landing site. Since the final position of the lander was not accurately defined, numerous ray-tracing simulations were performed to constrain the ambiguities on Philae position using the known position of Rosetta and the propagation time and paths inside and outside the nucleus. A least square statistical analysis between measurements and simulations lead to deduce a bulk relative permittivity about (1.27 ± 0.1); meanwhile, the uncertainty in the lander location was reduced to an area of about 21 by 34 square meters [1].
Ongoing theoretical and experimental simulations are providing more insights on the nucleus properties. Numerical ray-tracing simulations of the propagation at grazing angles have been performed for various subsurface permittivity models. They establish that a permittivity gradient in the shallow sub-surface would have a strong effect on the wave propagation. The permittivity probably decreases with depth, suggesting that a significant increase of dust/ice ratio with depth is unlikely [2]. Laboratory simulations of the permittivity of subsurface cometary analog materials [3], and of surface porous analog samples [4] have taken place. Results suggest 67P dielectric properties to be mainly controlled by porosity, the dust/ice volumetric ratio to range from 0.4 to 2.6 and the porosity to range from 75 to 85% [1].

Further on-going laboratory measurements will be discussed.
Supports from CNES and NASA are acknowledged.
[1] Kofman et al. Science 349, 6247 aab0639, 2015.
[2] Ciarletti et al. A&A (Rosetta issue), in press, 2015.
[3] E. Heggy et al. Icarus 221, 925, 2012.
[4] Brouet et al. A&A (Rosetta issue), in press, 2015.

**Author(s): A. Levasseur-Regourd[4]**, Wlodek Kofman[1], Alain Herique[1], Valérie Ciarletti[5], Essam Heggy[3], Jérémie Lasue[2]
**Institution(s):** *1. IPAG-CNRS, 2. IRAP-OMP, CNRS-UPS, 3. University of Southern California, 4. UPMC (Sorbonne Univ.), 5. UVSQ (UPSay)*

### 413.11 – 3D reconstruction of the final PHILAE landing site: Abydos

The Abydos region is the region of the final landing site of the PHILAE lander. The landing site has been potentially identified on images of this region acquired by the OSIRIS imaging system aboard the orbiter before (Oct 22, 2014) and after (Dec 6-13, 2014) the landing of PHILAE (Lamy et al., in prep.). Assuming that this identification is correct, we reconstructed the topography of Abydos in 3D using a method called ``multiresolution photoclinometry by deformation'' (MPCD, Capanna et al., The Visual Computer, 29(6-8): 825-835, 2013). The method works in two steps: (a) a DTM of this region is extracted from the global MPCD shape model, (b) the resulting triangular mesh is progressively deformed at increasing spatial resolution in order to match a set of 14 images of Abydos at pixel resolutions between 1 and 8 m. The method used to perform the image matching is the L-BFGS-b non-linear optimization (Morales et al., ACM Trans. Math. Softw., 38(1): 1-4, 2011).
In spite of the very unfavourable illumination conditions, we achieve a vertical accuracy of about 3 m, while the horizontal sampling is 0.5 m. The accuracy is limited by high incidence angles on the images (about 60 deg on average) combined with a complex topography including numerous cliffs and a few overhangs. We also check the compatibility of the local DTM with the images obtained by the CIVA-P instrument aboard PHILAE. If the Lamy et al. identification is correct, our DTM shows that PHILAE landed in a cavity at the bottom of a small cliff of 8 m height.

**Author(s): Claire Capanna[2]**, Laurent Jorda[2], Philippe Lamy[2], Gilles Gesquière[3], Cédric Delmas[1], Joëlle Durand[1], Philippe Gaudon[1], Eric Jurado[1]
**Institution(s):** *1. CNES, 2. Laboratoire d'Astrophysique de Marseille, 3. LIRIS*

### 413.12 – Report on the ground-based observation campaign of 67P/Churyumov-Gerasimenko

Rosetta gets closer to the nucleus than any previous mission, and returns wonderfully detailed measurements from the heart of the comet, but at the cost of not seeing the large scale coma and tails. The ground-based campaign fills in the missing part of the picture, studying the comet at about 1000 km resolution, and following how the overall activity of the comet varies. These data provide context information for Rosetta, so changes in the inner coma seen by the spacecraft can be correlated with the phenomena observable in comets. This will not only help to complete our understanding of the activity of 67P, but also to allow us to compare it with other comets that are only observed from the ground.
The ground-based campaign includes observations with nearly all major facilities world-wide. In 2014 the majority of data came from the ESO VLT, as the comet was still relatively faint and in Southern skies, but as it returns to visibility from Earth in 2015 it is considerably brighter, approaching its perihelion in August, and at Northern declinations. I will present results from the 2014 campaign, including visible wavelength photometry and spectroscopy, and the latest results from 2015 observations.

**Author(s): Emmanuel Jehin[1]**
**Institution(s):** *1. Université de Liège*

### 413.13 – Hubble Space Telescope Imaging Polarimetry of Comet 67P/Churyumov-Gerasimenko Obtained During the Rosetta Mission

We present pre- and post-perihelion, high-spatial resolution (0.05 arcsec/pixel) 0.6 micron imaging polarimetry of Comet 67P/Churyumov-Gerasimenko taken with the Advanced Camera for Surveys aboard the Hubble Space Telescope (HST). The pre-perihelion observations were obtained at two epochs chosen to bracket the times when the closest orbits of Rosetta were flown (down to 10 km for extended periods: 2014-Aug-19: $r_h$ = 3.52 au, $\Delta$ = 2.76 au, $\alpha \approx 12.0°$) and the Philae landing took place (2014-Nov-17: $r_h$ = 2.96 au, $\Delta$ = 3.43 au, $\alpha \approx 15.7°$). Our preliminary analyses of both pre-perihelion epochs shows that the polarization position angle lies in the scattering plane, thus is negative, with a degree of polarization p% ≈ -2%. The two post-perihelion epochs were matched to the first time after perihelion that the comet was observable with HST (2015-Oct-10: $r_h$ = 1.43 au, $\Delta$ = 1.80 au, $\alpha \approx 33.5°$), and when the comet was again viewed at small phase angle (2016-Feb-19: $r_h$ = 2.40 au, $\Delta$ = 1.49 au, $\alpha \approx 12.0°$). We discuss our polarimetry results in context with in situ measurements of dust particles obtained with the Rosetta spacecraft.

**Author(s): Dean C. Hines[8]**, Anny-Chantal Levasseur-Regourd [12], Edith Hadamcik[13], Vadym Kaydash[3], Matthew M. Knight [4], Ludmilla Kolokolova[11], Jian-Yang Li[6], Carey M. Lisse[1], Karri Muinonen[10], Max Mutchler[8], Yuriy Shkuratov[3], Colin Snodgrass[5], Michael L. Sitko[9], Matt G. G. T. Taylor[2], Gorden Videen[7], Padmavati A. Yanamandra-Fisher[7], Evgenij Zubko[3]
**Institution(s):** *1. Applied Physics Laboratory, 2. ESA ESTEC, 3. Kharkov National University, 4. Lowell Observatory, 5. MPI for Solar System Research, 6. Planetary Science Institute, 7. Space Science Institute, 8. Space Telescope Science Institute, 9. University of Helsinki, 10. University of Helsinki, 11. University of Maryland, 12. UPMC (Sorbonne Univ.), 13. UPMC/ LATMOS*

### 413.14 – Water production rates of recent comets (2015) by SOHO/SWAN and the SOHO/SWAN survey

The all-sky hydrogen Lyman-alpha camera, SWAN (Solar Wind Anisotropies), on the SOlar and Heliospheric Observatory (SOHO) satellite makes observations of the hydrogen coma of comets. Most water molecules produced by comets are ultimately photodissociated into two H atoms and one O atom producing a huge atomic hydrogen coma that is routinely observed in the daily full-sky SWAN images in comets of sufficient brightness. Water production rates are calculated using our time-resolved model (Mäkinen & Combi, 2005, Icarus 177, 217), typically yielding about 1 observation every 2 days on the average for each comet. Here we describe the progress in analysis of observations of comets observed in 2015 and those selected from the archive for analysis. These include comets C/2013 US10 (Catalina), C/2014 Q1 (PanSTARRS), and possibly 67P/Churyumov-Gerasimenko. A status update on the entire SOHO/SWAN archive of water production rates in comets will also be given. SOHO is an international cooperative mission between ESA and NASA. Support from grants NNX11AH50G from the NASA Planetary Astronomy Program and NNX13AQ66G from the NASA Planetary Mission Data Analysis Program are gratefully acknowledged, as is support from CNRS, CNES, and the Finnish Meteorological Institute (FMI).

**Author(s): Michael R. Combi[4]**, J. T. T. Mäkinen[2], Jean-Loup Bertaux[3], Eric Quémerais[3], Stéphane Ferron[1]
**Institution(s):** *1. ACRI-st, 2. Finnish Meterologoical Institute, 3. LATMOS/IPSI, Université de Versailles Saint-Quentin, 4. Univ. of Michigan*

### 413.15 – The primordial nucleus of Comet 67P/Churyumov-Gerasimenko

Observations of Comet 67P/Churyumov-Gerasimenko by Rosetta show that the nucleus is bi-lobed, extensively layered, has a low bulk density, a high dust-to-ice mass ratio (implying high porosity), and weak strength except for a thin sintered surface layer. The comet is rich in supervolatiles (CO, $CO_2$, $N_2$), may contain amorphous water ice, and displays little to no signs of aqueous alteration. Lack of phyllosilicates in Stardust samples from Comet 81P/Wild 2 provides further support that comet nuclei did not

contain liquid water.
These properties differ from those expected for 50-200 km diameter bodies in the primordial disk. We find that thermal processing due to Al-26, combined with collisional compaction, creates a population of medium-sized bodies that are comparably dense, compacted, strong, heavily depleted in supervolatiles, containing little to no amorphous water ice, and that have experienced extensive aqueous alteration. Irregular satellites Phoebe and Himalia are potential representatives of this population. Collisional rubble piles inherit these properties from their parents. We therefore conclude that observed comet nuclei are primordial rubble piles, and not collisional rubble piles.
We propose a concurrent comet and TNO formation scenario that is consistent with these observations. We argue that TNOs form due to streaming instabilities at sizes of about 50-400 km and that about 350 of these grow slowly in a low-mass primordial disk to the size of Triton, causing little viscous stirring during growth. We propose a dynamically cold primordial disk, that prevents medium-sized TNOs from breaking into collisional rubble piles, and allows for the survival of primordial rubble-pile comets. We argue that comets form by hierarchical agglomeration out of material that remains after TNO formation. This slow growth is necessary to avoid thermal processing by Al-26, and to allow comet nuclei to incorporate 3 Myr old material from the inner Solar System, found in Stardust samples. Growth in the Solar Nebula creates porous single-lobe nuclei, while continued growth in a mildly viscously stirred primordial disk creates denser outer layers, and allow bi-lobe nucleus formation through mergers.

**Author(s): Bjorn Davidsson[26]**, Holger Sierks[14], Carsten Guettler[14], Francesco Marzari[23], Maurizio Pajola[3], Hans Rickman[17], Michael A'Hearn[21], Anne-Therese Auger[1], Mohamed El-Maarry[18], Sonia Fornasier[13], Pedro Gutierrez[10], Horst Uwe Keller[9], Matteo Massironi[3], Colin Snodgrass[19], Jean-Baptiste Vincent[14], Cesare Barbieri[24], Philippe Lamy[11], Rafael Rodrigo[2], Detlef Koschny[20], Antonella Barucci[13], Jean-Loup Bertaux[12], Ivano Bertini[3], Gabriele Cremonese[8], Vania Da Deppo[4], Stefano Debei[25], Mariolino De Cecco[5], Clement Feller[13], Marco Fulle[7], Olivier Groussin[1], Stubbe Hviid[6], Sebastian Hoefner[14], Wing-Huen Ip[15], Laurent Jorda[11], Joerg Knollenberg[6], Gabor Kovacs[14], Joerg-Rainer Kramm[14], Ekkehard Kuehrt[6], Michael Kueppers[16], Fiorangela La Forgia[24], Luisa Lara[10], Monica Lazzarin[24], Jose Lopez Moreno[10], Richard Moissl-Fraund[16], Stefano Mottola[6], Giampiero Naletto[22], Nilda Oklay[14], Nicolas Thomas[18], Cecilia Tubiana[14]
**Institution(s):** *1. Aix Marseille Universite, CNRS, LAM (Laboratoire d'Astrophysique de Marseille), 2. Centro de Astrobiologia, CSIC-INTA, 3. Centro di Ateneo di Studi ed Attivita Spaziali "Giuseppe Colombo" (CISAS), University of Padova, 4. CNR-IFN UOS Padova LUXOR, 5. Department of Industrial Engineering – University of Padova, 6. Deutsches Zentrum fuer Luft- und Raumfahrt (DLR), 7. INAF - Osservatorio Astronomico, 8. INAF, Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio, 9. Institut fuer Geophysik und extraterrestrische Physik (IGEP), Technische Universitaet Braunschweig, 10. Instituto de Astrofisica de Andalucia (CSIC), 11. Laboratoire d'Astrophysique de Marseille, 12. LATMOS, CNRS/UVSQ/IPSL, 13. LESIA-Observatoire de Paris, CNRS, Universite Pierre et Marie Curie, Universite Paris Diderot, 14. Max-Planck-Institut fuer Sonnensystemforschung, 15. National Central University, Graduate Institute of Astronomy, 16. Operations Department, European Space Astronomy Centre/ESA, 17. PAN Space Research Center, 18. Physikalisches Institut der Universitaet Bern, 19. Planetary and Space Sciences, Department of Physical Sciences, The Open University, 20. Scientific Support Office, European Space Research and Technology Centre/ESA, 21. University of Maryland, Department of Astronomy, 22. University of Padova, Department of Information Engineering, 23. University of Padova, Department of Physics and Astronomy, 24. University of Padova, Department of Physics and Astronomy, Vicolo dell'Osservatorio, 25. University of Trento, 26. University of Uppsala, Dept. of Physics and Astronomy*

### 413.16 – Comet 67P observations with LOTUS: a new near-UV spectrograph for the Liverpool Telescope

The European Space Agency's Rosetta spacecraft has been orbiting comet 67P/Churyumov-Gerasimenko (hereinafter "67P") since August 2014, providing in-situ measurements of the dust, gas and plasma content of the coma within ~100km of the nucleus. Supporting the mission is a world-wide coordinated campaign of simultaneous ground-based observations of 67P (www.rosetta-campaign.net), providing wider context of the outer coma and tail invisible to Rosetta. We can now compare these observations, augmented by "ground truth" from Rosetta, with those of other comets past and future that are only observed from Earth.
The robotic Liverpool Telescope (LT) is part of this campaign due to its unique ability to flexibly and autonomously schedule regular observations over entire semesters. Its optical imagery has recently been supplemented by near-UV spectroscopy to observe the UV molecular bands below 4000Å that are of considerable interest to cometary science. The LT's existing spectrographs FRODOSpec and SPRAT cut off at 4000Å, so the Liverpool Telescope Optical-to-UV Spectrograph - LOTUS - was fast-track designed, built and deployed on-sky in just five months. LOTUS contains no moving parts; acquisition is made with the LT's IO:O imaging camera, and different width slits for calibration and science are selected by fine-tuning the telescope's pointing on an innovative "step" design in its single slit.
We present here details of the LOTUS spectrograph, and some preliminary results of our ongoing observations of comet 67P.

**Author(s): Jon Marchant[1]**, Helen Jermak[1], Iain Steele[1], Colin Snodgrass[3], Alan Fitzsimmons[2], Geraint Jones[4]
**Institution(s):** *1. Liverpool John Moores University, 2. Queen's University Belfast, 3. The Open University, 4. University College London*

## 414 – Active Asteroids

### 414.02 – The Reactivation of Main-Belt Comet 324P/La Sagra (P/2010 R2)

We present observations using the Baade Magellan and Canada-France-Hawaii telescopes showing that main-belt comet 324P/La Sagra, formerly known as P/2010 R2, has become active again for the first time since originally observed to be active in 2010-2011. The object appears point-source-like in March and April 2015 as it approached perihelion (true anomaly of ν~300 deg), but was ~1 mag brighter than expected if inactive, suggesting the presence of unresolved dust emission. Activity was confirmed by observations of a cometary dust tail in May and June 2015. We find an apparent net dust production rate of <0.1 kg/s during these observations. 324P is now the fourth main-belt comet confirmed to be recurrently active, a strong indication that its activity is driven by sublimation. It now has the largest confirmed active range of all likely main-belt comets, and also the most distant confirmed inbound activation point at R~2.8 AU. Further observations during the current active period will allow direct comparisons of activity strength with 324P's 2010 activity.

**Author(s): Henry H. Hsieh[2]**, Scott Sheppard[1]
**Institution(s):** *1. Carnegie Institution for Science, 2. Planetary Science Institute*

### 414.03 – Evidence for an Impact Event on (493) Griseldis

An extended feature associated with the main-belt asteroid (493) Griseldis has been detected in three R-band exposures of 330 to 350 sec duration spanning 5 hours taken on 2015 Mar 17 UT with the HyperSuprimeCam instrument on the 8-m Subaru telescope. Additional observations of Griseldis were taken with the 6.5-m Magellan telescope on 2015 Mar 21 UT, and the extended feature was still detected, though weaker. No extended feature was detected in one unfiltered 600 sec exposure taken with the 2.2-m University of Hawaii telescope on 2015 Mar 24 UT, or in Magellan images taken on 2015 Apr 18 and May 21 UT. Griseldis is a 46 km diameter P-type asteroid with semimajor axis of 3.12 AU, eccentricity of 0.17, inclination of 15 deg, and Tisserand parameter of 3.187 relative to Jupiter. The heliocentric distance on 2015 Mar

17 was 3.33 AU, thus the asteroid was closer to aphelion than it was to perihelion. The most recent perihelion passage was on 2013 Aug 17, and the orbital period is 5.5 years. Additional images in the Subaru and CTIO DECam archives from 2010 and 2012, respectively, show no signs of activity. The position angle of the extended feature does not match either the antisolar direction or the negative velocity vector of the asteroid. The rotational lightcurve of Griseldis is known to show a peak-to-peak amplitude of up to 0.45 mag over a 52-hour period. No anomalous brightening of the asteroid is evident in the 2015 photometry reported along with the astrometry of this object. The observations are consistent with the occurrence of an impact event on this asteroid. Additional analysis of the images is in progress.

**Author(s): David J. Tholen3**, Scott S. Sheppard[1], Chad A. Trujillo[2]
**Institution(s):** *1. Carnegie Inst., 2. Gemini Obs., 3. Univ. of Hawaii*

### 414.04 – Thermal alteration in carbonaceous chondrites and implications for sublimation in rock comets

Rock comets are small solar system bodies in Sun-skirting orbits (perihelion q < ~0.15 AU) that form comae rich in mineral sublimation products, but lack typical cometary ice sublimation products (H2O, CO2, etc.). B-class asteroid (3200) Phaethon, considered to be the parent body of the Geminid meteor shower, is the only rock comet currently known to periodically eject dust and form a coma. Thermal fracturing or thermal decomposition of surface materials may be driving Phaethon's cometary activity (Li & Jewitt, 2013). Phaethon-like asteroids have dynamically unstable orbits, and their perihelia can change rapidly over their ~10 Myr lifetimes (de León et al., 2010), raising the possibility that other asteroids may have been rock comets in the past. Here, we propose using spectroscopic observations of mercury (Hg) as a tracer of an asteroid's thermal metamorphic history, and therefore as a constraint on its minimum achieved perihelion distance.
B-class asteroids such as Phaethon have an initial composition similar to aqueously altered primitive meteorites such as CI- or CM-type meteorites (Clark et al., 2010). Laboratory heating experiments of ~mm sized samples of carbonaceous chondrite meteorites from 300K to 1200K at a rate of 15K/minute show mobilization and volatilization of various labile elements at temperatures that could be reached by Mercury-crossing asteroids. Samples became rapidly depleted in labile elements and, in particular, lost ~75% of their Hg content when heated from ~500-700 K, which corresponds to heliocentric distances of ~0.15-0.3 au, consistent with our thermal models. Mercury has strong emission lines in the UV (~ 185 nm) and thus its presence (or absence) relative to carbonaceous chondrite abundances would indicate if these bodies had perihelia in their dynamical histories inside of 0.15 AU, and therefore may have previously been Phaethon-like rock comets. Future space telescopes or balloon-borne observing platforms equipped with a UV spectrometer could potentially detect the presence or absence of strong ultraviolet mercury lines on rock comets or rock comet candidates.

**Author(s): Alessondra Springmann[2]**, Dante S Lauretta[2], Jordan K Steckloff[1]
**Institution(s):** *1. Purdue University, 2. University of Arizona*

## 415 – Comets: Physical Characteristics, Dynamics, and Composition

### 415.01 – Sizing Up the Comets: The NEOWISE Mission Survey of Cometary Nucleii

The NEOWISE mission has provided the largest cometary survey in the infrared. The NEOWISE mission was originally an augmentation to detect solar system objects, and specifically Near Earth Objects, using the Wide-Field Infrared Survey Explorer (WISE) spacecraft. Funded by NASA's Planetary Division through the Near-Earth Object Observation program, NEOWISE detected moving objects throughout the WISE mission[1-2], after which the spacecraft was placed in a state of hybernation. After 32 months, the re-christened NEOWISE spacecraft was returned to a zenith-pointing orbit. On December 23, 2013, the reactivated survey began[3].
While NEOWISE's primary purpose was the detection of NEOs, a total of 163 comets have been identified in the prime survey (January 7, 2010 - Febrauy 1, 2011), and over 75 have been observed during the NEOWISE reactivate mission to date. These observations have been made at multiple epochs, often when the comets were at large heliocentric distances or exhibited little or no activity. Preliminary analysis of the 25 NEOWISE-discovered comets has indicated possible differences between the size distributions of long-period comets (LPCs) and short-period comets (SPCs) in their raw (not de-biased) samples[4]. On average the observed LPCs were larger than the SPCs. We will discuss the results of the analysis of the larger sample of more than 65 nucleii extracted from the prime mission data, as well as the reactivated mission sample.
This publication makes use of data products from the Wide-field Infrared Survey Explorer, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, funded by the National Aeronautics and Space Administration, as well as data products from NEOWISE, which is a project of JPL/Caltech, funded by the Planetary Science Division of NASA. RS, SS, and EK were supported by the NASA Postdoctoral Program.
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**Author(s): James M. Bauer5**, Tommy Grav[8], A. K. Mainzer5, Emily Kramer5, Rachel A. Stevenson5, Yanga R. Fernández9, Joseph R. Masiero5, Carolyn R. Nugent3, Roc M. Cutri3, Sarah Sonnett5, Frank J. Masci3, Karen J. Meech4, Russel Walker7, Carey M. Lisse[1], Paul R. Weissman[8], John W. Dailey3, Nathan Blair3, Andrew Lucas3, Robert S. McMillan[6], Edward L. Wright[2]
**Institution(s):** *1. Applied Physics Laboratory, Johns Hopkins University, 2. Department of Astronomy, University of California, 3. Infrared Analysis and Processing Center (IPAC), California Institute of Technology, 4. Institute for Astronomy, University of Hawaii, 5. Jet Propulsion Lab., 6. Lunar and Planetary Laboratory, University of Arizona, 7. Monterey Institute for Research in Astronomy, 8. Planetary Science Institute, 9. University of Central Florida*

### 415.02 – Investigating the Effects of Temperature on the Signatures of Shocks Propagated Through Impacts into Minerals Found in Comets and Asteroids

Comets and asteroids are subjected to extremely cold conditions throughout their lifetimes. During their sojourns in the solar system, they are subjected to collisions at speeds that are easily capable of generating shock waves in their constituent materials. In addition to ices, more common silicate minerals such as olivines and pyroxenes are important components of these objects. The collision-induced shocks could affect the spectral signatures of those mineral components, which could in turn be detected telescopically. We have embarked on a project to determine how impact-generated shock might affect the reflectance spectra and structures of select silicates as both impact speed and target temperature are varied systematically.
While the effects of impact speed (in the form of shock stress) on numerous materials have been and continue to be studied, the role of target temperature has received comparatively little attention, presumably because of the operational difficulties it can introduce to experimentation. Our experiments were performed with the vertical gun in the Experimental Impact Laboratory of the Johnson Space Center. A liquid-nitrogen system was plumbed to permit cooling of the target container and its contents under vacuum to temperatures as low as -100°C (173 K). Temperatures were monitored by thermocouples mounted on the outside of the target

container. Because those sensors were not in contact with the target material at impact, the measured temperatures are treated as lower limits for the actual values. Peridot (Mg-rich olivine) and enstatite (Mg-rich orthopyroxene) were used as targets, which involved the impact of alumina ($Al_2O_3$) spheres at speeds of 2.0 – 2.7 km $s^{-1}$ and temperatures covering 25°C to -100°C (298 K to 173 K). We have begun collecting and analyzing data in the near to mid-IR with a Fourier-transform infrared spectrometer, and preliminary analyses show that notable differences in absorption-band strength and position occur as functions of both impact speed (peak shock stress) and initial temperature.
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**Author(s): Susan M. Lederer3**, Elizabeth A. Jensen4, Michael Fane1, Douglas C Smith1, Jacob Holmes1, Lindsay P. Keller3, Sean S. Lindsay5, Diane H. Wooden2, Mark J. Cintala3, Michael E. Zolensky3
**Institution(s):** *1. Cal State Univ SB, 2. NASA Ames Research Center, 3. NASA Johnson Space Center, 4. Planetary Science Institute, 5. Univ of Oxford*

### 415.03 – High precision comet trajectory estimates: the Mars flyby of C/2013 A1 (Siding Spring)

The Mars flyby of C/2013 A1 (Siding Spring) represented a unique opportunity for imaging a long-period comet and resolving its nucleus and rotation period. Because of the small encounter distance and the high relative velocity, the goal of successfully observing C/2013 A1 from the Mars orbiting spacecrafts posed strict requirements on the accuracy of the comet ephemeris estimate. These requirements were hard to meet, as comets are known for being highly unpredictable: astrometric observations can be significantly biased and nongravitational perturbations significantly affect the trajectory. Therefore, we remeasured a couple of hundred astrometric positions from images provided by ground-based observers and also observed the comet with the Mars Reconnaissance Orbiter's HiRISE camera on 2014 October 7. In particular, the HiRISE observations were decisive in securing the trajectory and revealed that nongravitational perturbations were larger than anticipated. The comet was successfully observed and the analysis of the science data is still ongoing. By adding some post-encounter data and using the Rotating Jet Model for nongravitational accelerations we constrain the rotation pole of C/2013 A1.

**Author(s): Davide Farnocchia4**, Steven R Chesley4, Marco Micheli2, Alan Delamere1, Rodney S Heyd5, David J Tholen3, Jon D Giorgini4, William M Owen4, Leslie K Tamppari4
**Institution(s):** *1. Delamere Support Services, 2. ESA NEO Coordination Center, 3. Institute for Astronomy, University of Hawaii, 4. Jet Propulsion Laboratory, California Institute of Technology, 5. Planetary Image Research Laboratory, Lunar and Planetary Laboratory, University of Arizona*

### 415.04 – The Resolved Nucleus and Coma of Comet Siding Spring from MRO Observations

Comet Siding Spring (C/2013 A1) is a dynamically new comet discovered on January 4, 2013. On October 19, 2014, just 6 days pefore perihelion, Siding Spring made an historic close approach (C/A) to Mars, closing to a distance of only 140,500 km. We used the HiRISE camera on the Mars Reconaissance Orbiter to observe the comet from October 17-20 (C/A-60 hr to C/A+15 hrs) obtaining 122 images, primarily in broadband filters centered near 500 (BG) and 700 (RED) nm, with another filter near 900 (IR) nm added near close approach. The HiRISE pixel scale in these observations is as small as 138 m/pix, essentially making this event a fortuitous natural flyby of a dynamically new comet.
Enhancement of the closest approach images using both an unsharp mask and a coma fitting and subtraction routine, reveals a sharply-defined crescent that changes its appearance as the viewing geometry varies during the comet's passage. The crescent is likely the illuminated limb of the nucleus, making this the first occasion on which the nucleus of a dynamically new comet has been resolved. Preliminary analyses indicate that the nucleus is elongated (prolate ellipsoid) with a length on the order of a kilometer.
Photometric measurements of the coma in a constant 48-km radius aperture show brightness variations in the RED filter sequence, with a periodicity of 8.1 hr. Because this is a measure of dust production, the single-peaked lightcurve represents the rotation period of the nucleus. During the observations, one primary fan feature is seen in the coma. The lightcurve variations, with amplitude of ~40% (60-140%) of the average brightness in the 48 km aperture, correlate to the feature visibility, indicating that the jet that produces it is the primary source of activity. The shape and direction of the fan suggests that the source is near a pole, producing a cone of dust around the spin axis. We anticipate that the long time baseline and wide range of viewpoints covered in the MRO images will be useful in computing an independent pole orientation.

**Author(s): Tony L. Farnham4**, W. Alan Delamere1, Michael S.P. Kelley4, Rodney Heyd2, Jian-Yang Li3
**Institution(s):** *1. Delamere Support Services, 2. Lunar and Planetary Laboratory, 3. Planetary Science Institute, 4. Univ. of Maryland*

### 415.05 – Comparing CN Features in Two Comets: 1P/Halley and 103P/Hartley 2

Comets 1P/Halley and 103P/Hartley 2 show distinct CN features in their respecive comae. Both comets are non-principal-axis rotators. 1P/Halley is the proto-type for Halley-type comets with the Oort Cloud as its possible source region, whereas 103P/Hartley 2 is a Jupiter-Family comet that possibly originated from the Kuiper Belt. Both comets were spacecraft targets and studied widely from both space and from the ground.
We will discuss the properties of CN features, and in particular the behavior of the derived outflow velocities based on the CN features present in the groundbased coma images of these two comets. The corresponding heliocentric distances for CN images of comet 1P/Halley range from approximately 0.8 AU to 2.0 AU (during its post-perihelion leg of the 1986 apparition). For CN images of comet 103P/Hartley 2, the corresponding heliocentric distances range from 1.31 AU through the perihelion (at 1.06 AU) to 1.25 AU (during its 2010 apparition).
Ultimately, these results will be used to understand the rotational states and the activity behaviors of these two comets.

**Author(s): Nalin H. Samarasinha2**, Cassandra Lejoly2, Jose Barrera2, Beatrice Mueller2, David Schleicher1
**Institution(s):** *1. Lowell Observatory, 2. Planetary Science Institute*

### 415.06 – Rotational Spin-up Caused $CO_2$ Outgassing on Comet 103P/Hartley 2

The Deep Impact spacecraft's flyby of comet 103P/Hartley 2 on November 4, 2010 revealed its nucleus to be a small, bilobate, and highly active world [1] [2]. The bulk of this activity is driven by $CO_2$ sublimation, which is enigmatically restricted to the tip of the small lobe [1]. Because Hartley 2's $CO_2$ production responds to the diurnal cycle of the nucleus [1], $CO_2$ ice must be no deeper than a few centimeters below the surface of the small lobe. However the high volatility of $CO_2$ would suggest that its sublimation front should recede deep below the surface, such that diurnal volatile production is dominated by more refractory species such as water ice, as was observed at comet Tempel 1 [3].
Here we show that both the near surface $CO_2$ ice and its geographic restriction to the tip of the small lobe suggest that Hartley 2 recently experienced an episode of fast rotation. We use the GRAVMAP code to compute the stability of slopes on the surface of Hartley 2 as a function of spin period. We determine that the surface of the active region of Hartley 2's small lobe becomes unstable at a rotation period of ~10-12 hours (as opposed to its current spin period of ~ 18 hours [1]), and will flow toward the tip of the lobe, excavating buried $CO_2$ ice and activating $CO_2$-driven activity. However, the rest of the surface of the nucleus is stable at these spin rates, and will therefore not exhibit $CO_2$ activity. We

additionally use Finite Element Model (FEM) analysis to demonstrate that the interior of Hartley 2's nucleus is structurally stable (assuming a cohesive strength of at least 5 Pa) at these spin rates.
The uncommonly high angular acceleration of Hartley 2, which has changed the nucleus spin period by two hours in three months [4], suggests that this episode of fast rotation may have existed only a few years or decades ago. Thus, Hartley 2 may provide an excellent case study into the reactivation of quiescent comet nuclei via rotational spin up, as would result from weak homogeneous gas emissions via the SYORP Effect.
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**Author(s): Jordan Steckloff2**, Kevin Graves2, Masatoshi Hirabayashi3, James Richardson1
**Institution(s):** *1. Arecibo Observatory, 2. Purdue University, 3. University of Colorado*

### 415.07 – The Distribution of Geometric Albedos of Jupiter-Family Comets From SEPPCoN and Visible-Wavelength Photometry

We present a preliminary estimate of the distribution of geometric albedos among the Jupiter-family comet (JFC) population. While an assumption of 4% is common and consistent with the heretofore limited number of known cometary albedos, the true average albedo and albedo spread have not been well constrained. By knowing a statistically-significant number of albedos, and thus the distribution of albedo values across the comet population, we can investigate overarching science questions about the evolution of cometary surfaces. Our current work makes use of and builds on the results of the Survey of Ensemble Physical Properties of Cometary Nuclei (SEPPCoN), in which we obtained new and independent estimates of the radii of 89 JFCs [1,2]. By using the thus-known radius and photometry of a bare nucleus, we can constrain its geometric albedo. We will present our preliminary albedo estimates for ~50 JFC nuclei, and we will discuss the implications of the ensemble of the results. These JFCs were all observed in R-band, and were all observed at relatively large heliocentric distances (usually >4 AU from the Sun) where the comets appeared inactive, thus minimizing coma contamination.
We acknowledge the support of NASA grant NNX09AB44G, of NSF grant AST-0808004, and of the Astrophysical Research Consortium/Apache Point Observatory for this work. References: [1] Y. R. Fernandez et al., 2013, Icarus 226, 1138. [2] M. S. Kelley et al., 2013, Icarus 225, 475.

**Author(s): Yanga R. Fernandez7**, Harold Weaver2, Carey Lisse2, Karen Meech5, Stephen Lowry6, James Bauer1, Alan Fitzsimmons4, Colin Snodgrass3
**Institution(s):** *1. Caltech/JPL, 2. JHU APL, 3. Open Univ., 4. Queen's Univ. Belfast, 5. UH-IfA, 6. Univ. Kent, 7. Univ. of Central Florida*

### 415.08 – The physical properties of water ice in comets: a comparative study

Detections of water ice in comets are notably scarce (~10 comets) and our knowledge of cometary ice remains poor. As such, we are not able to consider water-ice characteristics in the evaluation of comet nuclei formation scenarios, despite water ice being the major component of comets. To overcome this deficiency, we have begun a systematic, low-resolution near-infrared spectroscopic survey to look for and characterize water-ice grain halos in cometary comae. The ultimate goal is to survey a large sample of Jupiter-family and Oort cloud comets to understand the conditions that favor the detectability of a comet's water-ice grain halo and the factors, if any, that may control the observed water-ice properties. We report on the modeling approach to determine the relative abundances of the major components within the coma, their grain sizes, and the type of mixing (mixed within the coma, or mixed within each aggregate). We present results on a selected set of comets that were observed prior and during our survey.

**Author(s): Silvia Protopapa3**, Michael S.P. Kelley3, Bin Yang1, Jacqueline Keane2, Jessica Sunshine3, Michael F. A'Hearn3, Ludmilla Kolokolova3
**Institution(s):** *1. European Southern Observatory, 2. University of Hawaii, 3. University of Maryland*

### 415.09 – Volatile Composition of Comet C/2012 K1 (PanSTARRS)

On 2014 May 22 and 24 we characterized the volatile composition of the dynamically new Oort Cloud comet C/2012 K1 (PanSTARRS) using the long-slit, high resolution ($\lambda/\Delta\lambda \approx 25{,}000$) infared echelle spectrograph (NIRSPEC) at the 10m Keck 2 telescope on Maunakea, HI. We detected fluorescent emission from six primary species ($H_2O$, HCN, $CH_4$, $C_2H_6$, $CH_3OH$, and CO) and prompt emission from one product species (OH* - a directory proxy for $H_2O$). Upper limits were derived for $C_2H_2$ and $H_2CO$. We report rotational temperatures, production rates, and mixing ratios (relative to water). Based on the inventory of comets characterized to date, mixing ratios of trace gases in C/2012 K1 (PanSTARRS) are about normal – $CH_3OH$ and $C_2H_6$ are slightly enriched, CO, $CH_4$, HCN, and $H_2CO$ are average, and $C_2H_2$ is depleted. I will discuss C/2012 K1 (PanSTARRS) in the context of an emerging taxonomy for comets based on volatile composition.
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**Author(s): Nathan Roth3**, Erika Gibb3, Boncho P Bonev1, Michael A DiSanti2, Geronimo L Villanueva1, Lucas Paganini1, Michael J Mumma2
**Institution(s):** *1. Catholic University of America, 2. NASA Goddard Space Flight Center, 3. University of Missouri - St. Louis*

### 415.10 – The Volatile Composition of Comet C/2013 V5 (Oukaimeden) from Infrared Spectroscopy

We obtained high-quality pre-perihelion spectra of long-period comet C/2013 V5 (Oukaimeden) on 2014 September 5 and 6 ($R_h$ = 0.78 AU) with NIRSPEC at Keck 2, and on September 13 ($R_h$ = 0.50 AU) with CSHELL at the NASA-IRTF. Our observations targeted nine primary volatiles (i.e., native ices): H2O, CO, H2CO, CH3OH, HCN, NH3, C2H2, CH4, C2H6. Comparison of abundance ratios for trace volatiles relative to H2O with those measured for other comets reveals an overall depleted chemistry in Oukaimeden.
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**Author(s): Michael A. DiSanti2**, Boncho P. Bonev1, Erika L. Gibb3, Nathan X Roth3, Geronimo L. Villanueva1, Lucas Paganini1, Michael J. Mumma2
**Institution(s):** *1. CUA, 2. NASA's GSFC, 3. University of Missouri-St. Louis*

### 415.11 – The favorable apparition of comet C/2014 Q2 (Lovejoy), and unique insights from ground-based IR observations

In February 2015, we observed comet C/2014 Q2 (Lovejoy) on two consecutive nights, using NIRSPEC at the Keck Observatory, in Hawaii. Comet Q2 underwent strong activity and a favorable apparition, which triggered astronomical observing campaigns worldwide and yielded unique scientific results over a range of wavelength regimes. From the infrared (IR) observations we retrieve production rates, temperatures, cosmogonic parameters and abundances of native species (i.e. volatiles released directly from the nucleus) that are of unique importance in the interpretation of global properties and highly complementary to measurements performed at other wavelengths, both of native and product species in the coma. Our measurements show detection of several molecules we typically detect in the IR, and strong, unidentified lines. We also performed a deep search for HDO emission lines, yielding constraints of the D/H ratio. We will discuss our preliminary results in the context of complementary studies of C/2014 Q2 and compare the measured abundances with those in other comets.

**Author(s): Lucas Paganini[2]**, Michael J. Mumma[2], Erika L. Gibb[3], Michael A. DiSanti[2], Stefanie N. Milam[2], Boncho P. Bonev[2], Martin A. Cordiner[2], Steven Charnley[2], Sara Faggi[1], Geronimo L. Villanueva[2]
**Institution(s):** *1. INAF - Osservatorio Astrofisico di Arcetri, 2. NASA Goddard Space Flight Center, 3. University of Missouri, St. Louis*

### 415.12 – Outgassing and chemical evolution of C/2012 S1 (ISON)

Volatile production rates, relative abundances, rotational temperatures, and spatial distributions in the coma were measured in C/2012 S1 (ISON) using long-slit high-dispersion ($\lambda/\Delta\lambda \sim$ 25,000) infrared spectroscopy as part of a worldwide observing campaign. Spectra were obtained on UT 2013 October 26 and 28 with NIRSPEC at the W. M. Keck Observatory, and UT 2013 November 19 and 20 with CSHELL at the NASA IRTF. $H_2O$ was detected on all dates, with production rates increasing by about a factor of 40 between October 26 ($R_h$ = 1.12 AU) and November 20 ($R_h$ = 0.43 AU). Short-term variability of $H_2O$ was also seen as the production rate increased by nearly a factor of two during observations obtained over a period of about six hours on November 19. $C_2H_6$, $CH_3OH$ and $CH_4$ abundances were slightly depleted relative to $H_2O$ in ISON compared to mean values for comets measured at infrared wavelengths. On the November dates, $C_2H_2$, HCN and OCS abundances relative to $H_2O$ appear to be close to the range of mean values, whereas $H_2CO$ and $NH_3$ were significantly enhanced. We will compare derived chemical abundances in ISON to other comets measured with infrared spectroscopy.

**Author(s): Neil Dello Russo[1]**, Ronald J Vervack[1], Hideyo Kawakita[2], Anita Cochran[5], Adam J McKay[5], Walter M Harris[4], Harold A Weaver[1], Carey M Lisse[1], Michael A DiSanti[6], Hitomi Kobayashi[2], Nicolas Biver[3], Dominique Bockelée-Morvan[3], Jacques Crovisier[3], Cyrielle Opitom[7], Emmanuel Jehin[7]
**Institution(s):** *1. JHU-APL, 2. Koyama Astronomical Observatory, Kyoto Sangyo University, 3. LESIA, Observatoire de Paris, 4. Lunar and Planetary Laboratory, University of Arizona, 5. McDonald Observatory, 6. NASA-GSFC, 7. Université de Liège*

### 415.13 – Coma in Comet C/2012 S1 (ISON) at ~4 au

We analyze HST observations of Comet ISON (C/2012 S1) at heliocentric distance ~4 au and phase angle ~12–14 degree. The inner coma (< 5000 km) reveals two polarimetric features, positive degree of linear polarization $P = (2.48 \pm 0.45)\%$ at projected distances less than 236 km and negative polarization $P = -(1.6 \pm 0.45)\%$ at 1000 – 5000 km [Hines et al. 2014: ApJL 780, L32]. At these projected distances, average color slope was found to be ~6% per 100 nm [Li et al. 2013: ApJL 779, L3]. When considered simultaneously, these two features place significant constraint on the physical and chemical properties of dust particles [Zubko et al. 2015: *Planet. Space Sci.,* http://dx.doi.org/10.1016 /j.pss.2015.08.002].
We model this response with *agglomerated debris particles*, having highly irregular morphology and density of constituent material being consistent with *in situ* studies of comets. We consider particles of 28 different refractive indices that correspond to *in situ* studies of comets and plausible assumptions on chemical composition of cometary dust and ices. What emerges from our analysis is that the ISON coma was chemically heterogeneous at the epoch of observation. The positive polarization at small projected distances suggests a high spatial concentration of highly absorbing materials, such as amorphous carbon and/or organics highly irradiated with UV radiation. At larger distances, the negative polarization $P = -(1.6 \pm 0.45)\%$ and color slope ~6% per 100 nm appear consistent with organics slightly processed with UV radiation, tholins, Mg-Fe silicates, and Mg-rich silicates contaminated with ~10% (by volume) amorphous carbon. A significant abundance of pure water-ice particles and/or pure Mg-rich silicates must be ruled out in this region. These materials have been found *in situ* in other comets and also detected with imaging polarimetry in the circumnucleus halo regions. Analyses of polarimetric images suggest that Mg-rich silicates could originate from a refractory surface layer on the surface of cometary nuclei [Zubko et al. 2012: A&A 544, L8]. A depletion of such particles in Comet ISON could imply an absence of such a layer on its nucleus.

**Author(s): Gorden Videen[5]**, Evgenij Zubko[8], Dean C. Hines[6], Yuriy Shkuratov[8], Vadym Kaydash[8], Karri Muinonen[7], Matthew W. Knight[1], Michael L. Sitko[5], Carrey M. Lisse[1], Max Mutchler[6], Diane H. Wooden[3], Jian-Yang Li[4], Hiroshi Kobayashi[2]
**Institution(s):** *1. Johns Hopkins University APL, 2. Nagoya University, 3. NASA Ames Research Center, 4. Planetary Science Institute, 5. Space Science Institute, 6. Space Telescope Science Institute, 7. University of Helsinki, 8. V.N. Karazin Kharkov National University*

### 415.14 – Radio OH spectroscopic mapping survey of 26 comets: Trends in outflow velocity and collisional quenching

Between 2000-2015, we obtained 18cm OH spectra of 26 comets, using the Arecibo Observatory 305m Gordon Telescope and the National Radio Astronomy Observatory 100m R. W. Byrd Green Bank Telescope (GBT). Spectra of both long-period and periodic comets were obtained at 1667 and 1665 MHz (18cm wavelength) with a beam resolution of 2.9 arcminutes at Arecibo and 7.4 arcminutes at GBT. Heliocentric distances for comets in the sample range between 0.4 to 2.8 AU, with gas production rates from 0.1--30 x $10^{28}$ mol/s. A wide range of gas velocities are observed, from 0.5 to nearly 2 km/s, with the highest variability in outflow velocities for comets at heliocentric distances less than 1 AU. Mapping observations provide a direct constraint on the radius within which there is collisional quenching, an important factor in estimating total water production rates, and a useful constraint on coma density. We find that collisional quenching varies considerably, and generally exceeds what might be expected theoretically, so it is best when observations make a direct constraint on this value. We will present aggregate velocity, gas production, and quenching results from this comet survey, derived from a kinetic model utilizing Monte Carlo simulations.

**Author(s): Amy J. Lovell[1]**, Ellen S Howell[2]
**Institution(s):** *1. Agnes Scott College, 2. LPL/U. Arizona*

### 415.15 – High-resolution spectroscopy of the CN red system in comet C/2013 R1 (Lovejoy) using WINERED at Koyama Astronomical Observatory

CN radical has the strong electronic transition moments in optical wavelength region and CN has extensively observed in comets. Especially, the CN violet system ($B^2\Sigma^+$—$X^2\Sigma^+$) has been observed by using high-resolution spectroscopic technique in order to infer the isotopic ratios of carbon and nitrogen in comets via $^{12}C^{14}N$, $^{13}C^{14}N$ and $^{12}C^{15}N$. However, the wavelength range for this system (~388 nm) is severely extinct if a comet is close to the Sun (we have to observe the comet at low elevations from the ground-based observatories). On the other hand, CN radical also has the strong electronic transition in near-infrared (~1.1 microns), the CN red system ($A^2\Pi_i$—$X^2\Sigma^+$). Although there are few reports on the high-resolution spectra of this band in comets, this wavelength region is not severely affected by the telluric extinction and considered as the new window for the observations of the carbon and nitrogen isotopic ratios in comets.
High resolution near-infrared spectra of comet C/2013 R1 (Lovejoy) using the WINERED (R~3x104) spectrometer mounted on the 1.3-m Araki telescope at Koyama Astronomical Observatory were acquired on UT 2013 Nov 30. The heliocentric and geocentric distances were 0.91 AU and 0.49 AU, respectively. We detected strong emission lines of the CN red system (0,0) at around 1.1 microns. The rotational line intensities of this band approximately follow the Boltzmann distribution at ~300K for our observations. We present the detailed analysis of the CN red system in comet C/2013 R1 (Lovejoy) and discuss about the isotopic ratios in CN.

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**Author(s): Hideyo Kawakita[2]**, Yoshiharu Shinnaka[3], Sohei Kondo[2], Satoshi Hamano[2], Hiroaki Sameshima[2], Kenshi Nakanishi[1], Takafumi Kawanishi[1], Tetsuya Nakaoka[1], Shogo Otsubo[1], Masaomi Kinoshita[1], Yuji Ikeda[2], Ryo Yamamoto[4], Natsuko Izumi[4], Kei Fukue[4], Chikako Yasui[2], Hiroyuki Mito[2], Yuki Sarugaku[2], Noriyuki Matsunaga[2], Naoto Kobayashi[2]
**Institution(s):** *1. Kyoto Sangyo University, 2. LIH / Koyama Astronomical Observatory, 3. National Astronomical Observatory, 4. University of Tokyo*

### 415.16 – Nitrogen Isotopic Ratios in Cometary $NH_2$: Implication for $^{15}$N-fractionation in Ammonia

Isotopic ratios in cometary molecules are diagnostic for the physico-chemical conditions where molecules formed and are processed, from the interstellar medium to the solar nebula. Usually temperatures at the molecular formation control the fractionation of the heavier element in molecular species, e.g., D-fractionation in water.
In cometary volatiles, the $^{14}N/^{15}N$ ratios in CN have been well observed (Manfroid et al. 2009, A&A, 503, 613, and reference therein) and is consistent with the ratio in HCN (a most probable parent of CN) measured in few comets (Bockelée-Morvan et al. 2008, ApJ, 679, L49). Those ratios are enriched compared to the proto-solar value by a factor of ~3. In contrast to those Nitriles, there are only few reports on $^{14}N/^{15}N$ ratios in Ammonia (as Amine) (Rousselot et al. 2014, ApJ, 780, L17; Shinnaka et al. 2014, ApJ, 782, L16). Ammonia ($NH_3$) is usually the most abundant and HCN is the second most abundant N-bearing volatiles in cometary ice. Especially, recent observations of $^{15}NH_2$ revealed the $^{14}N/^{15}N$ ratios in $NH_3$ are comparable to those of CN. However, from the viewpoint of theoretical work, the enrichment of $^{15}$N in cometary $NH_3$ cannot be reproduced by current chemical network models. Information about the diversity of the $^{14}N/^{15}N$ ratios in $NH_3$ of individual comets is needed to understand the formation mechanisms/environments of $NH_3$ in the early solar system.
To clarify the diversity of the $^{14}N/^{15}N$ ratios in cometary $NH_3$, we determine the $^{14}N/^{15}N$ ratios in $NH_3$ for more than ten comets individually which include not only Oort cloud comets but also short period comets by using the high-resolution optical spectra of $NH_2$. These spectra were obtained with both the UVES mounted on the VLT in Chile and the HDS on the Subaru Telescope in Hawaii.
The derived $^{14}N/^{15}N$ ratios in $NH_3$ for more than ten comets show high $^{15}$N-enrichment compared with the elemental abundances of nitrogen in the Sun by about factor of ~3 and has no large diversity depending on these dynamical properties. We discuss about the origin of the formation conditions of cometary $NH_3$ and its physico-chemical evolution in the solar nebula based on our and other results.
This work was supported by JSPS, 15J10864 (Y. Shinnaka).

**Author(s): Yoshiharu Shinnaka3**, Hideyo Kawakita[1], Emmanuël Jehin[4], Alice Decock[2], Damien Hutsemékers[4], Jean Manfroid[4], Akira Arai[1]
**Institution(s):** *1. Koyama Astronomical Observatory of Kyoto Sangyo University, 2. LESIA, Observatoire de Paris, 3. National Astronomical Observatory of Japan, 4. Université de Liège*

### 415.17 – Spectroscopic studies of the molecular parentage of radical species in cometary comae

We have observed several comets using an integral-field unit spectrograph (the George and Cynthia Mitchell Spectrograph) on the 2.7m Harlan J. Smith telescope at McDonald Observatory. Full-coma spectroscopic images were obtained for various radical species (C2, C3, CH, CN, NH2). By constructing azimuthal average profiles from the full-coma spectroscopic images we can test Haser model parameters with our observations. The Haser model was used to determine production rates and possible parent lifetimes that would be consistent with the model. By iterating through a large range of possible parents lifetimes, we can see what range of values in which the Haser model is consistent with observations. Also, this type of analysis gives us perspective on how sensitive the model's fit quality is to changes in parent lifetimes. Here, we present the work completed to date, and we compare our results to other comet taxonomic surveys.

**Author(s): Benjamin Lewis[1]**, Donna Pierce[1], Anita Cochran[2]
**Institution(s):** *1. Mississippi State University, 2. UT-Austin*

### 415.18 – Gone in a Blaze of Glory: the Demise of Comet C/2015 D1 (SOHO)

We present studies of C/2015 D1 (SOHO), the first sunskirting comet ever seen from ground stations over the past half century. The Solar and Heliospheric Observatory (SOHO) witnessed its peculiar light curve with a huge dip followed by a flareup around perihelion: the dip was likely caused by sublimation of olivines, directly evidenced by a coincident temporary disappearance of the tail. The flareup likely reflects a disintegration event, which we suggest was triggered by intense thermal stress established within the nucleus interior. Photometric data reveal an increasingly dusty coma, indicative of volatile depletion. A catastrophic mass loss rate of ~105 kg $s^{-1}$ around perihelion was seen. Ground-based Xingming Observatory spotted the post-perihelion debris cloud. Our morphological simulations of post-perihelion images find newly released dust grains of size a >~ 15 μm in radius, however, a temporal increase in $a_{min}$ was also witnessed, possibly due to swift dispersions of smaller grains swept away by radiation forces without replenishment. Together with the fading profile of the light curve, a power law dust size distribution with index $\gamma = 3.2 \pm 0.1$ is derived. We detected no active remaining cometary nuclei over ~0.1 km in radius in post-perihelion images acquired at Lowell Observatory. Applying radial non-gravitational parameter, $A_1 = (1.209 \pm 0.118) \times 10^{-6}$ AU $day^{-2}$, from an isothermal water-ice sublimation model to the SOHO astrometry significantly reduces residuals and sinusoidal trends in the orbit determination. The nucleus mass ~$10^8$--109 kg, and the radius ~50--150 m (bulk density $\rho_d = 0.4$ g $cm^{-3}$ assumed) before the disintegration are deduced from the photometric data; consistent results were determined from the non-gravitational effects.

**Author(s): Man-To Hui[1]**, Quan-Zhi Ye[2], Matthew Manning Knight[3], Karl Battams[4], David Clark[2]
**Institution(s):** *1. Department of Earth, Planetary and Space Sciences, UCLA, 2. Department of Physics and Astronomy, University of Western Ontario, 3. Lowell Observatory, 4. Naval Research Laboratory*

### 415.19 – The Plasma Environment in Comets Over a Wide Range of Heliocentric Distances: Application to Coment C/2006 P1 (McNaught)

On 2007 January 12, comet C/2006 P1 (McNaught) passed its perihelion at 0.17 AU. Abundant remote observations offer plenty of information on the neutral composition and neutral velocities within 1 million kilometers of the comet nucleus. In early February, the *Ulysses* spacecraft made an in situ measurement of the ion composition, plasma velocity, and magnetic field when passing through the distant ion tail and the ambient solar wind. The measurement by *Ulysses* was made when the comet was at around 0.8 AU. With the constraints provided by remote and in situ observations, we simulated the plasma environment of Comet C/2006 P1 (McNaught) using a multi-species comet MHD model over a wide range of heliocentric distances from 0.17 to 1.75 AU. The solar wind interaction of the comet at various locations is characterized and typical subsolar standoff distances of the bow shock and contact surface are presented and compared to analytic solutions. We find the variation in the bow shock standoff distances at different heliocentric distances is smaller than the contact surface. In addition, we modified the multi-species model for the case when the comet was at 0.7 AU and achieved comparable water group ion abundances, proton densities, plasma velocities, and plasma temperatures to the *Ulysses*/SWICS and SWOOPS observations. We discuss the dominating chemical reactions throughout the comet-solar wind interaction region and demonstrate the link between the ion composition near the comet and in the distant tail as measured by *Ulysses*. The work at the University of Michigan was supported by the NASA Planetary Atmospheres grant NNX14AG84G.

**Author(s): Yinsi Shou3**, Michael Combi3, Yingdong Jia1, Tamas Gombosi3, Gabor Toth3, Martin Rubin2
**Institution(s):** *1. UCLA, 2. University of Bern, 3. University of Michigan*

### 415.20 – Planets Perturbing Planetoids: How Clear Is The Neighborhood?

IAU Resolution B5, adopted in Prague in 2006, states that a celestial body needs to have "cleared the neighbourhood around its orbit" to qualify as a planet. Pluto orbits within the Kuiper Belt, so it does not meet this criterion, but presumably the existence of Earth-crossing asteroids does not disqualify the Earth from planetary status. Stern and Levison (2002), Soter (2006), and Margot (2015) used equivalent criteria for planethood based on a gravitational scattering parameter Λ, which is proportional to the square of the planet's mass and inversely proportional to its orbital period. This parameter assumes the small bodies to be cleared begin with orbits like that of the planet. In reality, small bodies are fed in to the region of the planet at a more-or-less steady rate; for instance, some main-belt asteroids become Near-Earth Asteroids, while Kuiper Belt Objects can become Centaurs. I will present orbital integrations of small bodies from their source regions to quantify their steady-state populations at each planet in our Solar System, and will compare the results with predictions from a refined version of the Λ parameter.
Margot, J.-L. (2015) arXiv:1507.06300
Soter, S. (2006) *Astron. J.* **132**, 2513-2519
Stern, S.A., Levison, H.F. (2002) in *Highlights of Astronomy,* Vol. 12, pp. 205-213.

**Author(s): Henry C. (Luke) Dones1**
**Institution(s):** *1. Southwest Research Inst.*

### 415.21 – Finding long-lost Comet Lexell

Comet D/1770 L1 (Lexell) made the closest observed pass by a comet to the Earth at approximately 0.015 AU on 1 July 1770. A naked-eye object observed by many astronomers of the time, it was subsequently lost: the best contemporary estimates had it removed from its 1770 orbit by Jupiter in 1779 and sent to the outer Solar System.
Near-Earth asteroid 2010 JL33 has an orbit similar to that followed by Lexell's comet during its observed apparition. However, this NEA's nominal orbit, which is well-known on the basis of a decade-long arc which includes radar observations, does not approach the Earth at the correct time to be Lexell's comet. That is, unless modest non-gravitational forces are applied, in which case the famous near-miss can be reproduced.
Modern measurements of 2010 JL33 together with those Lexell's comet made in the 18th century -which include motion exceeding 40 degrees per day on the sky at closest approach- provide exquisite constraints on the dynamical processes at work, cometary, Yarkovsky or other. I will discuss the implications of and the conditions required for asteroid 2010 JL33 to be, in fact, long-lost comet Lexell.

**Author(s): Paul Wiegert1**
**Institution(s):** *1. Univ. of Western Ontario*

### 415.22 – A Continuing Analysis of Possible Activity Drivers for the Enigmatic Comet 29P/Schwassmann-Wachmann 1

We present results from our continuing effort to understand activity drivers in Comet 29P/Schwassmann-Wachmann 1 (SW1). While being in a nearly circular orbit around 6 AU, SW1 is continuously active and experiences frequent outbursts. Our group's effort is focusing on finding constraints on physical and dynamical properties of SW1's nucleus and their incorporation into a thermophysical model [1,2] to explain this behavior. Now we are analyzing coma morphology of SW1 before, during, and after outburst to place constraints on the spin-pole direction, spin period, and surface areas of activity (a spin period lower limit has been measured). Also, we are using the thermal model to investigate if the continuous activity comes from one or multiple processes, such as the release of trapped supervolatiles during the amorphous to crystalline (A-C) water ice phase transition and/or the direct sublimation of pockets of supervolatile ices, which may be primordial or from the condensation of gases released during the A-C phase transition. To explain the possibly quasi-periodic but frequent outbursts, we are looking into subsurface cavities where internal pressures can build, reaching and exceeding surrounding material strengths [3,4] and/or thermal waves reaching a pocket of supervolatile ices, causing a rapid increase in the sublimation rate. For all these phenomena, the model is constrained by comparing the output dust mass loss rate and its variability with what has been observed through optical imaging of the comet at various points in its orbit. We will present preliminary thermal modeling of a homogeneous progenitor nucleus that evolves into a body showing internal material layering, the generation of CO and $CO_2$ ice pockets, and the production of outbursts, thus bringing us closer to explaining the behavior of this intriguing comet.
[1] Sarid, G., et al.: 2005, PASP, **117**, 843. [2] Sarid, G.: 2009, PhD Thesis, Tel Aviv Univ. [3] Gronkowski, P., 2014, Astron. Nachr./AN **2, No. 335, 124-134.** [4] Gronkowski, P. and Wesolowski, M., 2015, MNRAS, **451**, 3068-3077. We thank the NASA Outer Planets Research Program (NNX12AK50G) and the Center for Lunar and Asteroid Surface Science (CLASS, NNA14AB05A) for support of this work.

**Author(s): Charles Alfred Schambeau5**, Yanga Fernandez5, Nalin Samarasinha4, Gal Sarid2, Beatrice Mueller4, Karen Meech3, Laura Woodney1
**Institution(s):** *1. California State University, San Bernardino, 2. Florida Space Institute, 3. Institute for Astronomy, 4. Planetary Science Institute, 5. University of Central Florida*

### 415.23 – Investigating the Spatial Structure of HCN Emission in Comet C/2012 F6 (Lemmon)

Comets are of particular interest in the field of Astrochemistry as they can be used as a direct probe of formation chemistry of the Solar System. Originating in the Oort Cloud reservoir, these long period objects experience relatively limited solar influence. The majority of cometary material (water, methane and ammonia ices) has remained in the same state as when it formed. These ices are precursors to more complex molecules which have been shown to form amino acids that are crucial for the development of life. HCN, or hydrogen cyanide, is of particular interest because it can form the nucleobase adenine ($C_5H_5N_5$). The goals of this project are to map the HCN distribution of Comet C/2012 F6 (Lemmon) and to show the simultaneous observation capabilities of the Atacama Large Millimeter/Submillimeter Array (ALMA), which allows the extraction of 7-m array, 12-m array and single dish observation data. On UT 2013 May 11, Comet Lemmon was observed using ALMA. The Cycle 1 configuration was used with the Band 6 receivers, with a 1.5 GHz range centered on the HCN transition at 265.86 GHz, which gave a spectral resolution of 0.07 km/s. We show that Comet Lemmon has both a compact HCN region (found with the 12-m array) and also an extended component, forming a tail-like structure in the anti-motion direction (found with the 7-m array). We were also able to extract the autocorrelation data (single dish) and show that it is viable. This project was supported and funded by NRAO in conjunction with the National Science Foundation (NSF), with special thanks to the Astronomy Department at University of Virginia.

**Author(s): Shawn Booth2**, Andrew Burkhardt2, Joanna Corby2, Niklaus Dollhopf2, Mark Rawlings1, Anthony Remijan1
**Institution(s):** *1. National Radio Astronomy Observatory, 2. University of Virginia*

### 415.24 – New Analysis of the Deep Impact Comet 9P/Tempel 1 Event Using High Resolution Spectroscopy: Evidence for High Velocity Long-Lived Emission from 630 nm [O( 1 D)] Emission

Thorough analysis of narrow bandpass high spectral resolution (R ≈100,000) observations of [O 1 D] 630nm emission from comet 9P/Tempel 1 taken over a ~1' FOV both before and after the Deep Impact event provides evidence for a long-lived high velocity jet-like feature. The observations were obtained with an all-reflective spatial heterodyne spectrometer (SHS) coupled to the McMath-Pierce Main telescope. Several spectra centered on Tempel 1 were acquired during the period of 07/04/2005-07 /06/2005 UT. We report here on the presence and evolution of a cometary emission feature that appears consistently and exclusively in the post-impact narrow-band spectra centered near the telluric [O 1 D] 630nm emission line. This cometary emission feature shows substantial and distinct Doppler shifts over consecutive post-impact observational nights and if the feature is the anticipated [O 1 D], the corresponding line of sight velocities are -13.4 to -6.5 km/s, relative to the comet's rest frame.

**Author(s): Jason B Corliss[2]**, Walt M Harris[2], Edwin J Mierkiewicz[1], Frederick L Roesler3
**Institution(s):** *1. Embry-Riddle Aeronautical University, 2. University of Arizona - LPL, 3. University of Wisconsin-Madison*

### 415.25 – Detection of known meteoroid streams using Pan-STARRS

Meteors are produced from meteoroids that are Near Earth Objects (NEOs). Created from the disruption of comets and asteroids, their study allows for the physical and chemical properties of parent bodies to be better constrained. Because most meteoroids are too small to be directly observed in space, ground-based camera networks (such as Weryk et al., 2008) are often used to detect fireballs produced from centimetre sized objects, and their mass influx can be extrapolated to larger sizes.
The mass/size distribution of meteoroid streams is an important topic, relating directly to the impact hazard to the Earth (see Brown et al., 2015). Unfortunately, the largest meteoroids interact with the Earth's atmosphere so infrequently that their observation is very biased and not predictable, but due to their large size, they may be visible in space. Barabanov and Smirnov (2005) presented detections of large possibly cometary meteoroids over 5 m in diameter, but their results could not be confirmed by Beech et al. (2004). More recently, Micheli and Tholen (2015) looked for objects in the meteoroid streams of several major showers, but found no stream objects.
The Pan-STARRS1 (PS1) telescope, operated by the University of Hawai`i, has a large seven square degree field-of-view which can reliably detect new NEOs. However, not every NEO candidate is followed up and linked into a well established orbit, possibly due to the fact that the smallest bodies will not be visible at the sensitivity limit of PS1 for very long, or that their predicted orbit is uncertain so follow up telescopes look in the wrong location. In this work, we present our results to date about searching for potential meteoroid streams (with an emphasis on cometary streams) with the PS1 telescope using its multi-year database of unlinked NEO detections. For recent observations, where possible, we have observed the true non-geocentric radiants directly during peak shower activity. The detection of known meteoroid streams will allow for additional follow up studies with other telescopes.

**Author(s): Robert J. Weryk[1]**, Richard J. Wainscoat[1]
**Institution(s):** *1. Univ. of Hawaii*

## 416 – Characterization of Extrasolar Planets

### 416.01 – The effects of $H_2$-He pressure broadening parameters on the retrieval of brown dwarf atmospheres

Brown dwarf atmospheres are compositionally very similar to the gas giant planets, made up of approximately 85% $H_2$ and 15% He, as well as other trace gases such as $CH_4$ and $H_2O$, depending on the spectral type. We have investigated the effects of using pressure broadening parameters related to $H_2$-He broadening and compared them to using air-broadening parameters for each of the major trace gases involved in brown dwarf atmospheres. We have identified from limited data sets that $H_2$-He broadening, relative to air broadening, can act to increase or decrease the Lorentzian broadening experienced by a given transition. This change in Lorentzian broadening is dependent on the gas considered and the transition's associated quantum numbers (such as rotational and vibrational quantum numbers). By altering the transition's lineshape, we also alter its opacity. Some gases are affected significantly at all pressure levels ($NH_3$, $CO_2$, $CH_4$), some at deep (~1bar) pressure levels (CO, $H_2O$), and others not at all (TiO, VO). We conclude, however, that these limited data sets do not provide the complex and comprehensive dependence of pressure broadening on the relevant quantum numbers that is available to air broadening, and we cannot say for certain how much this limits our results until more data is available. Our conclusions demonstrate the need for further study of $H_2$ and He broadening parameters for the relevant gases from both experimental and computational means. We present preliminary results of the knock-on effects that these broadening parameters have for the retrieval of atmospheric composition and thermal structure.

**Author(s): Ryan Garland[1]**, Patrick G. J. Irwin[1], Suzanne Aigrain[1], Joanna K Barstow[1]
**Institution(s):** *1. University of Oxford*

### 416.02 – Spitzer Secondary Eclipse Observations of Hot-Jupiters WASP-26b and CoRoT-1b

WASP-26b is a hot-Jupiter planet that orbits an early G star every 2.7566 days at a distance of 0.03985 AU. Using the Spitzer Space Telescope in 2010 as a part of the Spitzer Exoplanet Target of Opportunity program (program 60003) we observed two secondary eclipses of the planet, one in the 3.6 µm channel on 7 September and one in the 4.5 µm channel on 3 August. We also reanalize archival Spitzer data of CoRoT-1b, which is another hot Jupiter orbiting a G star every 1.5089686 days at a distance of 0.0254 AU, in the 3.6 and 4.5 µm channels. The eclipse depths for WASP-26b are 0.00117 ± 0.00012 and 0.001507 ± 0.00016, for the 3.6 and 4.5 µm channels respectively. The eclipse depths for CoRoT-1b are 0.0047 ± 0.0003 and 0.0046 ± 0.0004 respecitvely. We also refine their orbits using our own secondary eclipse measurements in combination with external radial-velocity and transit observations from both professional and amateur observers. Using our Bayesian Atmostpheric Radiative Transfer code, we characterize the atmospheres of these planets. Spitzer is operated by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA. This work was supported by NASA Planetary Atmospheres grant NNX12AI69G and NASA Astrophysics Data Analysis Program grant NNX13AF38G. Blecic holds a NASA Earth and Space Science Fellowship.

**Author(s): Emerson DeLarme[1]**, Joseph Harrington[1], Patricio Cubillos[1], Jasmina Blecic[1], Andrew SD Foster[1], Justin Garland[1], AJ Foster[1], Andrew Collier Cameron[2]
**Institution(s):** *1. University of Central Florida , 2. University of St Andrews*

### 416.04 – Observation and Analysis of Secondary Eclipses of WASP-32b

We report two *Spitzer* secondary eclipses of the exoplanet WASP-32b. Discovered in 2010 by Maxted et al, this hot-Jupiter planet has a mass of 3.6 ± 0.07 $M_j$, a radius of 1.18 ± 0.07 $R_j$, an equilibrium temperature of 1560 ± 50 K, and an orbital period of 2.71865 ± 0.00008 days around a G-type star. We observed two secondary eclipses in the 3.6 µm and 4.5 µm channels using the *Spitzer Space Telescope* in 2010 as a part of the *Spitzer* Exoplanet Target of Opportunity program (program 60003). We present eclipse depth estimates of 0.0013 ± 0.00023 in the 4.5 µm band and inconclusive results in the 3.6 µm band. We also report an infrared brightness temperature of 1538 ± 110 in the 4.5 µm channel and refinements of orbital parameters for WASP-32b from our eclipse measurement as well as amatuer and professional data that closely match previous results. *Spitzer* is operated by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA. This work was supported by NASA Planetary Atmospheres grant NNX12AI69G and NASA Astrophysics Data

Analysis Program grant NNX13AF38G. JB holds a NASA Earth and Space Science Fellowship.

**Author(s): Justin Garland[1]**, Joseph Harrington[1], Patricio E. Cubillos[1], Jasmina Blecic[1], Andrew S. Foster[1], Oliver Bowman[1], Pierre F. L. Maxted[2]
**Institution(s):** *1. University of Central Florida, 2. University of Keele*

### 416.05 – Secondary eclipse observations and the atmosphere of exoplanet WASP-34b

WASP-34b is a short-period exoplanet with a mass of 0.59 ± 0.01 Jupiter masses orbiting a G5 star with a period of 4.3177 days and an eccentricity of 0.038 ± 0.012 (Smalley, 2010). We observed WASP-34b using the 3.6 and 4.5 µm channels of the Infrared Array Camera aboard the Spitzer Space Telescope in 2010 (Program 60003). We applied our Photometry for Orbits, Eclipses, and Transits (POET) code to present eclipse-depth measurements, estimates of infrared brightness temperatures, and a refined orbit. With our Bayesian Atmospheric Radiative Transfer (BART) code, we characterized the atmosphere's temperature and pressure profile, and molecular abundances. Spitzer is operated by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA. This work was supported by NASA Planetary Atmospheres grant NNX12AI69G and NASA Astrophysics Data Analysis Program grant NNX13AF38G. J. Blecic holds a NASA Earth and Space Science Fellowship.

**Author(s): Ryan C. Challener[2]**, Joseph Harrington[2], Patricio Cubillos[2], Justin Garland[2], Andrew S. D. Foster[2], Jasmina Blecic[2], AJ Foster[2], Barry Smalley[1]
**Institution(s):** *1. Keele University, 2. University of Central Florida*

### 416.06 – Atmospheric, Orbital and Eclipse Depth Analysis of the Hot Jupiter HAT-P-30-WASP-51b

HAT-P-30-WASP-51b is a hot-Jupiter planet that orbits an F star every 2.8106 days at a distance of 0.0419 AU. Using the Spitzer Space Telescope in 2012 (Spitzer Program Number 70084) we observed two secondary eclipses of the planet, one in the 3.6 µm channel on 3 January and one in the 4.5 µm channel on 17 January. We present eclipse-depth measurements of 0.00163 ± 0.0001 and 0.00146 ± 0.00013 and we esitmate the infrared brightness temperatures to be 1900 ± 50 and 1600 ± 60 for these two channels, respectively, from an analysis using our Photometry for Orbits, Eclipses, and Transits (POET) pipeline. We also refine its orbit using our own secondary-eclipse measurements in combination with radial-velocity and transit observations from both professional and amateur observers. The most notable result from this orbital analysis is a detection of eccentricity in the planet's orbit. Using only the phase of our secondary eclipses, we can constrain ecosw to a minimum of 0.0084 ± 0.0004, a 20 sigma detection of one component of the orbit's eccentricity that is independent of the effects that stellar tides have on radial velocity data. We then characterize its atmosphere's temperature- pressure profile and molecular abundances using our Bayesian Atmospheric Radiative Transfer code (BART). Spitzer is operated by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA. This work was supported by NASA Planetary Atmospheres grant NNX12AI69G and NASA Astrophysics Data Analysis Program grant NNX13AF38G. J. Blecic holds a NASA Earth and Space Science Fellowship.

**Author(s): Andrew S. Foster[1]**, Joseph Harrington[1], Patricio Cubillos[1], Jasmina Blecic[1], A J Foster[1], Ryan Challener[1], Justin Garland[1]
**Institution(s):** *1. University of Central Florida*

### 416.07 – Chemical uncertainties in modeling hot Jupiters atmospheres

Most predictions and interpretations of observations in beyond our Solar System have occurred through the use of 1D photo-thermo-chemical models. Their predicted atmospheric compositions are highly dependent on model parameters. Chemical reactions are based on empirical parameters that must be known at temperatures ranging from 100 K to above 2500 K and at pressures from millibars to hundreds of bars. Obtained from experiments, calculations and educated-guessed estimations, these parameters are always evaluated with substantial uncertainties. However, although of practical use, few models of exoplanetary atmospheres have considered these underlying chemical uncertainties and their consequences. Recent progress has been made recently that allow us to (1) evaluate the accuracy and precision of 1D models of planetary atmospheres, with quantifiable uncertainties on their predictions for the atmospheric composition and associated spectral features, (2) identify the 'key parameters' that contribute the most to the models predictivity and should therefore require further experimental or theoretical analysis, (3) reduce and optimize complex chemical networks for their inclusion in multidimensional atmospheric models.
First, a global sampling approach based on low discrepancy sequences has been applied in order to propose error bars on simulations of the atmospheres HD 209458b and HD 189733b, using a detailed kinetic model derived from applied combustion models that was methodically validated over a range of temperatures and pressures typical for these hot Jupiters. A two-parameters temperature-dependent uncertainty factor has been assigned to each considered rate constant. Second, a global sensitivity approach based on high dimensional model representations (HDMR) has been applied in order to identify those reactions which make the largest contributions to the overall uncertainty of the simulated results. The HDMR analysis has been restricted to the most important reactions based on a non-linear screening method, using Spearman Rank Correlation Coefficients at different level of the modeled atmospheres. The individual contributions of some key reactions, as highlighted by this analysis, will be discussed.

**Author(s): Eric Hebrard[1]**, Shawn Domagal-Goldman[1]
**Institution(s):** *1. NASA Goddard Space Flight Center*

### 416.08 – On the parameterization of 1D vertical mixing in planetary atmospheres: insights from 2D and 3D simulations

Most of the current atmospheric chemistry models for planets (e.g., Krasnopolsky & Parshev 1981; Yung & Demore 1982; Yung, Allen & Pinto 1984; Lavvas et al. 2008; Zhang et al. 2012) and exoplanets (e.g., Line, Liang & Yung 2010; Moses et al. 2011; Hu & Seager 2014) adopt a one-dimensional (1D) chemical-diffusion approach in the vertical coordinate. Although only a crude approximation, these 1D models have succeeded in explaining the global-averaged vertical profiles of many chemical species in observations. One of the important assumptions of these models is that all chemical species are transported via the same eddy diffusion profile--that is, the assumption is made that the eddy diffusivity is a fundamental property of the dynamics alone, and does not depend on the chemistry. Here we show that, as also noticed in the Earth community (e.g., Holton 1986), this “homogenous eddy diffusion” assumption generally breaks down. We first show analytically why the 1D eddy diffusivity must generally depend both on the horizontal eddy mixing and the chemical lifetime of the species. This implies that the long-lived species and short-lived chemical species will generally exhibit different eddy diffusion profiles, even in a given atmosphere with identical dynamics. Next, we present tracer-transport simulations in a 2D chemical-diffusion-advection model (Shia et al. 1989; Zhang, Shia & Yung 2013) and a 3D general circulation model (MITgcm, e.g., Liu & Showman 2013), for both rapid-rotating planets and tidally-locked exoplanets, to further explore the effect of chemical timescales on the eddy diffusivity. From the 2D and 3D simulation outputs, we derive effective 1D eddy diffusivity profiles for chemical tracers exhibiting a range of chemical timescales. We show that the derived eddy diffusivity can depend strongly on the horizontal eddy mixing and chemistry, although the dependences are more complex than the analytic model predicts. Overall, these results suggest that caution is warranted when using 1D models with multiple species mixed by a single eddy diffusivity profile. Possible consequences will be discussed.

**Author(s): Xi Zhang[2]**, Adam P Showman[1]
**Institution(s):** *1. University of Arizona, 2. University of California Santa Cruz*

### 416.09 – Atmospheres of partially differentiated super-Earth exoplanets

Terrestrial exoplanets have been discovered in a range of sizes, densities and orbital locations that defy our expectations based upon the Solar System. Planets discovered to date with radii less than ~1.5-1.6 Earth radii all seem to fall on an iso-density curve with the Earth [1]. However, mass and radius determinations, which depend on the known properties of the host star, are not accurate enough to distinguish between a fully differentiated three-layer planet (core, mantle, ocean/atmosphere) and an incompletely differentiated planet [2]. Full differentiation of a planet will depend upon the conditions at the time of accretion, including the abundance of short-lived radioisotopes, which will vary from system to system, as well as the number of giant impacts the planet experiences. Furthermore, separation of metal and silicates at the much larger pressures found inside super-Earths will depend on how the chemistry of these materials change at high pressures. There are therefore hints emerging that not all super-Earths will be fully differentiated. Incomplete differentiation will result in a more reduced mantle oxidation state and may have implications for the composition of an outgassed atmosphere. Here we will present the first results from a chemical equilibrium model of the composition of such an outgassed atmosphere and discuss the possibility of distinguishing between fully and incompletely differentiated planets through atmospheric observations.
[1] Rogers, L. 2015. ApJ, 801, 41. [2] Zeng, L. & Sasselov, D. 2013. PASP, 125, 227.

**Author(s): Laura Schaefer[1]**, Dimitar Sasselov[1]
**Institution(s):** *1. Harvard University*

### 416.10 – A Novel Approach to Atmospheric Retrieval for Small Exoplanets

Retrieval of environmental parameters from the spectra of sub-Neptune and terrestrial extrasolar planets is extremely challenging due to the observational difficulty, the inherent complexity of planetary processes, and the likely diversity of environments for these small objects. The best retrieval techniques will use observations of the star-planet system along with knowledge of planetary processes gleaned from objects in the Solar System to constrain retrieved environmental parameters.
We present ongoing work of the Virtual Planetary Laboratory (VPL) to develop a versatile terrestrial atmosphere retrieval suite capable of capturing a wide range of terrestrial planet processes while employing robust statistics. Our novel approach is to produce fits to observed spectra that discriminate between degenerate solutions by considering limitations on planetary environments derived from known physics and chemistry. The forward model leverages the SMART 1-D line-by-line, fully multiple-scattering and widely validated radiative transfer model (Meadows & Crisp 1996) as the primary workhorse for computing transit transmission, thermal emission, and reflectance spectroscopy. Following the approach of the CHIMERA code (Line et al 2013; 2014), we employ a variety of inverse models for the problem of parameter estimation. Here we present preliminary results using optimal estimation for terrestrial and sub-Neptune planets. The model is being validated against synthetic, Solar System, and existing exoplanet observations.
This model will be used to explore the capabilities of key telescope architectures, to understand information loss when planets are viewed as a point source, and to provide a data analysis framework for future sub-Neptune, super-Earth, and Earth analog exoplanet observations.

**Author(s): Jacob Lustig-Yaeger3**, Victoria Meadows3, Michael Line[2], David Crisp[1]
**Institution(s):** *1. Jet Propulsion Laboratory, California Institute of Technology, 2. University of California Santa Cruz, 3. University of Washington*

### 416.11 – A study of temporal variability of clouds in exo-atmospheres using Earth observations as a proxy

Clouds are strongly linked to the dynamics of the atmosphere, and have been observed to vary over multiple spatial scales and timescales on Earth and the planets: hourly, diurnal, seasonal, interannual and decadal. The study of such variations in exoplanetary atmospheres could only be made through lightly constrained general circulation models (GCMs). In most cases, the exoplanet itself is unresolved from its star and individual cloud patches and their variations cannot be observed. However, temporal and spatial variation of cloud fields can have significant implications for the interpreting the observed phase-curve of the lights from the star-exoplanet system, yet it remains almost wholly unconstrained. To address this issue, we model Earth as an exoplanet, to understand changes in observables due to temporal and spatial variations of clouds by leveraging the rich datasets available for Earth. In particular, the International Satellite Cloud Climatology Project (ISCCP) has compiled cloud observations on Earth in the past three decades, producing a high-resolution dataset. We perform radiative transfer calculations using cloud profiles sampled from this dataset to produce disc integrated brightness and polarization phase curves which map seasonal and interannual cloud variations. This exercise gives us the first (pseudo)-observation based constraints for temporal variability of clouds in exo-atmospheres.

**Author(s): Pushkar Kopparla[1]**, Albert Zhai[2], Alice Zhai[2], Hui Su[2], Jonathan H Jiang[2], Yuk Ling Yung[1]
**Institution(s):** *1. California Institute of Technology, 2. Jet Propulsion Laboratory*

### 416.12 – Atmospheric Ozone Formation and Observation Effects on Waterless Rocky Exoplanets around M Dwarfs

It is recently proposed that up to two thousand bars of $O_2$ atmospheres could buildup on rocky planets near M dwarfs as the result of stellar luminosity evolution and runaway water loss (Luger and Barnes, 2015). Here we use a one-dimensional photochemical model to study ozone distributions in these hypothetical $O_2$-rich atmospheres. Our study showed that ozone layers in denser $O_2$ atmospheres locate at higher altitudes than that in the Earth's atmospheres. A higher ozone layer should generate stronger $O_3$ absorption feature, potentially different from that of our Earth. We also present the enhancement of transmission spectral features which could be useful to identify such dense $O_2$-rich atmospheres by future exoplanet characterization missions and facilities such as JWST.

**Author(s): Chuhong Mai[2]**, Feng Tian[1]
**Institution(s):** *1. Center for Earth System Sciences, Tsinghua University, 2. School of Earth and Space Exploration, Arizona State University*

### 416.13 – HST/WFC3 Updates Impacting Exoplanet Observers

We provide a summary of new Wide Field Camera 3 (WFC3) capabilities and updates to the Hubble Space Telescope (HST) proposal process of interest to exoplanet observers. In particular, we discuss recent studies on high precision photometry with spatial scanning that show up to 0.1% photometric repeatability for the UVIS channel and 0.5% for the IR channel. We describe a new IR sample sequence, spars5, which may open up more orient ranges and scheduling opportunities for exoplanet targets. Finally we present a new mid-cycle proposal scheme for HST that will allow observers to apply for up to 5 orbits outside the standard annual call for proposals; this will be especially advantageous for observers of recently discovered exoplanets.

**Author(s): Catherine Gosmeyer[1]**, Peter R. McCullough[1], Sylvia Baggett[1], Elena Sabbi[1]
**Institution(s):** *1. Space Telescope Science Institute*

### 416.14 – Forward Models of Exoplanets for Atmosphere Retrievals with JWST

We present models of extrasolar planets focusing on super-Earths and mini-Neptunes and incorporating self-consistent treatment of internal structures, radiative cooling and XUV-driven mass loss over time, and atmosphere models with 1-D radiative transfer and a range of compositions and cloud structures. These models are designed for performing retrievals of atmosphere parameters with data from the upcoming JWST mission.

**Author(s): Alex Howe[1]**, Adam Burrows[1]
**Institution(s):** *1. Princeton University*

### 416.15 – 3D modeling of clouds in GJ1214b's atmosphere

GJ1214b is a warm mini-Neptune/waterworld and one of the few low-mass exoplanets whose atmosphere is characterizable by current telescopes. Recent observations indicated a flat transit spectrum in near-infrared which has been interpreted as the presence of high and thick condensate clouds of KCl or ZnS or photochemical hazes. However, the formation of such high clouds/hazes would require a strong vertical mixing linked to the atmospheric circulation. In order to understand the transport, distribution and observational implications of such clouds/haze, we studied the atmospheric circulation and cloud formation on GJ1214b for H-dominated and water-dominated atmospheres using the Generic LMDZ GCM.
Firstly, we analyzed cloud-free atmospheres. We showed that the zonal mean meridional circulation corresponds to an anti-Hadley circulation in most of the atmosphere with upwelling at midlatitude and downwelling at the equator. This circulation should strongly impact cloud formation and distribution, leading to a minimum of cloud at the equator. We also derived 1D equivalent eddy diffusion coefficients. The corresponding values should favor an efficient formation of photochemical haze in the upper atmosphere of GJ1214b.
Secondly, we simulated cloudy atmospheres including latent heat release and radiative effects for KCl and ZnS clouds. We analyzed their impacts on the thermal structure. In particular, we fund that ZnS clouds may lead to the formation of a stratospheric thermal inversion. We showed that flat transit spectra consistent with HST observations are possible for cloud particle radii around 0.5 microns. Using the outputs of our GCM, we also generated emission and reflection spectra and phases curves.
Finally, our results suggest that primary and secondary eclipses and phase curves observed by JWST should provide strong constraints on the nature of GJ1214b's atmosphere and clouds.

**Author(s): Benjamin Charnay[2]**, Victoria Meadows[2], Jérémy leconte[1], Amit Misra[2], Giada Arney[2]
**Institution(s):** *1. LMD, 2. University of Washington*

### 416.16 – Polarisation of Planets and Exoplanets

We present observations of the linear polarisation of several hot Jupiter systems with our new high-precision polarimeter HIPPI (HIgh Precision Polarimetric Instrument). By looking at the combined light of the star and planet we aim to detect the polarised light reflected from the planet's atmosphere. This can provide information on the presence of, and nature of clouds in the atmosphere, and constrain the geometric albedo of the planet. The method is applicable to both transitting and non-transitting planets, and can also be used to determine the inclination of the system, and thus the true mass for radial velocity detected planets. To predict and interpret the polarisation from such observations, we have also developed an advanced polarimetric modelling capability, by incoroporating full polarised radiative transfer into our atmospheric modelling code VSTAR. This is done using the VLIDORT vector radiative transfer solver (Spurr, 2006). The resulting code allows us to predict disc-resolved, phase-resolved, and spectrally-resolved intensity and linear polarisation for any planet, exoplanet, brown dwarf or cool star atmosphere that can be modelled with VSTAR. We have tested the code by reproducing benchmark calculations in polarised radiative transfer, and by Solar System test cases, including reproducing the classic Hansen and Hovenier (1974) calculation of the polarisation phase curves of Venus.

Hansen, J.E., & Hovenier, J.W., 1974, J. Atmos. Sci., 31, 1137
Spurr, R., 2006, JQSRT, 102, 316.

**Author(s): Jeremy Bailey[1]**, Lucyna Kedziora-Chudczer[1], Kimberly Bott[1], Daniel V. Cotton[1]
**Institution(s):** *1. University of New South Wales*

### 416.17 – Constraining the Structure of Hot Jupiter Atmospheres Using a Hybrid Version of the NEMESIS Retrieval Algorithm

Understanding the formation environments and evolution scenarios of planets in nearby planetary systems requires robust measures for constraining their atmospheric physical properties. Here we have utilized a combination of two different parameter retrieval approaches, Optimal Estimation and Markov Chain Monte Carlo, as part of the well-validated NEMESIS atmospheric retrieval code, to infer a range of temperature profiles and molecular abundances of $H_2O$, $CO_2$, $CH_4$ and CO from available dayside thermal emission observations of several hot-Jupiter candidates. In order to keep the number of parameters low and henceforth retrieve more plausible profile shapes, we have used a parametrized form of the temperature profile based upon an analytic radiative equilibrium derivation in Guillot et al. 2010 (Line et al. 2012, 2014). We show retrieval results on published spectroscopic and photometric data from both the Hubble Space Telescope and Spitzer missions, and compare them with simulations from the upcoming JWST mission. In addition, since NEMESIS utilizes correlated distribution of absorption coefficients (k-distribution) amongst atmospheric layers to compute these models, updates to spectroscopic databases can impact retrievals quite significantly for such high-temperature atmospheres. As high-temperature line databases are continually being improved, we also compare retrievals between old and newer databases.

**Author(s): Mahmuda A. Badhan[2]**, Avi M Mandell[1], Brigette Hesman[2], Conor Nixon[1], Drake Deming[2], Patrick Irwin3, Joanna Barstow3, Ryan Garland3
**Institution(s):** *1. NASA Goddard Space Flight Center, 2. University of Maryland, 3. University of Oxford*

### 416.18 – Photochemical hazes in planetary atmospheres: solar system bodies and beyond

Recent transit observations of exoplanets have demonstrated the possibility of a wide prevalence of haze/cloud layers at high altitudes. Hydrocarbon photochemical haze could be the candidate for such haze particles on warm sub-Neptunes, but the lack of evidence for methane poses a puzzle for such hydrocarbon photochemical haze. The $CH_4$/CO ratios in planetary atmospheres vary substantially from their temperature and dynamics. An understanding of haze formation rates and plausible optical properties in a wide diversity of planetary atmospheres is required to interpret the current and future observations.

Here, we focus on how atmospheric compositions, specifically $CH_4$/CO ratios, affect the haze production rates and their optical properties. We have conducted a series of cold plasma experiments to constrain the haze mass production rates from gas mixtures of various $CH_4$/CO ratios diluted either in $H_2$ or $N_2$ atmosphere. The mass production rates in the $N_2$-$CH_4$-CO system are much greater than those in the $H_2$-$CH_4$-CO system. They are rather insensitive to the $CH_4$/CO ratios larger than at 0.3. Significant formation of solid material is observed both in $H_2$-CO and $N_2$-CO systems without CH4 in the initial gas mixtures. The complex refractive indices were derived for haze samples from $N_2$-$CH_4$, $H_2$-$CH_4$, and $H_2$-CO gas mixtures. These are the model atmospheres for Titan, Saturn, and exoplanets, respectively. The imaginary part of the complex refractive indices in the UV-Vis region are distinct among these samples, which can be utilized for modeling these planetary atmospheres.

**Author(s): Hiroshi Imanaka[2]**, Dale P. Cruikshank[1], Christopher P. McKay[1]
**Institution(s):** *1. NASA Ames Research Center, 2. SETI Institute*

**416.19 – The HST/STIS BAR5 Occulter: High Contrast in Space at Visible Wavelengths**
The Hubble Space Telescope currently has only one operational high contrast imaging coronagraphic mode, the 50CORON imaging mode of the Space Telescope Imaging Spectrograph (STIS). 50CORON includes two intersecting wedges and two bar occulting masks in an image plane ahead of the detector that block light from bright stars to reveal the faint emission from circumstellar disks or faint companions. Recently, the smallest supported inner working angle for these occulters was 0.3". We present in this poster the commissioning of new occulting locations on the detector that allow for inner working angles as close as 0.15" at the new BAR5 position. We show preliminary results for BAR5 using two nearby debris disks, AU Mic and Beta Pictoris, and provide interested users with a prescription for how to design their own high contrast imaging observations.

**Author(s): John H. Debes[1]**, Andras Gaspar[2], Glenn Schneider[2], Charles Proffitt[1]
**Institution(s):** *1. STScI, 2. The University of Arizona*

**416.20 – ARIEL: Atmospheric Remote-Sensing Infrared Exoplanet Large-survey**
More than 1,000 extrasolar systems have been discovered, hosting nearly 2,000 exoplanets. Ongoing and planned ESA and NASA missions from space such as GAIA, Cheops, PLATO, K2 and TESS will increase the number of known systems to tens of thousands. Of all these exoplanets we know very little, i.e. their orbital data and, for some of these, their physical parameters such as their size and mass. In the past decade, pioneering results have been obtained using transit spectroscopy with Hubble, Spitzer and ground-based facilities, enabling the detection of a few of the most abundant ionic, atomic and molecular species and to constrain the planet's thermal structure. Future general purpose facilities with large collecting areas will allow the acquisition of better exoplanet spectra, compared to the currently available, especially from fainter targets. A few tens of planets will be observed with JWST and E-ELT in great detail.
A breakthrough in our understanding of planet formation and evolution mechanisms will only happen through the observation of the planetary bulk and atmospheric composition of a statistically large sample of planets. This requires conducting spectroscopic observations covering simultaneously a broad spectral region from the visible to the mid-IR. It also requires a dedicated space mission with the necessary photometric stability to perform these challenging measurements and sufficient agility to observe multiple times ~500 exoplanets over mission life-time.
The ESA-M4 mission candidate ARIEL is designed to accomplish this goal and will provide a complete, statistically significant sample of gas-giants, Neptunes and super-Earths with temperatures hotter than 600K, as these types of planets will allow direct observation of their bulk properties, enabling us to constrain models of planet formation and evolution.
The ARIEL consortium currently includes academic institutes and industry from eleven countries in Europe; the consortium is open and invites new contributions and collaborations.

**Author(s): Giovanna Tinetti[1]**
**Institution(s):** *1. University College London*

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## 417 – Discoveries and Dynamics of Extrasolar Planets

**417.01 – The NASA Exoplanet Archive**
The NASA Exoplanet Archive is an online astronomical exoplanet and stellar catalog and data service that collates and cross-correlates astronomical data on exoplanets and their host stars and provides tools to work with these data. The Exoplanet Archive is dedicated to collecting and serving important public data sets involved in the search for and characterization of extrasolar planets and their host stars. The data include stellar parameters, exoplanet parameters and discovery/characterization data from the astronomical literature. The Archive also hosts mission and survey data, including Kepler pipeline data such as candidate lists and data validation products and ground-based surveys from SuperWASP and KELT. Tools provided for users to work with these data include a transit ephemeris predictor, light curve viewing utilities and a periodogram service.

**Author(s): Rachel L. Akeson[1]**
**Institution(s):** *1. NASA Exoplanet Science Institute, Caltech*

**417.02 – PICK2: Planets in Clusters with K2**
Open clusters are remarkable laboratories for a wide variety of astrophysical investigations. They comprise the most homogeneous samples of stars that we can ever hope to find. They are stars that share the same age, initial chemical composition, distance and dynamical environment. The fundamental property that distinguishes one star from another in a cluster is simply the stellar mass. This gives us the very rare opportunity to conduct well controlled astrophysical studies of stars, and as a result there is a vast astronomical literature focused on understanding and characterizing the members of stellar clusters.
We are searching for transiting planets in five open clusters in the NASA K2 mission Fields 4, 5 and 7. These clusters range in age from 125My (Pleiades) through the 625My ages of the Hyades and Praesepe, up to the much older Ruprecht 147 (2.5 Gyr) and M67 (3-5 Gyr) clusters. Examination of the distribution of planetary orbital parameters as well as the planetary multiplicity, radius and mass distributions as a function of stellar age (and in comparison with field stars from both K2 and Kepler) will provide a powerful test of theories of planetary system formation and dynamical evolution. The radii of hot Jupiters and Saturns as a function of cluster age will provide a sensitive test of theories to explain the population of inflated hot Jupiters.
Our team will process the K2 pixel files into light curves for each target star, and will then search these light curves for possible planet transit events. We will apply standard vetting procedures to remove likely false-positives and we will then model the transit profiles. We will then conduct an extensive set of ground-based follow-up observations using a wide range of observational facilities at our disposal. These will include imaging, high resolution visible and near-IR spectroscopy, precise radial velocity measurement, and ground-based observations of further transits, as appropriate.

**Author(s): William D. Cochran[6]**, Michael Endl[6], Marshall C. Johnson[6], Byeong-Cheol Lee3, Chan Park3, Inwoo Han3, Heike Rauer[2], Juan Cabrera[2], Szilard Csizmadia[2], Martin Paetzold5, David Yong[1], Martin Asplund[1], Artie P. Hatzes4
**Institution(s):** *1. Aust. Nat. Univ., 2. DLR, 3. KASI, 4. TLS Tautenburg, 5. Univ. Köln, 6. Univ. of Texas, Austin*

**417.03 – An Exo-Venus Around a Cool, Nearby Star**
We present the discovery and planetary confirmation of KOI-3138, a likely Earth-sized (1.08 Earth radii ) planet in a 9-day orbit around a nearby M Dwarf star. A planet transit was detected around KOI-3138 with the *Kepler* spacecraft and confirmed via false positive analysis using data from the UK Infrared telescope, Digital Sky Survey, and DSSI Speckle imaging. The planet's short orbital period places it close to its host star, making it an interesting Venus analog around a cool star.
It remains possible, although unlikely, that KOI-3138.01 instead orbits a bound, undetected binary companion to KOI-3138. Under these conditions, the planet becomes a mini-Neptune-sized planet orbiting a brown dwarf with a mass of ~0.05 solar mass. Follow-up radial velocity measurements on the host star are required in order to accurately assess the likelihood of this possibility. Specifically, detection of a significant radial velocity ( ~725 m/s) upon observation of KOI-3138 will indicate the presence of a bound companion that was not detected by our false positive analysis procedures. Such a companion, if detected, cannot be ruled out as the host star around which KOI-3138.01 orbits.
KOI-3138.01 is too small to induce a detectable "wobble" in its host

star. We therefore make no conclusions about mass or composition. However, there is reasonable incentive to determine these properties in the hopes of understanding the nature of habitable zones around M-type stars. Kepler-186f, a previously discovered Earth-like exoplanet, is similar in size to KOI-3138.01 and orbits the outer reaches of its star's conservative habitable zone. KOI-3138.01, also Earth-sized, orbits a similar star but resides much closer in. The two planets together span the range of distances within the habitable zones of M Dwarfs. Determining the composition and atmosphere of KOI-3138.01 is therefore useful in understanding the nature of habitable zone boundaries of such star types. This task may in fact be possible with the James Webb Space Telescope (JWST), which will characterize atmospheric compositions of nearby Earth-sized planets like KOI-3138.01 and thereby provide insight into the habitability of both known and to-be-discovered exoplanets.

**Author(s): Isabel Angelo[2]**, Jason F. Rowe[1], Steve B. Howell[1]
**Institution(s):** *1. NASA Ames Research Center, 2. UC Berkeley*

### 417.04 – Connections among spacing, composition, and flatness in super-Earth systems

The collection of thousands of super-Earths discovered by the Kepler Mission contains a wealth of information about the process of planet formation. Their spacing distribution is an archaeological artifact of the final stages of planet formation, when planets grow from embryos to super-Earths. We explore how the interplay between stirring and mergers establishes the spacing distribution and links it to the composition and flatness of planets in the system, with the latter influenced by damping by residual gas. We show how these links manifest in Kepler observables such as period ratio, number of transiting planets, and transit duration ratios. Our study theoretically motivates connections between architectures and compositions that reflect conditions during the end stages of planet formation and are not merely the result of selection effects.

**Author(s): Rebekah Ilene Dawson[1]**, Eve J. Lee[1], Eugene Chiang[1]
**Institution(s):** *1. University of California, Berkeley*

### 417.05 – Spin-Orbit Misalignment of Two-Planet-System KOI-89 via Gravity Darkening

We investigate the causes of spin-orbit misalignment in exoplanet systems via two-planet-system KOI-89. This system is of particular interest because it can experimentally constrain the numerous outstanding hypotheses that have been proposed to generate misalignments. We constrain both the spin-orbit angles and the relative alignment between the planes of the two orbits using gravity darkening. By fitting KOI-89's 17 long cadence quarters of Kepler photometry, we show that the 85-day-orbit and 208-day-orbit planets are misaligned from the host star's rotation axis by 72° ± 3° and 73° (+11° -5°), respectively. From these results, we limit KOI-89's causes of spin-orbit misalignment based on three criteria: agreement with KOI-89's fundamental parameters, the capability to cause extreme misalignment, and conformance with mutually aligned planets. We limit likely causes to star-disk binary interactions, disk warping via planet-disk interactions, Kozai resonance, planet-planet scattering, or internal gravity waves in the convective interior of the star. Our results disfavor planet-embryo collisions, chaotic evolution of stellar spin, magnetic torquing, coplanar high-eccentricity migration, and inclination resonance.

**Author(s): Johnathon Ahlers[1]**, Jason W Barnes[1], Rory Barnes[2]
**Institution(s):** *1. University of Idaho, 2. University of Washingon*

### 417.06 – Predicting Precession Rates from Secular Dynamics for Extra-solar Multi-planet Systems

Considering the secular dynamics of multi-planet systems provides substantial insight into the interactions between planets in those systems. Secular interactions are those that don't involve knowing where a planet is along its orbit, and they dominate when planets are not involved in mean motion resonances. These interactions exchange angular momentum among the planets, evolving their eccentricities and inclinations. To second order in the planets' eccentricities and inclinations, the eccentricity and inclination perturbations are decoupled. Given the right variable choice, the relevant differential equations are linear and thus the eccentricity and inclination behaviors can be described as a sum of eigenmodes. Since the underlying structure of the secular eigenmodes can be calculated using only the planets' masses and semi-major axes, one can elucidate the eccentricity and inclination behavior of planets in exoplanet systems even without knowing the planets' current eccentricities and inclinations. I have calculated both the eccentricity and inclination secular eigenmodes for the population of known multi-planet systems whose planets have well determined masses and periods. Using this catalog, and assuming a Gausian distribution for the eigenmode amplitudes and a uniform distribution for the eigenmode phases, I have predicted what range of precession rates the planets may have. Generally, planets that have more than one eigenmode significantly contribute to their eccentricity ('groupies') can have a wide range of possible precession rates, while planets that are 'loners' have a narrow range of possible precession rates. One might have assumed that in any given system, the planets with shorter periods would have faster precession rates. However, I show that in systems where the planets suffer strong secular interactions this is not necessarily the case.

**Author(s): Christa L. Van Laerhoven[1]**
**Institution(s):** *1. Canadian Institute for Theoretical Astrophysics (CITA)*

### 417.07 – Collisional Cascade in a Debris Disk from an External Perturber

The study of circumstellar debris disks has often been coupled with the study of planet formation. A thermally warm debris disk (~300 K) may indicate the presence of an exoplanet orbiting within and stirring the disk. However, there is another possible mechanism for heating a debris disk: an external stellar-mass perturber exciting the eccentricities and inclinations of the particles in a disk.
We explore the consequences of an external perturber on the evolution of a debris disk. The perturber excites the eccentricities of the particles in the disk via the Kozai-Lidov mechanism, triggering a collisional cascade among the planetesimals. These collisions produce smaller dust grains and damp the particles' larger eccentricities.
We present the results of our study of a such a disk using secular analysis and collisional N-body simulations. We will discuss the connections to observations of warm disks and the implications for planet formation.

**Author(s): Erika Nesvold3**, Smadar Naoz[1], Laura Vican[1], Benjamin Zuckerman[1], Erika Holmbeck[2]
**Institution(s):** *1. Department of Physics and Astronomy, UCLA, 2. Department of Physics, University of Notre Dame, 3. Department of Terrestrial Magnetism, Carnegie Institution of Washington*

### 417.08 – Detection and Characterization of Extrasolar Planets through Mean-Motion Resonances: Simulations of Hypothetical Debris Disks

A planet orbiting interior or exterior to a debris disk may produce signatures in the disk that reveal the planet's presence even if it remains undetected. These features appear near mean-motion resonances and provide a powerful tool to not only detect unseen planets in extra-solar systems, but also help constrain their mass and orbital parameters. I will present results from simulations of hypothetical debris disks both for interior and exterior resonances, showing that gaps can be opened in cold debris disks away from the orbit of the planet, and thus that not all disk gaps need contain a planetary body. The results allow us to constrain planet masses, semi-major axes and eccentricities based on the locations and widths of the gaps. Moreover, distinct features likely arising from Lindblad resonances are seen when the planet perturbing the disk has non-zero orbital eccentricity. Finally, I will present expressions that relate the planetary mass to the widths and locations of the observed gaps.

**Author(s): Maryam Tabeshian[1]**, Paul A Wiegert[1]
**Institution(s):** *1. Department of Physics and Astronomy, University of Western Ontario*

### 417.09 – Planetesimal dispersal during resonant coupled migration of giant planets

When two giant planets, during their early phases of evolution, are trapped in a mean motion resonance, they may migrate outwards. Along their path towards the outer regions of the disk, they scatter away most planetesimals within their gravitational reach. When the gaseous disk is finally dispersed, the leftover planetesimals may not be numerous enough to break the resonance lock nor to damp a potential eccentricity build-up produced during the coupled migration phase. We performed N-body numerical simulations showing that the planetesimal scattering during the coupled outward migration prevents a pair of planets like Jupiter and Saturn from breaking the 2:1 resonance, once they reach their present location. In addition, the planet eccentricities forced by the resonance lock remain large and are only slightly damped before most of the surviving planetesimals are ejected from the system.

**Author(s): Francesco Marzari[2]**, Gennaro D'Angelo[1]
**Institution(s):** *1. LANL, 2. Univ. of Padova*

## 418 – Origins of Planetary Systems

### 418.01 – Pebble Accretion and the Diversity of Planetary Systems

Understanding how planetary systems form and why they exhibit great diversity are key questions in planetary science. Recently, several studies of planet formation have focussed on a mechanism called ``pebble accretion''. Here, mm-to-m size particles in a protoplanetary disk are strongly affected by both gas drag and gravity during an encounter with a growing planet. This can substantially increase the capture probability, speeding up planetary growth, and providing a possible solution to the long-standing problem of how gas-giant planets form within the short lifetimes of protoplanetary disks (Lambrechts and Johansen 2012 Astron Astrophys 544, A32). It has also been suggested that pebble accretion can explain the profound difference between the rocky inner planets and the gas-rich outer planets of the Solar System (Morbidelli et al. 2015 Icarus 258, 418). Here I will present new simulations of planet formation in an evolving protoplanetary disk, spanning both the regions in which rocky and gaseous planets are likely to form. The simulations cover the runaway, oligarchic and gas-accretion phases of planetary growth, and include approximate models for pebble growth and the formation of asteroid sized planetesimals from pebbles. Planetary growth rates in these models are sensitive to the poorly-constrained properties of pebbles in a protoplanetary disk, and also the properties of the gaseous disk itself, especially the strength of turbulence. Different disk and pebble properties lead to a wide range of outcomes, including some cases resembling the Solar System, and may explain the observed diversity of extrasolar planetary systems.

**Author(s): John E. Chambers[1]**
**Institution(s):** *1. Carnegie Inst. of Washington*

### 418.02 – Planetesimals embedded in a gaseous disc vs mean-motion resonances

We study orbital evolution of km-sized planetesimals in a gaseous disc with one or more embedded giant protoplanets. Especially, we focus on the regions intersected by the inner mean-motion resonances with the innermost ("Jovian") protoplanet, e.g. 2:1, 5:2, 8:3, 3:1. The planetesimals orbiting in these regions are subject to combined effects of aerodynamic and resonant perturbations. We aim to numerically investigate two possible outcomes of this interplay. First, stable resonant islands can exist (as in Chrenko et al. 2015) and may slow down or capture planetesimals as they spiral sunward. In such a case, the resonances might serve as natural barriers for the flux of planetesimals and locally accelerate the accumulation of the solid material.
Second, the resonances can overcome the damping effects of the gas and pump the eccentricities of the crossing planetesimals (Marzari & Weidenschilling 2002). This process might generate eccentric orbits which lead to increased relative velocities with respect to the nebular gas and crossing of non-resonant (circular) orbits. The environment of the gaseous disc is simulated with the FARGO code (Masset 2000), which is a 2D Eulerian solver of the fluid equations with fast azimuthal advection. We modified the code so it can treat small planetesimals as test particles affected by the respective aerodynamic drag.
Acknowledgements: The work of OC and MB has been supported by Charles University in Prague, project GA UK No. 1062214.

**Author(s): Ondrej Chrenko[1]**, Miroslav Broz[1]
**Institution(s):** *1. Institute of Astronomy, Charles University in Prague*

### 418.03 – The Fragility of the Terrestrial Planets During a Giant Planet Instability

Many features of the outer solar system are replicated in numerical simulations if the giant planets undergo an orbital instability that ejects one or more ice giants. During this instability, the orbits of Jupiter and Saturn are believed to diverge, crossing their 2:1 mean motion resonance (MMR), and this resonance-crossing can excite the orbits of the terrestrial planets. Using a large ensemble of numerical simulations of this giant planet instability, we directly model the evolution of the terrestrial planet orbits during this process, paying special attention to those systems that reproduce the basic features of the outer planets. In systems that retain four giant planets and finish with Jupiter and Saturn beyond their 2:1 MMR, we find an 80-90% probability that at least one terrestrial planet is lost. Moreover, most systems that manage to retain all four terrestrial planets finish with terrestrial planet eccentricities and inclinations larger than the observed ones. There is less than a 20% chance that the terrestrial planet orbits will have a level of excitation comparable to the observed orbits. If we factor in the probability that the outer planetary orbits are well-replicated, we find a probability of 3% or less that the orbital architecture of the inner and outer planets are simultaneously reproduced in the same system. These small probabilities raise the prospect that the giant planet instability may have occurred before the terrestrial planets had formed. Such a scenario implies that the giant planet instability is not the source of the Late Heavy Bombardment and that the terrestrial planets completed their formation within the giant planets' post-instability configuration.

**Author(s): Nathan A. Kaib[2]**, John E. Chambers[1]
**Institution(s):** *1. Carnegie Institution for Science, 2. University of Oklahoma*

### 418.04 – On the Origin of the Kepler-36 System

The Kepler-36 system comprises two exoplanets: an inner terrestrial super-Earth (4.5 $M_E$) and an outer gaseous sub-Neptune (8.1 $M_E$). Both planets are orbiting very close to their host star (0.12 and 0.13 AU away) and to each other. Their orbital periods are in nearly a 7:6 ratio, a mean-motion resonance that is not usually populated. Finally, the inner planet is much denser than Earth (7.5 g/cm3), while the outer planet is substantially less dense (0.89 g/cm3), a surprise given the close proximity of their orbits.
We examine origin scenarios for Kepler-36 featuring planetary migration due to dissipative forces within the circumstellar gas disk. In our model, the planets did not form *in situ* but rather moved inwards through a region of smaller planetesimals and embryos. We assume that the outer body formed beyond the frost line with significant gas accretion to account for its low density. This sub-Neptune migrated inward and captured an embryo of negligible relative mass into a 2:1 orbital resonance. Collisions between this embryo and other bodies of similar mass broke the resonance and allowed the two planets to converge while the inner

one grew in mass and density.
Using HNDrag, an N-body code, we have found several scenarios that might explain the observations. Although our successful scenarios occur with low probability, this is actually a strength since few known systems share the peculiarities of Kepler-36. Our model explains the main observed features of this system in the context of standard planetary formation theory.

**Author(s): Thomas Rimlinger[1]**, Douglas Hamilton[1], Derek Richardson[1]
**Institution(s):** *1. University of MD, College Park*

### 418.05 – KOI2138 -- a Spin-Orbit Aligned Intermediate Period Super-Earth

A planet's formation and evolution are encoded in spin-orbit alignment -- the planet's inclination relative to its star's equatorial plane. While the solar system's spin-orbit aligned planets indicate our own relatively quiescent history, many close-in giant planets show significant misalignment. Some planets even orbit retrograde! Hot Jupiters, then, have experienced fundamentally different histories than we experienced here in the solar system. In this presentation, I will show a new determination of the spin-orbit alignment of 2.1 $R_{Earth}$ exoplanet candidate KOI2138. KOI2138 shows a gravity-darkened transit lightcurve that is consistent with spin-orbit alignment. This measurement is important because the only other super-Earth with an alignment determination (55 Cnc e, orbit period 0.74 days) is misaligned. With an orbital period of 23.55 days, KOI2138 is far enough from its star to avoid tidal orbit evolution. Therefore its orbit is likely primordial, and hence it may represent the tip of an iceberg of terrestrial, spin-orbit aligned planets that have histories that more closely resemble that of the solar system's terrestrial planets.

**Author(s): Jason W. Barnes[1]**
**Institution(s):** *1. University of Idaho*

### 418.06 – Sustained Accretion on Gas Giants Surrounded by Low-Turbulence Circumplanetary Disks

Gas giants more massive than Saturn acquire most of their envelope while surrounded by a circumplanetary disk (CPD), which extends over a fraction of the planet’s Hill radius. Akin to circumstellar disks, CPDs may be subject to MRI-driven turbulence and contain low-turbulence regions, i.e., dead zones. It was suggested that CPDs may inhibit sustained gas accretion, thus limiting planet growth, because gas transport through a CPD may be severely reduced by a dead zone, a consequence at odds with the presence of Jupiter-mass (and larger) planets. We studied how an extended dead zone influences gas accretion on a Jupiter-mass planet, using global 3D hydrodynamics calculations with mesh refinements. The accretion flow from the circumstellar disk to the CPD is resolved locally at the length scale Rj, Jupiter's radius. The gas kinematic viscosity is assumed to be constant and the dead zone around the planet is modeled as a region of much lower viscosity, extending from ~Rj out to ~60Rj and off the mid-plane for a few CPD scale heights. We obtain accretion rates only marginally smaller than those reported by, e.g., D'Angelo et al. (2003), Bate et al. (2003), Bodenheimer et al. (2013), who applied the same constant kinematic viscosity everywhere, including in the CPD. As found by several previous studies (e.g., D’Angelo et al. 2003; Bate et al. 2003; Tanigawa et al. 2012; Ayliffe and Bate 2012; Gressel et al. 2013; Szulágyi et al. 2014), the accretion flow does not proceed through the CPD mid-plane but rather at and above the CPD surface, hence involving MRI-active regions (Turner et al. 2014). We conclude that the presence of a dead zone in a CPD does not inhibit gas accretion on a giant planet. Sustained accretion in the presence of a CPD is consistent not only with the formation of Jupiter but also with observed extrasolar planets more massive than Jupiter. We place these results in the context of the growth and migration of a pair of giant planets locked in the 2:1 mean motion resonance

**Author(s): Gennaro D'Angelo[1]**, Francesco Marzari[2]
**Institution(s):** *1. NASA Ames Research Center, 2. University of Padova*

## 419 – Mars's Atmosphere

### 419.01 – Collision-Induced Dissociation Cross Sections Relevant to Atmospheric Loss from Mars

The flow onto an atmosphere of the solar wind plasma, a plasma trapped in a planetary magnetic field, or a local pick-up ion plasma produces chemistry, heating and atmospheric loss. These processes, which affect its evolution, are often lumped together as atmospheric sputtering (Johnson 1994). When the atmosphere near the exobase is atomic, then laboratory data, calculations or scaled models for the collision cross sections are usually available for use in Monte Carlo simulations of atmospheric sputtering. However, atmospheres on a number of planetary bodies have molecules at the exobase and in the corona for which cross section data is often not available. Of particular interest are studies of the atmosphere of Mars in which there can be are significant levels of CO2 and CO in the exobase region. Here we present new calculations using improved potential energy surfaces of collision-induced dissociation of incident O atoms (~10eV-1keV), formed by neutralization of pick-up O+ incident on CO and CO2 molecules and compare their importance to our earlier estimates (e.g., Johnson and Liu 1998; Johnson et al. 2002) and discuss their relevance to simulations of atmospheric loss from Mars.

**Author(s): Hayley N Williamson[1]**, Cathy Tully[1], Robert Johnson[1]
**Institution(s):** *1. University of Virginia*

### 419.02 – Modeling Results on the Seasonal Influence at the Martian Exosphere

Analysis of HST ACS/SBC images of Mars in the far-ultraviolet taken in Oct-Nov 2007 and May-November 2014 indicate seasonal influence as a driving factor of the hydrogen corona, as has been reported earlier. To derive the changes in number density and temperature, the data must be compared to a radiative transfer model to simulate the resonantly scattered optically thick Lyman α emission from the exosphere of Mars. This work presents details on the modeling process used to analyze the data and the corresponding uncertainties. The escape flux is highly dependent on the characteristics of the martian exosphere like the exobase temperature and number density of H atoms as well as the presence or absence of a superthermal population of hydrogen atoms. Detailed studies on the workings of the radiative transfer model indicate degeneracy between temperature and number density values that can fit the data. Therefore it is difficult to accurately determine the characteristics of the martian hydrogen exosphere without independent measurement of at least one of the variables. However, HST observations have the advantage of observing a large portion of the dayside exosphere with intensity profiles extending from altitudes of 700 - 30,000 km giving a better estimate of the best-fit temperature and density values which characterize the martian exosphere under different seasonal conditions. Comparisons of the latitudinal symmetry from the HST images indicate the exosphere to be symmetric beyond 2.5 martian radii due to the broad trajectories of atoms at high altitudes.

**Author(s): Dolon Bhattacharyya[1]**, John Clarke[1], Jean-Loup Bertaux[2], Jean-Yves Chaufray[2], Majd Mayyasi[1]
**Institution(s):** *1. Boston University, 2. LATMOS*

### 419.03 – Stationary Planetary Waves in the Mars Winter Atmosphere as seen by the Radio Science Experiment MaRS on Mars Express

Stationary (Rossby) Waves are excited by the interaction of the zonally varying topography with the strong eastward winter jets. They lead to distinctive longitudinal temperature variations which contribute significantly to the asymmetry of the seasonal polar CO2 ice caps and are also important for the dust redistribution in the planetary atmosphere.

Radio Science profiles from the Mars Express Radio Science Experiment MaRS at northern and southern high latitudes are used to gain insight into winter stationary wave structures on both hemispheres.
Mars Global Surveyor (MGS) radio occultation measurements from the same season and year with their exceptionally good longitudinal and temporal coverage can be used to estimate the influence of transient eddies. Transient waves are especially important in the northern winter hemisphere.
Wave number 2 stationary waves, driven by topography, are dominant in the northern winter latitudes while the wave number 1 wave is the most significant wave number during southern winter. The wave amplitudes peak around winter solstice on both hemispheres.
Radio occultation measurements provide the unique opportunity to determine simultaneous measurements of temperature and geopotential height structures. Assuming geostrophic balance, these measurements can be used to determine meridional winds and eddy heat fluxes which provide further insight into the contribution of stationary waves to the heat exchange between the poles and the lower latitudes.

**Author(s): Silvia Tellmann3**, Martin Pätzold3, Bernd Häusler[2], Leonard G. Tyler[1], David P. Hinson[1]
**Institution(s):** *1. Department of Electrical Engineering, Stanford University, 2. Institut für Raumfahrttechnik und Weltraumnutzung, Universität der Bundeswehr München, 3. Rheinisches Institut für Umweltforschung (RIU), Department of Planetary Research*

### 419.04 – Traveling Waves in the northern hemisphere of Mars - Structure, Variability and Energetics

Investigations of the variability, structure and energetics of traveling waves in the northern hemisphere of Mars were conducted with the MarsWRF general circulation model. Using a simple annually repeatable dust scenario, the model reproduces the general characteristics of the observed traveling waves, including major wave periods and thermal signatures of traveling waves, suppression of transient eddy activity near the surface at northern winter solstice, and wave mode transitions among zonal wavenumber m = 1, 2 and 3 eastward traveling waves near the surface. Simulated wave structures in the temperature field differ from those in the geopotential field. Wave energetics calculations indicate a mixed baroclinic-barotropic nature for representative wave modes. This is consistent with Barnes et al. (1993). There is a large contrast in wave energetics between the near surface and higher altitudes, as well as between the poleward and equatorward side of the maximum eddy available potential energy at higher altitudes. The modeled transient eddies exhibit strong zonal variations in kinetic energy and various energy transfer terms. In particular, the eddy kinetic energy for a time period dominated by a m = 3 traveling wave shows local maxima in Acidalia, Utopia, and Arcadia, which are the origination locations of “flushing” dust storms. The eddy kinetic energy for a time period transitioning from m = 2 to m = 3 traveling waves shows local maxima in Acidalia and Utopia. There are direct energy exchanges between thermal tides and traveling waves, but the exchange rate is much slower than other major energetics terms. When thermal tides are removed from the MarsWRF simulation, the amplitudes of m = 3 traveling waves are greatly reduced. In the meantime, the isotherms of the northern baroclinic zone slope more towards the pole, satisfying an empirical condition for weaker traveling waves near the surface. However, this change cannot fully explain the strength of the simulated m = 3 traveling waves, as both weak and occasional strong m = 3 waves emerge from very similar zonal mean temperature structures.

**Author(s): Huiqun Wang[2]**, Anthony D. Toigo[1]
**Institution(s):** *1. APL, 2. SAO*

### 419.05 – Large-Scale Weather Disturbances in Mars’ Southern Extratropics

Between late autumn and early spring, Mars’ middle and high latitudes within its atmosphere support strong mean thermal gradients between the tropics and poles. Observations from both the Mars Global Surveyor (MGS) and Mars Reconnaissance Orbiter (MRO) indicate that this strong baroclinicity supports intense, large-scale eastward traveling weather systems (i.e., transient synoptic-period waves). These extratropical weather disturbances are key components of the global circulation. Such wave-like disturbances act as agents in the transport of heat and momentum, and generalized scalar/tracer quantities (e.g., atmospheric dust, water-vapor and ice clouds). The character of large-scale, traveling extratropical synoptic-period disturbances in Mars' southern hemisphere during late winter through early spring is investigated using a moderately high-resolution Mars global climate model (Mars GCM). This Mars GCM imposes interactively lifted and radiatively active dust based on a threshold value of the surface stress. The model exhibits a reasonable "dust cycle" (i.e., globally averaged, a dustier atmosphere during southern spring and summer occurs). Compared to their northern-hemisphere counterparts, southern synoptic-period weather disturbances and accompanying frontal waves have smaller meridional and zonal scales, and are far less intense. Influences of the zonally asymmetric (i.e., east-west varying) topography on southern large-scale weather are examined. Simulations that adapt Mars’ full topography compared to simulations that utilize synthetic topographies emulating key large-scale features of the southern middle latitudes indicate that Mars’ transient barotropic/baroclinic eddies are highly influenced by the great impact basins of this hemisphere (e.g., Argyre and Hellas). The occurrence of a southern storm zone in late winter and early spring appears to be anchored to the western hemisphere via orographic influences from the Tharsis highlands, and the Argyre and Hellas impact basins. Geographically localized transient-wave activity diagnostics are constructed that illuminate dynamical differences amongst the simulations and these are presented.

**Author(s): Jeffery L. Hollingsworth[1]**, Melinda A. Kahre[1]
**Institution(s):** *1. NASA Ames Research Center*

### 419.06 – The Mars Dust and Water Cycles: Investigating the Influence of Clouds on the Vertical Distribution and Meridional Transport of Dust and Water

The dust and water cycles are critical to the current Martian climate, and they interact with each other through cloud formation. Dust modulates the thermal structure of the atmosphere and thus greatly influences atmospheric circulation. Clouds provide radiative forcing and control the net hemispheric transport of water through the alteration of the vertical distributions of water and dust. Recent advancements in the quality and sophistication of both climate models and observations enable an increased understanding of how the coupling between the dust and water cycles (through cloud formation) impacts the dust and water cycles. We focus here on the effects of clouds on the vertical distributions of dust and water and how those vertical distributions control the net meridional transport of water. We utilize observations of temperature, dust and water ice from the Mars Climate Sounder (MCS) on the Mars Reconnaissance Orbiter (MRO) and the NASA ARC Mars Global Climate Model (MGCM) to show that the magnitude and nature of the hemispheric exchange of water during NH summer is sensitive to the vertical structure of the simulated aphelion cloud belt. Further, we investigate how clouds influence atmospheric temperatures and thus the vertical structure of the cloud belt. Our goal is to isolate and understand the importance of radiative/dynamic feedbacks due to the physical processes involved with cloud formation and evolution on the current climate of Mars.

**Author(s): Melinda A. Kahre[2]**, Robert M. Haberle[2], Jeffery L. Hollingsworth[2], Amanda S. Brecht[1], Richard A. Urata[1]
**Institution(s):** *1. BAER Institute, 2. NASA Ames Research Center*

### 419.07 – In Situ Observations of Line-of-Sight Extinction Reveals the Depth of the Planetary Boundary Layer within Gale Crater, Mars

Imagers onboard the Mars Science Laboratory have been used to derive line-of-sight extinction coefficients within Gale Crater, Mars.

The images in use have similar pointings and look at roughly the same section of the north crater rim some 30 km away. The observations are taken, on average, once every seven sols and have spanned more than an entire martian year. Another longstanding and more frequent observation is one in which the total column optical depth above Gale Crater can be derived. When comparing the two datasets, one can conclude that the air within the northern part of the crater supports less dust per volume than the bulk atmosphere above the crater. As such, little to no mixing has been observed between the two air masses. More recently, line-of-sight extinction variations with height have allowed the depth of the planetary boundary layer (PBL) to be examined by comparing morning and noon-time imaging. The top of the PBL can be seen as a change in the slope of the extinction. Below this change of slope, we observe that the PBL is well mixed with near constant extinction. The reduced extinction within the PBL may indicate that, in contrast to other Mars landing sites where mixing is implicated in dust lifting, that the relatively mild dynamics of mixing at Gale contribute to clearing of the PBL by enhancing the delivery of dust to the surface. Above the PBL, extinction increases rapidly. The PBL is typically seen to be shallower than the height of the crater rim, some 2 km above the crater floor. Not only was a suppressed PBL within Gale Crater predicted before landing, the fact that extinction is seen to increase above the PBL provides more evidence that the air mass above the crater initially supports more dust on average than the air lower down in the crater.

**Author(s): Casey A Moore3**, John E Moores3, Mark T Lemmon2, Jason Van Beek1
**Institution(s):** *1. Malin Space Science Systems, 2. Texas A&M University, 3. York University*

### 419.08 – Ice Cloud Optical Depth Mapping from MRO-CRISM Multispectral Data

The Mars Reconnaissance Orbiter (MRO) Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) multi-spectral mapping data are a reduced spectral sampling mapping set using only 72 of its 545 channels. This reduction allowed for greater spatial coverage and the creation of nearly complete maps after several sols of orbits. Using data from late 2006 through early 2008 I have created 6 such maps in order to measure ice cloud optical depth as a function of position for each of them. Optical depth is retrieved using a DISORT-based radiative transfer code[1]. One of the inputs for the code is surface reflectance which is not known at each point, a priori, but instead is fit from a linear combination of surface endmember spectra—the endmember coefficients for each endmember, along with dust and ice optical depth, are adjustable model parameters that are varied until the RMS error between model and data is a minimum. Surface spectral endmembers are recovered through a combination of principal component analysis (PCA) and target transformation (TT) which first reduces the dimensionality of the data (from 72 to 4) and then creates a data cloud in this space of possible potential endmembers derived from best fits of a spectral library [2–4]. The actual endmembers are chosen from extrema of this candidate cloud.
I will present six ice cloud optical depth maps made using this technique with a 3-endmember surface model.

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**Author(s): David R. Klassen1**
**Institution(s):** *1. Rowan Univ.*

### 419.09 – Detections and Sensitive Upper Limits for Methane and Related Trace Gases on Mars during 2003-2014, and planned extensions in 2016

Five groups report methane detections on Mars; all results suggest local release and high temporal variability [1-7]. Our team searched for $CH_4$ on many dates and seasons and detected it on several dates [1, 9, 10]. TLS (Curiosity rover) reported methane upper limits [6], and then detections [7] that were consistent in size with earlier reports and that also showed rapid modulation of $CH_4$ abundance.
[8] argued that absorption features assigned to Mars $^{12}CH_4$ by [1] might instead be weak lines of terrestrial $^{13}CH_4$. If not properly removed, terrestrial $^{13}CH_4$ signatures would appear on the blue wing of terrestrial $^{12}CH_4$ even when Mars is red-shifted – but they do not (Fig. S6 of [1]), demonstrating that terrestrial signatures were correctly removed. [9] demonstrated that including the dependence of $\delta^{13}CH_4$ with altitude did not affect the residual features, nor did taking $\delta^{13}CH_4$ as zero. Were $\delta^{13}CH_4$ important, its omission would have overemphasized the depth of $^{13}CH_4$ terrestrial absorption, introducing emission features in the residual spectra [1]. However, the residual features are seen in absorption, establishing their origin as non-terrestrial – [8] now agrees with this view.
We later reported results for multiple organic gases ($CH_4$, $CH_3OH$, $H_2CO$, $C_2H_6$, $C_2H_2$, $C_2H_4$), hydroperoxyl ($HO_2$), three nitriles ($N_2O$, $NH_3$, HCN) and two chlorinated species (HCl, $CH_3Cl$) [9]. Most of these species cannot be detected with current space assets, owing to instrumental limitations (e.g., spectral resolving power). However, the high resolution infrared spectrometers (NOMAD, ACS) on ExoMars 2016 (Trace Gas Orbiter) will begin measurements in late 2016. In solar occultation, TGO sensitivities will far exceed prior capabilities.
We published detailed hemispheric maps of $H_2O$ and HDO on Mars, inferring the size of a lost early ocean [10]. In 2016, we plan to acquire 3-D spatial maps of HDO and $H_2O$ with ALMA, and improved maps of organics with iSHELL/NASA-IRTF.
**References: [**1] Mumma et al. Sci09; [2] Formisano et al. Sci04; [3] Krasnopolsky et al. Icar04; [4] Fonti and Marzo A&A10; [5] Krasnopolsky, Icar12; [6] Webster et al. Sci13; [7] Webster et al. Sci15; [8] Zahnle et al. Icar11; [9] Villanueva et al. Icar13; [10] Villanueva et al. Sci15.

**Author(s): Michael J. Mumma2**, Geronimo L. Villanueva2, Robert E. Novak1
**Institution(s):** *1. Iona College, 2. NASA's GSFC*

### 419.10 – Longitudinal Maps of Mars' $O_2$ (singlet Delta) Emission for $L_s$=72.5° and $L_s$=88.0°

We report longitudinal maps of the $O_2$ (singlet Delta) emission rate (a tracer for high-altitude ozone) taken at two seasonal points, $L_s$=72.5° (03 April 2010) and $L_s$=88.0° (10 February 2014) using CSHELL at NASA's IRTF. On these dates, the entrance slit of the spectrometer was positioned E-W on Mars centered at the sub-Earth point, but, on 10 Feb 2014 additional spectra were taken with the slit positioned 3 arc seconds North of the sub-Earth point. On both dates, spectral/spatial images (near 1.27 microns) were repeatedly taken over a four-hour period. Spectral extracts from these images were taken at 0.6 arcsec intervals along the slit. A model consisting of solar continuum with Fraunhofer lines, two-way transmission through Mars' atmosphere, and a one-way transmission through the Earth's atmosphere was used to isolate and analyze individual spectral lines. Boltzmann analysis of these lines yielded the rotational temperature (~175 K) that was used to determine the total emission rate from the measured lines.
The slit on 03 Apr 2010 crossed the morning terminator, yielding measurements between 06:00-14:00 Local Time; on 10 Feb 2014, the slit went through the evening terminator (10:00-18:00 LT). For both dates, data were taken over a four-hour interval in UT. When displayed versus local time, the extracted emission rates reveal similar patterns of growth before mid-day and of decline before sunset, regardless of surface topography. The measured emission rates, that peak after noon local time, depend on the angles to both Sun and Earth. The post-noon emission rates (10 Feb 2014), vary with latitude, because they depend on the location of the hygropause.
This work was partially funded by grants from NASA's Planetary Astronomy Program (344-32-51-96), NASA's Astrobiology Program (344-53-51), and the NSF-RUI Program (AST-805540). We thank the administration and staff of the NASA-IRTF for awarding observing times and coordinating our observations.

**Author(s): Robert E. Novak[1]**, Michael J. Mumma[2], Geronimo L. Villanueva[2]
**Institution(s):** *1. Iona College, 2. NASA-GSFC*

### 419.11 – Diurnal and Interannual Variation in Absorption Lines of Isotopic Carbon Dioxide in Mars Atmosphere

Groundbased observations of Mars in 2003, 2007, 2012, and 2014 have detected transitions of carbon dioxide containing the stable minor isotopes of oxygen and carbon as well as the primary isotopes, using the ultrahigh resolution spectrometer HIPWAC at the NASA Infrared Telescope Facility. The most well characterized minor isotope is O-18, due to strong lines and observational opportunities. The average estimated O-18/O-16 isotope ratio is roughly consistent with other in situ and remote spectroscopic measurements but demonstrates an additional feature in that the retrieved ratio appears to increase with greater ground surface temperature. These conclusions primarily come from analyzing a subset of the 2007 data. Additional observations have been acquired over a broad range of local time and meridional position to evaluate variability with respect to ground surface temperature. These additional observations include one run of measurements with C-13. These observations can be compared to local in situ measurements by the *Curiosity* rover to narrow the uncertainty in absolute isotope ratio and extend isotopic measurements to other regions and seasons on Mars. The relative abundance of carbon dioxide heavy isotopes on Mars is central to estimating the primordial atmospheric inventory on Mars. Preferential freeze-distillation of heavy isotopes means that any measurement of the isotope ratio can be only a lower limit on heavy isotope enrichment due to past and current loss to space.

**Author(s): Timothy A. Livengood[1]**, Theodor Kostiuk[2], Tilak Hewagama3, John R. Kolasinski[2], Wade G. Henning[1]
**Institution(s):** *1. CRESST/UMD/GSFC, 2. NASA GSFC, 3. University of Maryland*

### 419.12 – The search for active release of volcanic gases on Mars

The study of planetary atmospheres by means of spectroscopy is important for understanding their origin and evolution. The presence of short-lived trace gases in the martian atmosphere would imply recent production, for example, by ongoing geologic activity. On Earth, sulfur dioxide ($SO_2$), sulfur monoxide (SO) and hydrogen sulfide ($H_2S$) are the main sulfur-bearing gases released during volcanic outgassing. Carbonyl sulfide (OCS), also released from some volcanoes on Earth (e.g., Erebus and Nyiragongo), could be formed by reactions involving $SO_2$ or $H_2S$ inside magma chambers. We carried out the first ground-based, semi-simultaneous, multi-band and multi-species search for such gases above the Tharsis and Syrtis volcanic regions on Mars. The submillimeter search extended between 23 November 2011 and 13 May 2012 which corresponded to Mars' mid Northern Spring and early Northern Summer seasons (Ls = 34–110°). The strong submillimeter rotational transitions of $SO_2$, SO and $H_2S$ were targeted using the high-resolution heterodyne receiver (aka Barney) on the Caltech Submillimeter Observatory. We reached sensitivities sufficient to detect a volcanic release on Mars that is 4% of the $SO_2$ released continuously from Kilauea volcano in Hawaii, or 5% that of the Masaya volcano in Nicaragua. The infrared search covered OCS in its combination band ($\nu_2+\nu_3$) at 3.42 µm at two successive Mars years, during Mars' late Northern Spring and mid Northern Summer seasons, spanning $L_s = 43^o$ and $L_s = 147^o$. The targeted volcanic districts were observed during the two intervals, 14 Dec. 2011 to 6 Jan. 2012 in the first year, and 30 May 2014 to 16 June 2014 in the second year, using the high resolution infrared spectrometer (CSHELL) on NASA's Infrared Telescope Facility (NASA/IRTF). We will present our results and discuss their implications for current volcanic outgassing activity on the red planet. We gratefully acknowledge support from the NASA Planetary Astronomy Program under NASA contract NNH14CK55B that supported A.K. and A.T., RTOP 344-32-07 and NASA's Astrobiology Program (RTOP 344-53-51) that supported M.J.M., and G.L.V.

**Author(s): Alain Khayat[2]**, Geronimo Villanueva[1], Michael Mumma3, Alan Tokunaga[2]
**Institution(s):** *1. Catholic University of America, 2. Institute for Astronomy, 3. NASA Goddard Spaceflight Center*

### 419.13 – Solar wind Mars interaction during the MAVEN Deep Dip campaigns: multi-fluid MHD simulations based upon the SWIA, NGIMS and MAG measurements

The 3-D Mars multi-fluid Block Adaptive Tree Solar-wind Roe Upwind Scheme (BATS-R-US) MHD code is used to study the solar wind interaction with the Martian upper atmosphere during the MAVEN Deep Dip campaigns. MAVEN made the first comprehensive measurements of Martian thermosphere and ionosphere composition, structure, and variability at altitudes down to ~130 km in the subsolar region during the second of its Deep Dip campaigns. MAVEN will start its fourth Deep Dip campaign this September and a large quantity of useful data will be returned for this study as well. In this study we adopt the MAVEN measurements as the multi-fluid MHD inputs. The estimated solar wind density and velocity, the estimated interplanetary magnetic field (IMF), and the exactly measured neutral atmosphere profile are taken from the SWIA, MAG and NGIMS instruments, respectively. We will compare the calculated ionosphere ion profiles with the NGIMS measurements. In the meantime, we will show the calculations of the global ion escape rates based upon actual measured neutral atmosphere profiles during the MAVEN Deep Dip campaigns.

**Author(s): Chuanfei Dong[6]**, Stephen W Bougher[6], Yingjuan Ma3, Gabor Toth[6], Shannon M. Curry[2], Andrew F. Nagy[6], Jasper S. Halekas5, Janet G. Luhmann[2], Paul Mahaffy[1], Mehdi Benna[1], Jack E. P. Connerney[1], Jared Espley[1], David L. Mitchell[2], David A. Brain4, Bruce M. Jakosky4
**Institution(s):** *1. NASA Goddard Space Flight Center, 2. University of California, 3. University of California, 4. University of Colorado, 5. University of Iowa, 6. University of Michigan*

### 419.14 – He Bulge Detection by MAVEN Neutral Gas and Ion Mass Spectrometer (NGIMS) in the Upper Atmosphere of Mars

Studies of the Venusian atmospheres have demonstrated enhanced He densities at high latitudes and on the night-side detections. To determine if Mars has a similar enhanced He 'bulge' in the same region, we compared several periapsis passes from night to dayside. The first six weeks of the MAVEN prime mission had periapsis at high latitudes on the night-side, followed by the next three months at mid latitudes on the dayside moving to low latitudes on the night-side. In addition to its normal orbit, which has a periapsis of approximately 150 km, MAVEN conducts a few deep dip orbits where the spacecraft has a periapsis closer to 125km. The first deep dip was at dusk at mid latitudes, the second at noon at the equator, with the third going from dawn to night in the southern hemisphere. Initial analysis of the Neutral Gas and Ion Mass Spectrometer (NGIMS) closed source data from all orbits with good pointing revealed an enhanced He density on the night-side orbits and a decreased He density on the dayside. This enhancement of He demonstrates a bulge at Mars that will continue to be explored over the course of the mission.

**Author(s): Meredith K Elrod[1]**, Paul R Mahaffy[1], Roger Yelle[2], Shane Stone[2], Mehdi Benna[1], Bruce Jakowski3
**Institution(s):** *1. NASA Goddard SFC, 2. University of Arizona, 3. University of Colorado, Boulder*

### 419.15 – New Observations of Molecular Nitrogen by the Imaging Ultraviolet Spectrograph on MAVEN

The Martian ultraviolet dayglow provides information on the basic state of the Martian upper atmosphere. The Imaging Ultraviolet Spectrograph (IUVS) on NASA's Mars Atmosphere and Volatile Evolution (MAVEN) mission has observed Mars at mid and far-UV wavelengths since its arrival in September 2014. In this work, we describe a linear regression method used to extract components of UV spectra from IUVS limb observations and focus in particular on

molecular nitrogen ($N_2$) photoelectron excited emissions. We identify $N_2$ Lyman-Birge-Hopfield (LBH) emissions for the first time at Mars and we also confirm the tentative identification of $N_2$ Vegard-Kaplan (VK) emissions. We compare observed VK and LBH limb radiance profiles to model results between 90 and 210 km. Finally, we compare retrieved $N_2$ density profiles to general circulation (GCM) model results. Contrary to earlier analyses using other satellite data that indicated $N_2$ densities were a factor of three less than predictions, we find that $N_2$ abundances exceed GCM results by about a factor of two at 130 km but are in agreement at 150 km.

**Author(s): Michael H. Stevens7**, J. S. Evans2, Nicholas M Schneider4, A.I.F Stewart4, Justin Deighan4, Sonal K. Jain4, Matteo M.J. Crismani4, Arnaud Stiepen4, Michael S. Chaffin4, William E. McClintock4, Greg M.. Holsclaw4, Franck Lefevre5, Franck Montmessin5, Daniel Y. Lo6, John T. Clarke1, Stephen W. Bougher3, Bruce M. Jakosky4
**Institution(s):** *1. Center for Space Physics, Boston University, 2. Computational Physics, Inc., 3. Department of Climate and Space Sciences and Engineering, University of Michigan, 4. Laboratory for Atmospheric and Space Physics, 5. LATMOS/CNRS, 6. Lunar and Planetary Laboratory, University of Arizona, 7. Space Science Division, Naval Research Laboratory*

## 419.16 – Two Types of Aurora on Mars as Observed by MAVEN's Imaging UltraViolet Spectrograph

The Imaging UltraViolet Spectrograph (IUVS) on the MAVEN spacecraft has detected two distinct types of auroral emission on Mars. First, we report the discovery of a low altitude, diffuse aurora spanning much of Mars' northern hemisphere coincident with a solar energetic particle outburst. IUVS observed northerly latitudes during late December 2014, detecting auroral emission in virtually all nightside observations for ~5 days spanning virtually all geographic longitudes. The vertical profile showed emission down to ~70 km altitude (1 microbar), deeper than confirmed at any other planet. The onset and duration of emission coincide with the observed arrival of solar energetic particles up to 200 keV precipitating directly and deeply into the atmosphere. Preliminary modeling of the precipitation, energy deposition and spectral line emission yields good matches to the observations. These observations represent a new class of planetary auroras produced in the Martian middle atmosphere. Given minimal magnetic fields over most of the planet, Mars is likely to exhibit aurora more globally than Earth.
Second, we confirm the existence of small patches of discrete aurora near crustal magnetic fields in Mars' southern hemisphere, as observed previously by SPICAM on Mars Express (Bertaux et al., Nature, 435, 790-794 (2005)). IUVS observed southern latitudes in July and August 2015, detecting discrete auroral emission in ~1% of suitable observations. Limb scans resolved both vertically and along-slit indicate this type of auroral emission was patchy on the scale of ~40 km, and located at higher altitudes ~140 km. The higher altitudes imply a lower energy of precipitating particles. The mix of spectral emissions also differed signficiantly from the diffuse aurora, indicating different excitation and quenching processes. We will discuss the observed properties of the aurora and associated charged particle precipitation, as well as the broader implications of this high-energy deposition into Mars' atmopshere.

**Author(s): Nicholas M. Schneider4**, J. Deighan4, S.K. Jain4, A. Stiepen4, D. Larson7, D.L. Mitchell7, C.O. Lee7, R. Lillis7, D. Brain4, W.E. McClintock4, M.S. Chaffin4, M. Crismani4, G.M. Holsclaw4, B.M. Jakosky4, C. Mazelle2, J.S. Evans3, A.I.F. Stewart4, M.H. Stevens6, J.T. Clarke1, F. Montmessin5, F. Lefevre5, D. Lo4
**Institution(s):** *1. Center for Space Physics, Boston University, 2. CNRS, Institut de Recherche en Astrophysique et Planétologie, France, 3. Computational Physics, Inc., 4. LASP, Univ. of Colorado, 5. LATMOS/IPSL, 6. Space Science Division, Naval Research Laboratory, 7. Space Sciences Lab, University of California at Berkeley*

## 419.17 – Combined analysis of Far UV and Mid UV spectra obtained by the MAVEN IUVS instrument in a Stellar Occultation Mode

In this presentation, we will focus on the results obtained by the Imaging Ultraviolet Spectrograph (IUVS) onboard the Mars Atmosphere and Volatile and Evolution (MAVEN) mission while performing stellar occultations observations. In the IUVS wavelength range, $CO_2$ possesses a distinct and broad signature shortward of 200 nanometers which allows one to retrieve $CO_2$ concentration and subsequently to deduce atmospheric pressure and temperature profiles from 30 to 150 km of altitude (upper troposphere up to the thermosphere) as well as the concentration of other atmospheric consitituents (clouds/aerosols, ozone and molecular oxygen). The occultation technique relies on the determination of atmospheric transmission at various altitudes above the surface. Only relative measurements are needed to infer species abundances, and thus the method is self-calibrated.
The ratio of spectra taken through (close to Mars) and outside (far from Mars) the atmosphere gives an atmospheric transmission at each altitude. If any absorbing or/and scattering species is present along the optical path, photons are lost and resulting transmissions are lower than 1. The sampling rate yields a vertical resolution typically greater than 3 km on the vertical. For Mars, the sounded region inside which a quantity of atmospheric constituents can be derived lies generally between 20 and 150 km depending on the atmospheric state (dust loading). The compiled dataset has already yielded a variety of results, showing high concentrations of ozone in the deep polar night as well as the detection of a highly elevated aerosol layer potentially made of $CO_2$ ice.

**Author(s): Franck Montmessin2**, Hannes Groeller4, Gaétan Lacombe2, Nicholas M. Schneider3, Roger Yelle4, Ian Stewart3, Justin Deighan3, John Clarke1, Franck Lefevre2, Lucio Baggio2, William E. McClintock3, Gregory M. Holsclaw3, Bruce M. Jakosky3
**Institution(s):** *1. Boston University, 2. CNRS LATMOS, 3. LASP, 4. LPL*

## 419.18 – MAVEN/IUVS Observations of the Gaseous Perturbation from Comet C/2013 A1 (Siding Spring) on Mars and its Constant Metallic Ion Layer

The close passage of comet C/2013 A1 (Siding Spring) by Mars afforded the newly arrived Mars Atmosphere and Volatile EvolutioN (MAVEN) mission the opportunity to observe a cometary perturbation to the upper atmosphere. The most dramatic atmospheric effect was the ablation of cometary dust that produced a transient metallic ion layer near 120 km, higher than the predicted (90 km) constant metallic ion layer from sporadic dust ablation due to the extreme relative velocity of the comet (56 km/s). Additionally, cometary gases such as $H_2O$, $CO_2$ and their daughter species delivered mass and energy to the upper atmosphere, where the temperature at 150 km was predicted to increase by 30 K.
The Imaging Ultraviolet Spectrograph (IUVS) on MAVEN takes limb scans at periapse to construct altitude profiles of various ultraviolet species. Using a Multiple Linear Regression (MLR) technique to extract spectral features, we analyze the observations of the perturbed atmosphere to determine whether the gaseous mass and energy deposition is distinguishable within typical atmospheric variation. Furthermore, we use all subsequent dayside observations to identify the metallic ion layer, represented by the presence of $Mg^+$, and compare these observations with a robust numerical model of ablation, CAMBOD (Chemical Ablation Model).

**Author(s): Matteo Michael James Crismani1**, Nicholas Schneider1, Sonal Jain2, John Plane3, Justin Deighan2
**Institution(s):** *1. CU Boulder, 2. Laboratory for Atmospheric and Space Physics, 3. University of Leeds*

## 419.19 – The ExoMars 2016 mission

The ExoMars programme is a joint activity by the European Space Agency (ESA) and ROSCOSMOS, Russia. It consists of the ExoMars 2016 mission with the Trace Gas Orbiter, TGO, and the Entry Descent and Landing Demonstrator, Schiaparelli, and the

Exomars 2018 mission which carries a lander and a rover.
The TGO scientific payload consists of four instruments. These are: ACS and NOMAD, both infrared spectrometers for atmospheric measurements in solar occultation mode and in nadir mode, CASSIS, a multichannel camera with stereo imaging capability, and FREND, an epithermal neutron detector for search of subsurface hydrogen. ESA is providing the TGO spacecraft and the Schiaparelli Lander demonstrator and two of the TGO instruments and ROSCOSMOS is providing the launcher and the other two TGO instruments.
After the arrival of the ExoMars 2018 mission at the surface of Mars, the TGO will handle the communication between the Earth and the Rover and lander through its UHF communication system. The 2016 mission will be launched by a Russian Proton rocket from Baikonur in January 2016 and will arrive at Mars in October the same year. This presentation will cover a description of the 2016 mission, including the spacecraft, its payload and science and the related plans for scientific operations and measurements.

**Author(s): Håkan Svedhem[1]**, Jorge Vago[1], Rolf de Groot[1]
**Institution(s):** *1. ESA/ESTEC*

### 419.20 – Self- and $CO_2$-broadened line shape parameters for infrared bands of HDO

Knowledge of $CO_2$-broadened HDO line widths and their temperature dependence is required to interpret infrared spectra of the atmospheres of Mars and Venus. However, this information is currently absent in most spectroscopic databases. We have analyzed nine high-resolution, high signal-to-noise spectra of HDO and HDO+$CO_2$ mixtures to obtain broadening coefficients and other line shape parameters for transitions of the $\nu_2$ and $\nu_3$ vibrational bands located at 7.13 and 2.70 μm, respectively. The gas samples were prepared by mixing equal amounts of high-purity distilled $H_2O$ and 99% enriched $D_2O$. The spectra were recorded at different temperatures (255-296 K) using a 20.38 cm long coolable cell [1] installed in the sample compartment of the Bruker IFS125HR Fourier transform spectrometer at the Jet Propulsion Laboratory in Pasadena, CA. The retrieved HDO spectroscopic parameters include line positions, intensities, self- and $CO_2$-broadened half-width and pressure-induced shift coefficients and the temperature dependences for $CO_2$ broadening. These spectroscopic parameters were obtained by simultaneous multispectrum fitting [2] of the same interval in all nine spectra. A non-Voigt line shape with speed dependence was applied. Line mixing was also observed for several transition pairs. Preliminary results compare well with the few other measurements reported in the literature.

[1] K. Sung et al., *J. Mol. Spectrosc.* **162**, 124-134 (2010).
[2] D. C. Benner et al., *J. Quant. Spectrosc. Radiat Transfer* **53**, 705-721 (1995).

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**Author(s): Mary-Ann H. Smith[4]**, V. Malathy Devi[5], D. Chris Benner[5], Keeyoon Sung[2], Arlan W. Mantz[1], Robert R. Gamache[6], Geronimo L. Villanueva[3]
**Institution(s):** *1. Connecticut College, 2. Jet Propulsion Laboratory, California Institute of Technology, 3. NASA Goddard Space Flight Center, 4. NASA Langley Research Center, 5. The College of William and Mary, 6. University of Massachusetts*

### 419.21 – Simulating Helium abundances in the Martian upper atmosphere using 1-D and 3-D models

Chemically inert species, such as Helium, serve as an excellent tracer for the interplay between turbulent eddy diffusive processes and molecular diffusive processes. Using species such as Helium, we can effectively constrain the altitude of the homopause—or the transition from the well-mixed lower atmosphere to the mass-separation characteristic of the upper atmosphere. In this study, we will use the Mars Global Ionosphere-Thermosphere Model (M-GITM) to examine the impacts of altering the turbulent diffusion coefficient (eddy diffusion coefficient) on the simulated abundances of Helium. Using data obtained by the Neutral Gas and Ion Mass Spectrometer (NGIMS) onboard the Mars Atmosphere and Volatile Evolution (MAVEN) mission as a benchmark, we can examine what possible values for eddy diffusion in the thermosphere are most likely present in Mars's upper atmosphere—in other words, we can assess where the mean homopause altitude is most likely located during the MAVEN mission. Furthermore, we will compare and contrast the results obtained when using a strictly classical, 1-D treatment of the problem with a more complete coupled, global 3-D treatment of the Martian atmosphere.

**Author(s): Jared M Bell[2]**, S. W. Bougher[3], Paul Mahaffy[1], Meredith Elrod[1]
**Institution(s):** *1. Goddard Space Flight Center, 2. National Institute of Aerospace, 3. University of Michigan*

### 419.22 – Boundary location of Mars nightside ionospheric plasma in term of the electron density

Photo-ionized Mars atmosphere is forming an ionosphere and shielding the solar wind with creating barriers of bow shock. Inside the bow shock ionospheric plasma interact with solar wind plasma and result different boundaries. A question is how far the ionospheric plasma can stand off the solar wind.
On the dayside, *in-situ* data set from Mars magnetosphere missions often observed the sharp gradient of the thermal plasma flux and ion composition change as well as the drop off of the magnetic fluctuation simultaneously as a outer boundary of the ionospheric plasma and an obstacle to the solar wind. Several models have constructed the shape of the boundary based on the statistical observations [e.g., Trotignon et al., 2006; Edberg et al., 2008].
On the nightside, plasma instrument onboard Phobos 2 observed the particles and magnetic field characteristics similar to the dayside. However, the number of data is still too few to understand the general location of boundaries. We will present the characteristics of the nightside magnetospheric boundary region in term of the electron density. MAVEN Langmuir probe measurement (LPW) can estimate the electron density using the spacecraft environment. As MAVEN pass from the bow shock and sheath region into the magnetosphere the electron density often show a sharp gradient (the density jumps two orders of magnitudes in a few seconds). Comparing this to the data from particle instrument, the sharp electron density gradient was often associated with the transition of the characteristic energy of ions. Several hundreds of boundaries crossing by MAVEN allow us to investigate the statistical view of the boundary. We searched for a large electron density gradient as an indicator of the plasma boundary to identify the location of the ionospheric/solar wind plasma boundary. The results show that the many of the nightside boundaries locates close to the tail region of Mars forming elliptical shape of boundary. We will provide the empirical model of this boundary location and discuss the influence of solar wind.

**Author(s): Michiko W. Morooka[2]**, Laila Andersson[2], Bob Ergun[2], Christopher Fowler[2], Adam Woodson[2], Tristan Weber[2], Greg Delory[4], David Andrews[6], Niklas Edberg[6], Anders Eriksson[6], David Michell[5], Jack Connerney[3], Jacob Gruesbeck[3], Jasper Halekas[1]
**Institution(s):** *1. Department of Physics and Astronomy, University of Iowa, 2. Laboratory for Atmospheric and Space Physics, University of Colorado at Boulder, 3. NASA/GSFC, 4. Space Sciences Laboratory & Center for Integrative Planetary Sciences, University of California, Berkeley, 5. Space Sciences Laboratory, University of Calfolnia, Berkeley, 6. Swedish Institute of Space Physics*

### 419.23 – Examining Traveling Waves in Mars Atmosphere Reanalyses

Synoptic-scale eddies (traveling waves) are a key feature of the variability of Mars atmosphere weather in the extratropics, and are linked to the initiation of dust storms. Mars reanalyses, which combine satellite observations with simulations from a Mars Global Climate Model (MGCM), provide a four-dimensional picture of the evolution of these waves in terms of temperature, winds, pressure, and aerosol fields. The Ensemble Mars Atmosphere Reanalysis System (EMARS) has created multiple years of Mars weather maps through the assimilation of Thermal Emission Spectrometer (TES) and Mars Climate Sounder (MCS) temperature profiles using the ensemble Kalman filter and the GFDL MGCM. We investigate the robustness of the synoptic eddies to changes in the aerosol fields, model parameters, data assimilation system design, and observation dataset (TES vs. MCS). We examine the evolution of wavenumber regimes, their seasonal evolution, and interannual variability. Finally, reanalysis fields are combined with spacecraft visible imagery (e.g. MGS Mars Orbital Camera), demonstrating the link between meteorological fields (temperature, pressure, and wind) and dust fronts.

**Author(s): Steven J. Greybush[2]**, R. John Wilson[1]
**Institution(s):** *1. GFDL, 2. The Pennsylvania State University*

### 419.24 – Abiotic production of NO3 in the atmosphere of Early Mars

Recent Curiosity/SAM measurements of Martian sediments have shown the presence of NO3 trapped in the samples. The ratio of nitrate to perchlorate has been suggested to be an indicator for habitability (Stern et al. 2015). However, the efficiency of the production of nitrate in the atmosphere has never been studied for the case of the active young Sun. To evaluate the effect of the abiotic production of nitrates, we apply our 1D atmospheric photochemical collisional model for the nitrogen-rich and CO2 atmosphere of early Mars, and calculate the production rate of NO3 mediated by the precipitation of energetic particles associated with the coronal mass ejections from the young Sun.
We propose a method to check the hypothesis of the abiotic production: if the production is driven by the precipitating particles, then the magnetic shielding would reduce the NO3 production at the equator. Thus, samples collected at high latitudes should contain greater concentration of nitrates if the weathering did not homogenize it.

**Author(s): Guillaume Gronoff[2]**, vladimir airapetian[1], Eric Hebrard[1]
**Institution(s):** *1. NASA GSFC, 2. SSAI/ Nasa LaRC*

### 419.25 – New Approaches in estimating Dust Devil Parameters, Trajectories and Populations from Single-Station Measurements on Mars and Earth

A Monte-Carlo modeling approach (Lorenz, J. Atm. Sci., 2014) using a power law population function and empirical correlations between diameter and longevity can be used to reconcile single-station pressure records of vortex close-approaches with visual counts of dust devils and Large Eddy Simulations (LES). That work suggests that on Earth, the populations can be reconciled if dust-lifting occurs with a typical threshold corresponding to core pressure drop of 0.8 mb, a little higher than the ~0.3 mb estimated in laboratory experiments. A similar analysis can be conducted at Mars. The highest vortex production rates in LES, indicated from field encounters, and extrapolated from visual counts, appear to be of the order of 1000 per km2 per day.
Recent field experiments at a playa near Goldstone, CA (Lorenz et al., Bulletin of the Seismological Society of America, in press) show that dust devils cause a ground tilt, due to the negative pressure load of the vortex on the elastic ground, that can be detected with a broadband seismometer like that on InSight. Dust devils therefore can serve as a ‘seismic source’ to characterize the shallow subsurface.
Observations of the InSight landing area in Elysium by Reiss and Lorenz (Icarus, submitted) show that dust devil trails are abundant, but smaller in diameter than those at Gusev. This may indicate a shallower Planetary Boundary Layer (PBL) at this site and season : Fenton and Lorenz (Icarus, 2015) found that observed dust devil height and spacing in Amazonis relates to the PBL thickness.
Quantitative assessment of dust devil effects (e.g. electrical and magnetic signatures) requires knowledge of encounter geometry, notably miss distance. A recent heuristic approach has been developed (Lorenz, Icarus, submitted) to fit an analytic vortex model to pressure, windspeed and direction histories to recover this geometry. Some ambiguities exist, but can be constrained with camera images and/or the azimuth history estimated from seismic data.

**Author(s): Ralph Lorenz[1]**
**Institution(s):** *1. JHU/APL*

### 419.26 – Response of the Martian induced magnetosphere to variations in solar forcing

Solar forcing and compression of Mars' induced magnetosphere may play an important role in oxygen loss at Mars via enhanced ionization and heating of the lower atmosphere, and in the formation of ambipolar electric fields in the upper atmosphere. Steep electron temperature gradients in the upper atmosphere can produce strong ambipolar fields at altitudes where collisions are infrequent, leading to increased outflow of $O^+$ and $O_2^+$. Such enhanced escape has been observed in simulations of Mars’ ionosphere where the ambipolar field was artificially varied to study its influence on escape. It is important, therefore, to understand how solar wind forcing modulates electron density- and temperature-versus-altitude profiles in Mars' ionosphere.
During the first five days of May 2015, MAVEN’s Langmuir Probe and Waves Instrument (LPW) observed variations in the location and extent of the transition region between the shocked solar wind and the Martian ionosphere in the dayside hemisphere. Solar wind densities and velocities derived from MAVEN’s Solar Wind Ion Analyzer (SWIA) indicate that the solar wind dynamic pressure was also highly variable during this period. In this work we investigate how the shapes of the electron density- and temperature-versus-altitude profiles measured by LPW depend on the location and extent of the transition region as determined from Solar Wind Electron Analyzer (SWEA) spectra, and on solar wind forcing as determined from SWIA and MAVEN Magnetometer (MAG) measurements over this five-day period.

**Author(s): Adam Woodson[1]**, Tristan Weber[1], Laila Andersson[1], Robert Ergun[1], David Andrews3, Tiffany Chamandy[1], John Connerny[2], Greg Delory5, Anders Eriksson3, Christopher Fowler[1], Jasper Halekas4, Paul Mahaffy[2], David Mitchell5, Michiko Morooka[1]
**Institution(s):** *1. CU Boulder Laboratory for Atmospheric and Space Physics, 2. NASA Goddard Space Flight Center, 3. Swedish Institute of Space Physics, 4. U Iowa Department of Physics and Astronomy, 5. UC Berkely Space Sciences Laboratory*

## 420 – Mars: Surface and Interior

### 420.01 – First results of the PlanetFour Citizen Science project

PlanetFour (http://www.planetfour.org) is a Citizen Science project about analyzing surface images from the south pole of Mars. Main objectives are studying the surface atmosphere interactions at the pole, especially during the local spring. CO2 gas jets that are created by basal sublimation of the seasonal CO2 ice layer deposit fine dust into the atmosphere and coarser regolith on top of the ice sheet in form of fan-shaped albedo features The fine dust that entered the atmosphere is believed to have an important effect on the atmospheric temperature profile. The seasonal removal of regolith over many years results in topographical features called araneiform. These are dendritic troughs that connect to a common center. Their constant modification represents ongoing change in the surface topography of Mars today.
A further objective is to map the orientations of the regolith deposits. These orientations are controlled by the local winds that existed at the time of jet eruption. Repeated surface observations constrain the time of eruption and are therefore able to provide wind data points for atmospheric meso-scale simulations.

The image data used in the PlanetFour project comes from the HiRISE camera of the Mars Reconnaissance Orbiter. Planet Four citizens are asked to identify and outline fans in the presented tiles. We cluster the resulting markings into final locations using the DBScan clustering algorithm, after which the object coordinates are back-projected into latitude and longitude coordinates with a standard ISIS image calibration pipeline.
Outcomes are catalogs of object locations, estimated sizes and wind directions. With these catalogs we study the activity over time per region, compare these activity time-series between seasons and compare the strength of observed activity between different regions around the pole. The derived wind directions are used to improve atmospheric meso-scale simulations at Mars' south pole, which is part of an ongoing NASA SSW project. We will present results from the first publication of the PlanetFour project.

**Author(s): Klaus-Michael Aye3**, Meg Schwamb[1], Ganna Portyankina3, Candice J Hansen[2]
**Institution(s):** *1. Institute of Astronomy & Astrophysics, Academia Sinica, 2. Planetary Science Institute, 3. University of Colorado Boulder*

### 420.02 – Mineralogical Stratigraphy of Ganges Chasma, Mars

Mars' Valles Marineris canyon system reveals a several-kilometer deep stratigraphies sequence that extends thousands of kilometers; this sequence thus represents a unique opportunity to explore millions of years of volcanic and aqueous activity in this region of Mars. Of particular interest to the study of both volcanic and aqueous processes is Ganges Chasma, which lies on the northeastern boundary of the Valles Marineris canyon system on Mars. The canyon likely opened during the Late Noachian to Early Hesperian, modifying previously emplaced Noachian-aged volcanic plains. During formation, volcanic activity from the nearby Tharsis shield complex emplaced olivine-rich dikes throughout the region. After formation, sulfate-bearing Interior Layered Deposits (ILDs) were emplaced in Ganges and many other chasmata throughout the Valles Marineris system. Today, Ganges reveals a complex stratigraphy, including wide-spread olivine-rich sands, hydrated minerals on the plateaus surrounding the canyon, and a central sulfate-rich ILD. Here, we present updated stratigraphies of Ganges Chasma, using new data from the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM), and synthesizing it with previous data sets. Olivine sands are traced back to source outcrops on the canyon floor, and new outcrops of hydrated minerals on the surrounding plateau are identified and mapped. Recently reported spectroscopic signatures of ankerite and smectite in the chasm are assessed, and new olivine-rich outcrops identified and mapped. Understanding the stratigraphy of Ganges Chasma will help us compare stratigraphies among the chasmata of the Valles Marineris, further building our understanding of the geologic history of this large region of Mars.

**Author(s): Selby Cull-Hearth[1]**, M. Caroline Clark[1]
**Institution(s):** *1. Bryn Mawr College*

### 420.03 – ChemCam at Gale Crater: Highlights and Discoveries from Three Years of Chemical Measurements on Mars

ChemCam has undertaken a detailed chemical investigation of the rocks and soils at Gale crater over the last three years with over six thousand separate geochemical measurements. Recent recalibration of the ChemCam data using a new library of >350 geochemical standards has enabled increased elemental accuracies over a wider compositional range. The increased accuracy combined with ChemCam's small spot size allows for the chemistry of mineral end members including feldspars, high silica, oxide rich grains to be identified. ChemCam has observed both sedimentary and igneous compositions. Igneous compositions are generally present in conglomerates and in float rocks. Compositions show a wide range of igneous chemistry ranging from basaltic to feldspar rich assemblages.
Sedimentary rocks have a wide range of compositions reflecting both differences in chemical source regions and in depositional and diagenetic histories. The "Sheepbed" mudstones cluster around Martian average crustal compositions. The "Kimberley" outcrop showed enhanced potassium reaching concentrations up to ~6 wt% $K_2O$. More recent observations in the Murray Formation at the base of Mt. Sharp reveal mudstones that are lower in magnesium and higher in silica and aluminum than the more basaltic mudstones previously investigated. Extremely high silica (75-85 wt%) deposits have also been identified. The high silica observations were associated with increased $TiO_2$, While the Murray mudstones are generally low in magnesium, local enhancements in magnesium have also been noted associated with resistant facies in the outcrop. Chemical trends also indicate that iron oxide phases may also be present as cements. Sandstone facies with a mafic composition are also present. Veins in the unit also show a wide range of compositions indicating fluid chemistries rich in calcium sulfate, fluorine, magnesium and iron were present. Vein chemistry could be the result of distinct fluids migrating through from a distance with a pre-established chemical signature, fluids locally evolved from water rock interactions, or both. Thus the chemical relationships between the Pahrump bedrock and the veins' chemistry can be used to constrain the origin of the fluids.

**Author(s): Diana L. Blaney[8]**, Roger Wiens5, Sylvestre Maurice[12], Olivier Gasnault[12], Ryan Anderson[18], John Bridges[15], Nathan Bridges[1], Samuel Clegg5, Benton Clark[11], Bethany Ehlmann[2], Melinda D Dyar[6], Martin Fisk9, Raymond Francis[8], Cecile Fabre[13], Olivier Forni[12], Jens Frydenvang[14], Jeffery Johnson[1], Nina Lanza5, Richard Leveille4, Jeremie Lasue[12], Laetitia Le Deit[17], Nicholas Mangold[17], Noureddine Melikechi3, Marion Nachon[17], Horton Newsom[16], Valerie Payre[13], William Rapin[12], Violane Sautter7, David Vaniman[10], John Grotzinger[2], Ashwin Vasavad[8], Joy Crisp[8]
**Institution(s):** *1. Aplied Physics Laboratory, 2. California Institute of Technology, 3. Deleware State University, 4. John H. Chapman Space Centre, 5. Los Alamos National Laboratory, 6. Mount Holyoke College, 7. Museum National d'Historie Naturelle, 8. NASA Jet Propulsion Laboratory, California Institute of Technology, 9. Oregon State University, 10. Planetary Science Institute, 11. Space Science Institute, 12. Université Paul Sabatier; UPS-OMP; Institute de Recherche en Astrophysique et Planetologie (IRAP), 13. University Lorraine, 14. University of Copenhagen, 15. University of Leicester, 16. University of New Mexico, 17. Univertisty of Nantes, 18. US Geologic Survey*

### 420.04 – Sub-surface gas flow in porous bodies

Gas flow within porous media is of importance for various bodies in the Solar System. It occurs within the Martian soil, might be significant in the porous interiors of comets and also within dusty planetesimals in the Solar Nebula. In regimes of low atmospheric pressure, thermal creep leads to an efficient gas flux if temperature gradients are present, e.g. by solar insolation. This flow can lead to erosion or supports the exchange of volatiles within a porous body. Experiments showed that this gas flux dominates over diffusive gas transport under Martian conditions with gas velocities on the order of cm/s. Results from the Rosetta spacecraft suggest that eolian processes occur on comets which might be related to thermal creep gas flow. Here, we present new results of microgravity experiments on a thermally induced gas flow. Gas velocities and their dependence on the atmospheric pressure for different gases (Helium and air) are studied as well as the influence of the geometry of the pores.

**Author(s): Jens Teiser[1]**, Mathias Schywek[1], Caroline de Beule[1], Gerhard Wurm[1]
**Institution(s):** *1. University Duisburg-Essen*

### 420.05 – Permeability Barrier Generation in the Martian Lithosphere

Permeability barriers develop when a magma produced in the interior of a planet rises into the cooler lithosphere and crystallizes more rapidly than the lithosphere can deform (Sparks and Parmentier, 1991). Crystallization products may then clog the porous network in which melt is propagating, reducing the permeability to almost zero, i.e., forming a permeability barrier.

Subsequent melts cannot cross the barrier. Permeability barriers have been useful to explain variations in crustal thickness at mid-ocean ridges on Earth (Magde et al., 1997; Hebert and Montési, 2011; Montési et al., 2011). We explore here under what conditions permeability barriers may form on Mars.
We use the MELTS thermodynamic calculator (Ghiorso and Sack, 1995; Ghiorso et al., 2002; Asimow et al., 2004) in conjunction with estimated Martian mantle compositions (Morgan and Anders, 1979; Wänke and Dreibus, 1994; Lodders and Fegley, 1997; Sanloup et al., 1999; Taylor 2013) to model the formation of permeability barriers in the lithosphere of Mars. In order to represent potential past and present conditions of Mars, we vary the lithospheric thickness, mantle potential temperature (heat flux), oxygen fugacity, and water content.
Our results show that permeability layers can develop in the thermal boundary layer of the simulated Martian lithosphere if the mantle potential temperature is higher than ~1500°C. The various Martian mantle compositions yield barriers in the same locations, under matching variable conditions. There is no significant difference in barrier location over the range of accepted Martian oxygen fugacity values. Water content is the most significant influence on barrier development as it reduces the temperature of crystallization, allowing melt to rise further into the lithosphere. Our lower temperature and thicker lithosphere model runs, which are likely the most similar to modern Mars, show no permeability barrier generation. Losing the possibility of having a permeability barrier likely changed the character of volcanism on Mars, maybe preventing the formation of new localized volcanic edifices in the Amazonian.

**Author(s): Joe Schools[1]**, Laurent Montési[1]
**Institution(s):** *1. University of Maryland*

### 420.06 – New estimates of the Martian landers and rovers coordinates by combining Doppler data and topography model

We propose here a new method to determine the three coordinates of a spacecraft landed on Mars with a high accuracy as early as the very beginning of the mission. The method consists of determining first the in-equatorial plane coordinates with Doppler data only and then inferring the Z-coordinate (along the polar axis) using the MOLA topography model. The method is applied to several landed missions, providing good estimate of the Z-coordinate of Viking lander 1, Pathfinder and Spirit, but failing to improve the Z of Opportunity and Viking lander 2. Finally, the method is applied in the InSight landing ellipse showing the high probability to get InSight's Z coordinate with a precision better than 10m after only a couple of days of observations.

**Author(s): Sebastien Le Maistre[1]**
**Institution(s):** *1. Jet Propulsion Laboratory*

## 500 – Comet 67P/C-G -- Nucleus

### 500.01 – Mass, Density and Composition of the Nucleus 67P/Churyumov-Gerasimenko

Cometary nuclei consist mostly of dust and water ice, but the internal structure of a comet nucleus is essentially unknown. Bulk properties such as mass, volume (size and shape), and particularly the density, must be known for constraining its internal structure. The radio science experiment RSI on the Rosetta spacecraft derived the mass and the gravity field of comet 67P/Churyumov-Gerasimenko at distances varying between 100 km and 10 km, and together with the current best estimates of the volume by the OSIRIS camera, the bulk density of the nucleus. A model of the internal structure is derived from the information of two shape models by comparing observed and theoretical gravity coefficients. The comet nucleus appears to be a body of low mass, low density and high porosity with approximately four times more dust than ice by mass and 1.5 times more dust than ice by volume.

**Author(s): Martin Paetzold[6]**, Tom Andert7, Matthias Hahn[6], Sami W. Asmar3, Jean-Pierre Barriot[8], Michael K. Bird[6], Bernd Häusler7, Kerstin Peter[6], Silvia A. Tellmann[6], Eberhard Grün[1], Paul Weissman3, Holger Sierks5, Laurent Jorda4, Frank Preusker[2], Frank Scholten[2]
**Institution(s):** *1. Max-Planck-Institute for Nuclear Physics, 2. Institut für Planetenforschung, DLR-Berlin-Adlershof, 3. Jet Propulsion Laboratory, Caltech, 4. Laboratoire d'Astrophysique de Marseille, 5. Max-Planck-Institut für Sonnensystemforschung, 6. Rheinisches Institut für Umweltforschung an der Universität zu Köln, 7. Universität der Bundeswehr München, 8. Universite de la Polynesie Francaise*

### 500.02 – MIRO Observations of subsurface temperatures of the nucleus of 67P/Churyumov-Gerasimenko

Observations of the nucleus of 67P/Churyumov-Gerasimenko in the millimeter-wave continuum have been obtained by the Microwave Instrument for the Rosetta Orbiter (MIRO). We present pre-perihelion data obtained at wavelengths of 0.5 mm and 1.6 mm during August 2014-July 2015 over a range of heliocentric distance between 3.62 and 1.25 AU. The data are fit to simple models of the nucleus thermal emission in order to characterize the observed behavior and make quantitative estimates of important physical parameters, including thermal inertia and absorption properties at the MIRO wavelengths. MIRO brightness temperatures on the irregular surface of 67P/C-G are strongly affected by the local solar illumination conditions, and there is a strong latitudinal dependence of the mean brightness temperature as a result of the seasonal orientation of the comet's rotation axis with respect to the Sun. The MIRO emission exhibits strong diurnal variations, which indicate that it arises from within the thermally varying layer in the upper centimeters of the surface. The data are quantitatively consistent with very low thermal inertia values, between 10-30 J $K^{-1}$ $m^{-2}$ $s^{-1/2}$ with the 0.5 mm emission arising from 1 cm beneath the surface and the 1.6 mm emission from a depth of 4 cm. The MIRO brightness temperatures are also affected by the sublimation of ice at or beneath the surface and provide a valuable constraint on distribution of the water production from the nucleus.

**Author(s): F. Peter Schloerb3**, Stephen Keihm[1], Paul von Allmen[1], Mathieu Choukroun[1], Emmanuel Lellouch[2], Cedric Leyrat[2], Samuel Gulkis[1], Mark Hofstadter[1]
**Institution(s):** *1. JPL, 2. LESIA-Observatoire de Paris, 3. Univ. of Massachusetts*

### 500.03 – Meter-scale thermal contraction crack polygons on comet 67P/Churyumov-Gerasimenko

Since August 2014, high spatial resolution images of the nucleus of comet 67P/Churyumov-Gerasimenko have been acquired by the OSIRIS camera onboard Rosetta, enabling to identify meter-scale features on the surface (Thomas et al., 2015; El-Maary et al., 2015). Here, we report on the detection and characterization of thermal contraction polygons. We have identified more than 6000 polygons on 67P, using OSIRIS images with a spatial resolution down to 1.6 m/pixel. They are observed in consolidated terrains, from flat terrains to steep terrains such as cliffs and pit walls. The size of polygons is in the range 1 – 10 m, with a mean value of 3 m. Polygons detected on 67P show morphologies with an elevated center. Polygons are known to form on Mars and Earth when the thermal stress of the surface icy materials exceeds their tensile strength, therefore forming fractures (Lachenbruch, 1962; Mangold, 2005; Marchant & Head, 2007). The size, shape and spatial distribution of polygons across the surface provide constraints on their formation and evolution processes, the sub-surface water ice content, the thermal history of the surface and the mechanical properties of the surface material (e.g., Mellon et al., 2008; Levy et al., 2011).

**Author(s): Anne-Thérèse Auger[1]**, Mohamed Ramy El-Maarry[4], Olivier Groussin[1], Laurent Jorda[1], Sylvain Bouley[2], Antoine Séjourné[2], Claire Capanna[1], Sebastian Höfner[3], Holger Sierks[3]
**Institution(s):** *1. Aix-Marseille Université, Laboratoire d'Astrophysique de Marseille, 2. Laboratoire GEOPS, 3. Max-Planck-Institut für Sonnensystemforschung, 4. Physikalisches Institut, University of Bern*

### 500.04 – Using quantitative analysis to understand the current and past physical processes that sculpted the Philae landing site

The CIVA cameras onboard PHILAE provided the first ever in situ images of the surface of a comet (Bibring et al., Science, 2015). The panorama acquired by CIVA at the landing site on the 67P comet reveals a rough terrain dominated by fractures and agglomerates of consolidated materials. While the composition of these materials is unknown, they provide unique structures to constrain the conditions prevailing at the surface of a comet. A quantitative analysis of the microscopic structures (grains that look like pebbles and fractures) will be presented. The pebble size distribution will be compared to the size distribution of other cometary materials such as boulders at the touchdown site (Mottola et al. Science, 2015), boulders surrounding the landing site (Lucchetti et al., A&A, submitted), >7m sized boulders globally distributed on the comet (Pajola et al., A&A, 2015), grains collected by the COSIMA experiment onboard Rosetta (Langevin et al., JGR, submitted) as well as population of grains remotely observed in coma and jets of other comets. The nature of the pebbles will be then discussed in relation to both endogenic and exogenic processes that could explain their formation. The fractures exhibit two different size distributions that are correlated to the texture of the landscape. Among different physical processes, we will evaluate whether thermal fatigue induced by diurnal temperature variations (Delbo et al. Nature, 2014) could be a mechanism of surficial fragmentation.

**Author(s): Francois Poulet[3]**, Alice Lucchetti[1], Jean-Pierre Bibring[3], Yves Langevin[3], John Carter[3], Marco Delbo[6], Pascal Eng[3], Brigitte Gondet[3], Laurent Jorda[5], Stéphane Le Mouélic[4], Stefano Mottola[2], Cédric Pilorget[3], Mathieu Vincendon[3], Gabriele Cremonese[1]
**Institution(s):** *1. University of Padova, 2. DLR, 3. Institut d'Astrophysique Spatiale, 4. LPG-Université de Nantes/CNRS, 5. Observatoire de Marseille, 6. UNS-CNRS-Observatoire de la Cote d'Azur*

### 500.05 – Temporal morphological changes at the surface of comet 67P/Churyumov-Gerasimenko

A key scientific question, to understand how comets work and whether they still contain pristine materials at or near their surface, is to understand how the nucleus is changing with time and to which extent activity modifies its surface. Rosetta, which has been orbiting comet 67P/Churyumov-Gerasimenko since August 2014, offers a unique opportunity to tackle this fundamental question. Here, we report on temporal morphological changes detected on the surface of the nucleus of comet 67P by the OSIRIS cameras. Changes have been detected in several regions and in particular in the Imhotep region, where they are visible in the form of roundish features that are growing in size from a given location in a preferential direction. Terrains bluer than the surroundings appear during changes, suggesting the presence of (water) ice exposed on the surface.

**Author(s): Olivier Groussin[1]**, H. Sierks[6], C. Barbieri[3], P. Lamy[1], R. Rodrigo[2], D. Koschny[7], H. Rickman[4], H. U. Keller[5]
**Institution(s):** *1. Aix Marseille Université, CNRS, LAM (Laboratoire d'Astrophysique de Marseille) UMR 7326, 2. Centro de Astrobiologia (INTA-CSIC), 3. Department of Physics and Astronomy, Padova University, 4. Department of Physics and Astronomy, Uppsala University, 5. Institute of Planetary Research, DLR, 6. Max-Planck-Institut für Sonnensystemforschung, 7. Scientific Support Office, European Space Agency*

### 500.06 – The 67P nucleus composition and temporal variations observed by the OSIRIS cameras onboard Rosetta

Since August 2014, the comet 67P/Churyumov-Gerasimenko has been mapped by the NAC and WAC cameras of the OSIRIS imaging system in the 250-1000 nm wavelength range. OSIRIS got the most detailed maps at the highest spatial resolution of a comet nucleus surface. Here we report on the colors and spectrophotometry of the whole 67P nucleus from images acquired since the first Rosetta bound orbits in August 2014 up to the comet perihelion passage. Globally, the nucleus shows a red spectral behavior and it has spectrophotometric properties similar to those of bare cometary nuclei, of primitive D-type asteroids such us Jupiter Trojans, and of the moderately red Transneptunians. No clear absorption bands have been identified yet in the UV-VIS-NIR range, except for a potential absorption centered at 290 nm, possibly due to $SO_2$ ice. The nucleus shows an important phase reddening, with disk-averaged spectral slopes increasing from 11%/(100 nm) to 16%/(100 nm) in the 1.3-54° phase angle range. On the basis of the spectral slope, we identified three different groups of regions, characterized by a low, medium, and high spectral slope, respectively. The three groups are distributed everywhere on the nucleus, with no evident distinction between the two lobes of the comet. The comet southern hemisphere, that has been observed by Rosetta since April 2015, shows a lack of spectrally red regions associated to the absence of wide spread smooth or dust covered terrains. Several local bright and spectrally blue patches have been identified on the nucleus and attributed to exposed water ice on the surface. In particular we observed big (> 1500 $m^2$) bright ice rich areas in the southern hemisphere which completely sublimated in a few weeks. We see evidence of very bright patches in the NUV-blue region close to the morning shadows that are compatible with the presence of frosts/ices. These patches disappear when fully illuminated by the Sun indicating that important processes of sublimation and recondensation of volatiles are taking place on the nucleus.

**Author(s): Sonia Fornasier[4]**, Maria Antonietta Barucci[4], Clement Feller[4], Prasanna J.D. Deshapriya[4], Antoine Pommerol[6], Luisa Lara[3], Nilda Oklay[5], Mike A'Hearn[1], Bjorn Davidsson[2], Davide Perna[4], Holger Sierks[5]
**Institution(s):** *1. Department for Astronomy, University of Maryland, 2. Department of Physics and Astronomy, 3. IAA-CSIC, 4. LESIA-Observatoire de Paris, CNRS, Univ. Paris Diderot, Univ. Pierre et Marie Curie, 5. Max-Planck-Institut für Sonnensystemforschung, 6. Physikalisches Institut, Univ. of Berna*

### 500.07 – Variegation of active regions on comet 67P/Churyumov-Gerasimenko

Since Rosetta spacecraft's arrival to the comet 67P, the OSIRIS scientific imager (Optical, Spectroscopic, and Infrared Remote Imaging System, Keller et al. 2007) is successfully observing the nucleus with high spatial resolution in the 250-1000 nm range thanks to set of 26 dedicated filters.
While 67P has a typical red spectral slope, the active areas tend to display bluer spectra (Sierks et al. 2015, Fornasier et al. 2015). We performed a spectral analysis of the active areas and derived spectral characteristics of them, possibly indicating the presence of material enriched in volatiles.
The 'activity thresholds' spectral method (Oklay et al, 2015) is used for the identification of the active areas. In most cases, areas detected with this technique have been later on confirmed as active sources (Lara et al. 2015, Lin et al. 2015, Vincent et al. 2015) by direct detection of dust jets. This technique is therefore able to identify currently active areas, but also predicts which regions of the surface are likely to become activated once they receive enough insolation.
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**Author(s): Nilda Oklay[6]**, Jean-Baptiste Vincent[6], Sonia Fornasier[5], Maurizio Pajola[1], Sebastien Besse[3], Luisa M. Lara[4], Maria Antonietta Barucci[5], Stefano Mottola[2], Holger Sierks[6], Antoine Pommerol[7], Nafiseh Masoumzadeh[6], Monica Lazzarin[1], Frank Scholten[2], Frank Preusker[2], Ian Hall[6]
**Institution(s):** *1. CISAS, 2. DLR, 3. ESA, 4. IAA-CSIC, 5. LESIA, 6. MPS, 7. Physikalisches Institut, Universität Bern*

### 500.08 – 67P/CG morphological units and VIS-IR spectral classes: a Rosetta/VIRTIS-M perspective

VIRTIS-M, the 0.25-5.1 µm imaging spectrometer on Rosetta (Coradini et al., 2007), has mapped the surface of 67P/CG nucleus since July 2014 from a wide range of distances. Spectral analysis of global scale data indicate that the nucleus presents different terrains uniformly covered by a very dark (Ciarniello et al., 2015) and dehydrated organic-rich material (Capaccioni et al., 2015). The morphological units identified so far (Thomas et al., 2015; El-Maarry et al., 2015) include dust-covered brittle materials regions (like Ash, Ma'at), exposed material regions (Seth), large-scale depressions (like Hatmehit, Aten, Nut), smooth terrains units (like Hapi, Anubis, Imhotep) and consolidated surfaces (like Hathor, Anuket, Aker, Apis, Khepry, Bastet, Maftet). For each of these regions average VIRTIS-M spectra were derived with the aim to explore possible connections between morphology and spectral properties. Photometric correction (Ciarniello et al., 2015), thermal emission removal in the 3.5-5 micron range and georeferencing have been applied to I/F data in order to derive spectral indicators, e.g. VIS-IR spectral slopes, their crossing wavelength (CW) and the 3.2 µm organic material band's depth (BD), suitable to identify and map compositional variations. Our analysis shows that smooth terrains have the lower slopes in VIS (<1.7E-3 1/µm) and IR (0.4E-3 1/µm), CW=0.75 µm and BD=8-12%. Intermediate VIS slope=1.7-1.9E-3 1/µm, and higher BD=10-12.8%, are typical of consolidated surfaces, some dust covered regions and Seth where the maximum BD=13% has been observed. Large-scale depressions and Imhotep are redder with a VIS slope of 1.9-2.1E-3 1/µm, CW at 0.85-0.9 µm and BD=8-11%. The minimum VIS-IR slopes are observed above the Hapi, in agreement with the presence of water ice sublimation and recondensation processes observed by VIRTIS in this region (De Sanctis et al., 2015).
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**Author(s): Gianrico Filacchione[2]**, Fabrizio Capaccioni[2], Mauro Ciarniello[2], Andrea Raponi[2], Maria Cristina De Sanctis[2], Federico Tosi[2], Giuseppe Piccioni[2], Priscilla Cerroni[2], Maria Teresa Capria[2], Ernesto Palomba[2], Andrea Longobardo[2], Alessandra Migliorini[2], Stephane Erard3, Gabriele Arnold[1], Dominique Bockelee-Morvan3, Cedric Leyrat3, Bernard Schmitt5, Eric Quirico5, Antonella Barucci3, Thomas B. McCord4, Katrin Stephan[1], David Kappel[1]
**Institution(s):** *1. DLR, 2. INAF-IAPS, 3. LESIA, Obs Paris, 4. The Bear Fight Institute, 5. Univ. Grenoble Alpes, CNRS, IPAG*

### 500.09 – Comet 67P/Churyumov-Gerasimenko: Non-Gravitational Forces Based on its Detailed Shape

Non-gravitational forces caused by sublimation on a cometary nucleus influence its orbital parameters and its rotational properties. Based on thermal models and rough estimates of the nucleus shape properties such as its mass and density can be derived [1, 2]. The uncertainty of the nucleus shape influences the quality of the results. Changes of the angular momentum of the nucleus rotation are more strongly influenced by details of the shape and surface. The long term observations of the nucleus of comet 67P/Churyumov-Gerasimenko by OSIRIS [3] during the rendezvous with ESA's Rosetta spacecraft result in a very detailed shape model [3]. We use a shape model with > 105 facets to simulate the distributed forces due to sublimation and to calculate their exerted torques. The determination of the overall activity and its spatial and timely distribution over the nucleus remains a major challenge. Early observations revealed that the rotation period had changed from its last perihelion passage in 2009 [4]. The detailed shape model along with thermal modeling makes it possible to calculate the diurnal activity of the facets [6, 7]. The net torque integrated over the whole surface causes a change in the angular momentum. We also calculate the forces acting on the motion of the nucleus. This can be monitored by determinations of the spacecraft positions during the Rosetta mission. We will compare our results with the traditional approach to calculate the non-gravitational forces [8].
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**Author(s): Horst Uwe Keller3**, Stefano Mottola3, Yuri Skorov5, Björn Davidsson[2], Pedro Gutiérrez 4, Laurent Jorda[1], Lucie Maquet[6]
**Institution(s):** *1. Aix Marseille Université, CNRS, LAM, 2. Department of Physics and Astronomy, Uppsala University, 3. Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Planetenforschung, Asteroiden und Kometen, 4. Instituto de Astrofísica de Andalucía (CSIC), 5. Max-Planck-Institut für Sonnensystemforschung, 6. Scientific Support Office, European Space Astronomy Centre/ESA*

## 501 – Extrasolar Planets: Discovery and Dynamics

### 501.01 – Discovery and follow-up of 51 Eri b, a directly-imaged Jupiter-like exoplanet and status of the GPIES campaign.

Directly detecting thermal emission from young extrasolar planets allows measurement of their atmospheric composition, gravity and luminosity, which is influenced by their formation mechanism. The

Gemini Planet Imager Exoplanet Survey (GPIES) is targeting 600 young, nearby stars using the GPI instrument. The star 51 Eridani (51 Eri) was chosen as an early target for the survey due to its youth and proximity. We discovered a planet orbiting the ~20 Myr-old beta Pic moving group member star 51 Eridani at a projected separation of 13 astronomical units (Macintosh et al. Science, 2015). Near-infrared observations show a spectrum with strong methane and water vapor absorption. Modeling of the spectra and photometry yields a luminosity of $L/L_{\odot}$=1.6-4.0 × $10^{-6}$ and an effective temperature of 600-750 K. For this age and luminosity, “hot-start” formation models indicate a mass twice that of Jupiter. This planet also has a sufficiently low luminosity to be the first directly imaged exoplanet to be consistent with the 'cold-start' core accretion process that may have formed Jupiter.
Follow-up observations scheduled in Fall 2015 will allow us to constrain the orbit of this exoplanet and derive more information on its atmosphere. These new data, and additional interesting targets, will be presented and discussed.
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**Author(s): Franck Marchis[9]**, Eric L. Nielsen[9], Sarah Blunt[9], Julien Rameau[4], Travis Barman[5], Robert J. De Rosa[3], Quinn Konopacky[2], Mark S. Marley[6], Christian Marois[7], Laurent Pueyo[10], Abhijith Rajan[8], Jason J. Wang[3], Bruce Macintosh[1], James R. Graham[3]
**Institution(s):** *1. Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, 2. Center for Astrophysics and Space Sciences, University of California, 3. Department of Astronomy, UC Berkeley, 4. Institut de Recherche sur les Exoplanètes, Départment de Physique, Université de Montréal, 5. Lunar and Planetary Laboratory, University of Arizona, 6. NASA Ames Research Center, MS 245-3, 7. National Research Council of Canada Herzberg, 8. School of Earth and Space Exploration, Arizona State University, 9. SETI Institute, 10. Space Telescope Science Institute*

### 501.02 – The SuPerPiG search for short period planets in the K2 dataset

Planets with orbital periods of less than a day present real challenges to theories of planet formation and evolution, and yet numerous objects with periods as short as a few hours have been found. So close to their host stars that some are actively disintegrating, these planets' origins remain unclear, and even modified models for planet formation and evolution with significant inward migration have trouble accounting for their periods. They thus provide an important probe of the innermost region of the protoplanetary disk. We report on the ongoing efforts of the Short-Period Planets Group (SuPerPiG, http://www.astrojack.com/research/superpig/) to find additional short-period planets in the K2 Mission, using the light curve products produced by the Vanderburg and Johnson k2sff pipeline (Vanderburg & Johnson 2014, https://archive.stsci.edu/prepds /k2sff/). Preliminary results from Campaign 2, including accounting for a 6-hour pseudo transit signal introduced by the Kepler spacecraft thruster re-pointing, will be presented.

**Author(s): Elisabeth R. Adams[2]**, Brian Jackson[1]
**Institution(s):** *1. Boise State University, 2. Planetary Science Institute*

### 501.03 – A Quantitative Criterion for Defining Planets

The IAU definition of 'planet' needs improvement because it is neither quantitative nor general. The current definition applies only to solar system bodies and does not allow for the classification of exoplanets. The current definition can also be misunderstood or misconstrued because of its qualitative nature (e.g., "has cleared the neighbourhood around its orbit").
A simple metric can be used to determine whether a planet or exoplanet can clear its orbital zone during a characteristic time scale, such as the lifetime of the host star on the main sequence. This criterion requires only estimates of star mass, planet mass, and orbital period, making it possible to immediately classify 99% of all known exoplanets. All 8 planets and all classifiable exoplanets satisfy the criterion.
I will describe the development of the metric and apply it to solar system bodies, exoplanets, and pulsar planets. I will then show how this metric could be used to quantify, generalize, and simplify the definition of 'planet'. A preprint is available at http://arxiv.org /abs/1507.06300

**Author(s): Jean-Luc Margot[1]**
**Institution(s):** *1. University of California, Los Angeles*

### 501.04D – Dynamical Heating Induced by Dwarf Planets on Cold Kuiper Belt-like Debris Disks

With the use of long-term numerical simulations, we study the evolution and orbital behavior of cometary nuclei on cold Kuiper belt-like debris disks under the gravitational in uence of dwarf planets (DPs); we carry out these simulations with and without the presence of a Neptune-like giant planet. This comprehensive study shows that in the absence of a giant planet, 10 DPs are enough to induce strong radial and vertical heating on the orbits of belt particles. On the other hand, the presence of a giant planet close to the debris disk, acts as a stability agent reducing the radial and vertical heating. With enough DPs, even in the presence of a Neptune-like giant planet some radial heating remains; this heating grows steadily, re-lling resonances otherwise empty of cometary nuclei. This seems to work as a plausible secular process able to provide material that, after falling into the resonances with the giant, through resonant chaotic diusion, could sustain a rate of new comets spiraling into the inner planetary system.

**Author(s): Marco Antonio Muñoz-Gutiérrez[1]**, Barbara Pichardo[1], Mauricio Reyes-Ruiz[1], Antonio Peimbert[1]
**Institution(s):** *1. Instituto de Astronomía, UNAM*

### 501.05 – Masses of the Five Small Planets Around Kepler-80

Kepler has discovered hundreds of multi-transiting systems which hold tremendous potential both individually and collectively for understanding the formation and evolution of planetary systems. Many of these systems are quite compact, containing 3-7 relatively small planets with periods less than 100 days; these are known as Systems with Tightly-packed Inner planets, or STIPs. One ultra-compact STIP is KOI-500/Kepler-80, a planetary system containing five transiting planets ranging in size from 1.5 to 2.8 times the radius of the Earth that orbit in a tightly-packed configuration with periods between 1 and 10 days. In addition to its close packedness, the outer four planets are in a unique dynamical configuration with two interconnected three-body resonances. Using transit timing variations (TTVs) caused by the gravitational perturbations, we perform a fully self-consistent dynamical analysis of the system, finding best-fit masses for the outer four planets to be each around five Earth masses. We also performed extensive testing of synthetic systems, and have determined that eccentricities cannot be reliably detected, but that assuming circular orbits does not significantly affect the mass estimates. We will present the inferred properties for Kepler-80 and discuss these results in context of (ultra-compact) STIPs and the small planet mass-radius relation.

**Author(s): Mariah G MacDonald[1]**, Darin Ragozzine[1], Daniel C Fabrycky[2]
**Institution(s):** *1. Florida Institude of Technology, 2. University of Chicago*

### 501.06 – The search for Exomoons

There are hundreds of Exoplanets which the data are available for dynamical investigation. There is a wealth of diversity of

Exoplanets types and the expectation in finding our Earth-living conditions in another planet motivates the search for Extra-solar planets. A satellite around a planet in the habitable zone would, in addition, contributes to keep the climate. The main objective of this work is to provide a list of the best planet candidates to harbor a detectable exomoon by the current telescopes, such as the Kepler mission, so as to guide the searches. The planets were sorted out into class groups according to their masses and radii. For each planet we have calculated the stability region where an exomoon can exist for a long period of time. The outer boundary is determined from the critical stability limit obtained from dynamical numerical simulation of a restrict three body problem, whereas the inner boundary is given by the Roche limit. Moreover, the satellite has to be bigger than a certain value to be detected in the noisy transit lightcurves of the CoRoT and Kepler missions. We determined the maximum radius of the stability zone for several planet types, and proved that the relation reported in a previous work by Domingos et al. (2006) only for hot Jupiters, is valid for all planet class. Considering moons of different densities (ice, ice-rock, rock, rock-iron, iron) able to survive within the calculated stability region and with a minimum detectable size, we derived a list of the best 38 planet candidates with orbiting moons. A list of the top ten planet candidates where exomoons should be searched within the Kepler transit lightcurves is given. These planets could harbor big enough moons to be detected above the data noise, for any moon composition.

**Author(s): Ana Helena Fernandes Guimarães[2]**, Adriana Benetti Marques Valio[2], Luis Ricardo Moretto Tusnski[1], Ernesto Vieira-Neto[3]
**Institution(s):** *1. INPE - Instituto Nacional de Pesquisas Espaciais, 2. Mackenzie Presbyterian University, 3. UNESP - University of State of São Paulo*

### 501.07 – The Primordial Destruction of Moons around Giant Exoplanets through Disk-Driven Planetary Migration

The extensive array of satellites around Jupiter and Saturn makes it reasonable to suspect that similar systems of moons might exist around giant extrasolar planets. Observational surveys have revealed a significant population of such giant planets residing at distances of about 1 AU, leading to speculation that some of these 'exomoons' might be capable of maintaining liquid water on their surfaces. Accordingly, many recent efforts have specifically hunted for moons around giant exoplanets. Owing to the lack of detections thus far, it is worth asking whether certain processes intrinsic to planet formation might lead to the loss of moons. Here, we highlight that giant planets are thought to undergo inward migration within their natal disks and show that the very process of migration naturally captures moons into a so-called "evection resonance". Within this resonance, the lunar orbit's eccentricity grows until the moon is lost, either by collision with the planet or through tidal disruption. Whether moons survive or not is critically dependent upon where the planet began its inward trek. In this way, the presence or absence of exomoons can inform us on the extent of inward migration, for which no reliable observational proxy currently exists.

**Author(s): Christopher Spalding[1]**, Konstantin Batygin[1], Fred C Adams[2]
**Institution(s):** *1. California Institute of Technology, 2. University of Michigan*

### 501.08 – Tidal Decay and Disruption of Gaseous Exoplanets

Many gaseous exoplanets in short-period orbits are on the verge of Roche-lobe overflow, and observations, along with orbital stability analysis, show tides probably drive significant orbital decay. Thus, the coupled processes of orbital evolution and tidal disruption likely shape the observed distribution of close-in exoplanets and may even be responsible for producing the shortest-period solid planets. However, the exact outcome for an overflowing planet depends on its internal response to mass loss and variable stellar insolation, and the accompanying orbital evolution can act to enhance or inhibit the disruption process. The final orbits of the denuded remnants of gas giants may be predictable from their mass-radius relationship, and so a distinctive mass-period relationship for some short-period solid planets may provide evidence for their origins as gaseous planets. In this presentation, we will discuss our work on tidal decay and disruption of close-in gaseous planets using a new model that accounts for the fact that short-period planets have hot, distended atmospheres, which can result in overflow even for planets that are not officially in Roche lobe contact. We will also point out that the orbital expansion that can accompany mass transfer may be less effective than previously realized because the resulting accretion disk may not return all of its angular momentum to the donor, as is usually assumed. Both of these effects have bee incorporated into the fully-featured and robust Modules for Experiments in Stellar Astrophysics (MESA) suite.

**Author(s): Brian K. Jackson[1]**, Phil Arras5, Emily Jensen[1], Sarah Peacock4, Pablo Marchant3, Kaloyan Penev[2]
**Institution(s):** *1. Boise State University, 2. Princeton University, 3. Universität Bonn, 4. University of Arizona, 5. University of Virginia*

## 502 – Jovian Planet Magnetospheres, Aurorae, and Atmospheres

### 502.01 – Transport of magnetic flux in Saturn's inner magnetosphere

The dynamics of the Saturnian magnetosphere, which rotates rapidly with an internal plasma source provided by Enceladus, qualitatively resembles those of the jovian magnetosphere powered by Io. The newly added plasma is accelerated to the corotation speed and moves outward together with the magnetic flux. In the near tail region, reconnection cuts the magnetic flux, reconnects it into plasma-depleted inward moving flux tubes and outward moving massive plasmoids. The buoyant empty tubes then convect inward against the outward flow to conserve the total magnetic flux established by the internal dynamo. In both jovian and saturnian magnetospheres, flux tubes with enhanced field strength relative to their surroundings are detected in the equatorial region. Recent observations show that there are flux tubes with reduced field strength off the equator in the saturnian magnetosphere. To understand the formation mechanism of both types of flux tubes, we have surveyed all the available 1-sec magnetic field data from Cassini. The systematic statistical study confirms the different latitudinal distributions of the two types of flux tubes. In addition, enhanced-field flux tubes are closer to the planet while reduced-field flux tubes can be detected at larger distances; both types of flux tubes become indistinguishable from the background magnetic flux inside an L-value of about 4; the local time distribution of both types of flux tubes are similar and they contain about the same amount of magnetic flux. Therefore, the two types of flux tubes are the same phenomena with different manifestations in different plasma environments. When the surrounding plasma density is high (near the equator and closer to the plasma source region), the flux tubes are compressed and have enhanced field strength inside; while in the low-plasma density region (off the equator and further from the plasma source region), the flux tubes expand and have reduced field strength inside.

**Author(s): Christopher T. Russell[2]**, H. R. Lai[2], H. Y. Wei[2], Y. D. Jia[2], M. K. Dougherty[1]
**Institution(s):** *1. Imperial College London, 2. UC, Los Angeles*

### 502.02 – Ground-based and Space-based Observations of Jovian Mid-Infrared Aurora During the Cassini Flyby of Jupiter 2000–2001

We report on a re-examination and re-analysis of hydrocarbon emission spectra collected from Jupiter using ground-based ultra-high spectral resolution infrared heterodyne spectroscopy (IRHS) and space-based Fourier transform spectroscopy (FTS) from the Cassini spaceraft during its flyby of Jupiter in 2000-2001. Auroral emission by ethane was measured from Earth with the

Heterodyne Instrument for Planetary Wind and Composition, HIPWAC, in December 2000 and in February 2001. Shapes of individual emission lines of ethane near 12 μm wavelength were measured from the polar regions of Jupiter at spectral resolving power of 1,000,000. These observations were conducted in concert with scheduled observations of the Jovian auroral region by the Cassini Composite Infrared Spectrometer (CIRS) at resolving powers of ~2000 before and after closest approach on December 30, 2000. The HIPWAC measurements complement CIRS' broad spectral and spatial coverage with its uniquely high spectral resolution and spatial discrimination from the ground comparable to that at Cassini's closest approach. Fully resolved ethane line measurements retrieve both temperature and ethane abundance information at the north and south auroral hot spots. CIRS data at coarser spectral resolution provide extended spatial distributions covering a broad spectral band, including abundances and auroral response of several hydrocarbon constituents in the 8–13 micrometer spectral region (ethane, methane, ethylene, and acetylene). Preliminary studies of both data sets reveal temporal variability and low enhancement of the thermal infrared aurorae during the flyby compared to other periods observed. Analyses of both data sets will be reported and retrievals will be compared. Results will be useful to interpreting the Juno mission, since this work provides complementary information and diagnostics to study Jupiter in a spectral region and altitude range not directly probed by Juno.

**Author(s): Theodor Kostiuk4**, Tilak Hewagama5, Timothy A. Livengood5, Kelly E. Fast3, Gordon L. Bjoraker4, Ronald Carlson1, Frank Schmülling 2, Conor A. Nixon4
**Institution(s):** *1. Catholic University of America, 2. DLR, 3. NASA HQ, 4. NASA's GSFC, 5. University of Maryland*

### 502.03 – Jupiter Climatological Database from Frequent 5-25 μm Mid-IR Spectral Mapping using IRTF/TEXES

We report on the development of a long-term Jovian Climatological Database (JCliD) to explore variability in Jupiter's atmospheric temperatures, winds, clouds and composition– from long-term seasonal changes to short-term major upheavals. Radiometrically calibrated spectral scan maps of Jupiter have been regularly obtained using the TEXES instrument (Texas Echelon cross Echelle Spectrograph, Lacy et al. 2002, PASP 114, p153-168) between 2012 and 2015. Ten settings between 5 and 25 μm (10-20 $cm^{-1}$ wide settings at spectral resolutions of 2000-10000) were selected to be sensitive to jovian temperatures (via $H_2$, $CH_4$ and $CH_3D$), tropospheric phosphine and ammonia, tropospheric haze opacity and stratospheric hydrocarbons ethane and acetylene. Diffraction-limited spatial resolutions of 0.6-1.6" were achieved. Observations over consecutive nights allow the creation of full spatial maps for comparison with the visible light record, revealing ephemeral stratospheric wave activity, NEB hotspots, heating at the northern auroral oval, and complex thermal signatures associated with tropospheric vortices, waves and barges. Full spectra are inverted via the NEMESIS retrieval algorithm (Irwin et al., 2008, JSQRT 109, p1136-1150) to map temperatures at multiple altitudes (1-600 mbar), winds, aerosol opacity and gaseous composition. The spatial and spectral resolutions of the resulting maps surpass those obtained during the Cassini flyby of Jupiter in 2000, and permit temporal interpolation to understand the environmental conditions related to the emergence and evolution of discrete features. In December 2014 we find warmer temperatures in the northern stratosphere (a seasonal effect in late northern summer despite Jupiter's small axial tilt); a hemispheric asymmetry in the tropospheric $PH_3$ distribution due to variations in the vigour of vertical mixing and photolytic shielding; elevated $PH_3$, aerosols and $NH_3$ in the equatorial zone (EZ) related to equatorial uplift; elevated aerosol opacity in the northern and southern tropical zones (NTrZ and STrZ); and enhanced $PH_3$ and aerosols over the Great Red Spot. Maps of retrieved properties will be assembled as a database (JCliD) to aid in the interpretation of Juno data during 2016-2017.

**Author(s): Leigh N. Fletcher4**, Glenn S. Orton2, Thomas K. Greathouse3, James Sinclair2, Patrick G.J. Irwin5, Rohini S. Giles5, Therese Encrenaz1, Pierre Drossart1
**Institution(s):** *1. LESIA, Observatoire de Paris, 2. NASA Jet Propulsion Laboratory, 3. Southwest Research Institute, 4. University of Leicester, 5. University of Oxford*

### 502.04 – Are Brown Barges the Deserts of the Upper Jovian Atmosphere?

Since the descent of the Galileo probe into one of Jupiter's 5-μm hot spots, these regions have been characterized as the driest and clearest regions on the planet. We are presenting evidence that this generalization could be premature, at least for Jupiter's upper troposphere. Diffraction-limited mid-infrared images of Jupiter taken from the Subaru Telescope using the COMICS instrument, the Very Large Telescope (UT3) using the VISIR instrument, and the Gemini South Telescope using the T-ReCS instrument resolve regions with the highest brightness anywhere on the planet at wavelengths near 9.8-10.5 μm, a region sensitive to the abundance of ammonia gas above its condensation level. These brightnesses are so high that they require ammonia abundances that are many times lower than anywhere else on the planet. A similar drop of the optical thicknesses of clouds near the ammonia-gas condensation level is required, diagnosed using 8.7-8.9-μm radiances. These features are also detected but not spatially resolved in observations obtained at NASA's Infrared Telescope Facility using the MIRSI imager and the TEXES scanning spectrometer. Most are located along the northern edge of the North Equatorial Belt and are associated with cyclonic features known as "brown barges". They are not associated with detectable changes in upper-tropospheric temperatures, requiring convective activity to take place at depths with very rapid dynamical readjustment. Regions bright at 8-10 μm are not always bright in the deep 5-μm window, implying that some brown barges are clear of condensate gases and clouds only down to 0.6 bars but others are clear down to 2-3 bars, a possible consequence of observing them in different phases of their "life cycle". These, other discrete features and broader regions will be the objects of intensive investigations by the Juno mission and associated Earth-based observational support in 2016 to 2018.

**Author(s): Glenn S. Orton4**, James Sinclair4, Leigh Fletcher8, Takuya Fujiyoshi7, Padma Yanamandra-Fisher6, John Rogers1, Patrick Irwin9, Thomas Greathouse5, Raiyan Seede10, Jason Simon2, Marian Nguyen3, Matthew Lai3
**Institution(s):** *1. British Astronomical Association, 2. California Institute of Technology, 3. California State University, 4. JPL, 5. Southewest Research Institute, 6. Space Science Institute, 7. Subaru Telescope, 8. University of Leicster, 9. University of Oxford, 10. University of Paris Sorbonne Abu Dhabi*

### 502.05 – First results from the Hubble OPAL Program: Jupiter in 2015

The Hubble 2020: Outer Planet Atmospheres Legacy (OPAL) program is a Director's Discretionary program designed to generate two yearly global maps for each of the outer planets to enable long term studies of atmospheric color, structure and two-dimensional wind fields. This presentation focuses on Jupiter results from the first year of the campaign. Data were acqured January 19, 2015 with the WFC3/UVIS camera and the F275W, F343N, F395N, F467M, F502N, F547M, F631N, F658N, and F889N filters. Global maps were generated and are publicly available through the High Level Science Products archive: https://archive.stsci.edu/prepds/opal/ Using cross-correlation on the global maps, the zonal wind profile was measured between +/- 50 degrees latitude and is in family with Voyager and Cassini era profiles. There are some variations in mid to high latitude wind jet magnitudes, particularly at +40°and -35° planetographic latitude. The Great Red Spot continues to maintain an intense orange coloration, as it did in 2014. However, the interior shows changed structure, including a reduced core and new filamentary features. Finally, a wave not previously seen in Hubble images was also observed and is interpreted as a baroclinic instability with associated cyclone formation near 16° N latitude. A similar feature was observed faintly in Voyager 2 images, and is consistent with the Hubble feature in location and scale.

**Author(s): Amy A. Simon[2]**, Michael H Wong3, Glenn S. Orton[1]
**Institution(s):** *1. Jet Propulsion Laboratory/Caltech, 2. NASA's GSFC, 3. University of California at Berkeley*

## 502.06 – Ammonium Hydrosulfide: Coloring Jupiter's Clouds

The appearance and composition of Jupiter's Great Red Spot (GRS) have been studied for over a century, yet there still is no consensus for what is causing the GRS's color. As the GRS is believed to originate in tropospheric clouds, it seems likely that one or more cloud components may contribute to the GRS's color. Recently, we have begun to investigate whether either ammonium hydrosulfide ($NH_4SH$), a predicted cloud component, or its radiation-chemical products can produce color and/or an ultraviolet-visible spectrum similar to what has been observed on Jupiter via remote sensing (e.g., Simon et al., 2015). Our initial experiments relied on infrared spectroscopy to quantify the radiolytic and thermal stability of $NH_4SH$ and to identify the new chemical products formed during MeV ion irradiation (Loeffler et al., 2015). This DPS presentation will cover some of our most recent results detailing the ultraviolet-visible spectral and color changes observed during irradiation and post-irradiation warming of $NH_4SH$ ices. This work is funded by NASA's Outer Planets and Planetary Atmospheres programs.

**Author(s): Mark J. Loeffler[1]**, Reggie L. Hudson[1], Nancy J. Chanover[2], Amy A. Simon[1]
**Institution(s):** *1. NASA GSFC, 2. New Mexico State University*

## 502.07 – Deriving Saturn's Zonal Winds from Cassini Radio Occultations

Tracking cloud features from visible images have provided detailed maps of the meridional variation of the mean zonal winds on the giant planets, including Saturn. Filters at different wavelengths can provide information on the vertical structure of the zonal winds, but that is approximate, and the altitudes of winds observed with a given filter generally vary with location, because cloud heights do. Radio occultations provide vertical profiles of refractivity, pressure, and temperature vs. altitude. Zonal winds can be derived from the assumption of gradient wind balance, which relates the zonal wind to the change of geopotential height with latitude along an isobar. Occultations have the advantage that vertical profiles of winds can be obtained in the troposphere and stratosphere. There are, however, complicating factors. In general, the meridional distribution of occultation soundings is limited and unevenly distributed. Moreover, one needs to know the geometry of the occulting atmosphere to correctly account for the path of the refracted radio signal. The zonal winds matter, because they distort isobaric surfaces. For example, an inversion that includes Saturn's oblateness from uniform rotation, based on the Voyager System III period, would yield equatorial temperature profiles that are shifted by ~ 2 K relative to one that also includes the differential rotation associated with the cloud-tracked zonal winds. In retrieving vertical profiles of atmospheric variables from occultation soundings, one also needs an additional symmetry assumption to make the inversions tractable. Typically one uses the zonal winds based on cloud-tracking studies, and assumes they are axisymmetric and barotropic, so that both the gravitational and centrifugal forces are derivable from a potential, and the surfaces of constant geopotential height, pressure, and temperature coincide. This forms the basis for an iterative approach. The pressures and temperatures so retrieved from the occultation soundings are not barotropic, but the zonal winds derived from the gradient wind equation can be added to the cloud-tracked winds used in the inversions. We discuss Saturn's equatorial soundings as an illustration.

**Author(s): F. Michael Flasar[2]**, Paul J. Schinder[1]
**Institution(s):** *1. Cornell University, 2. NASA's GSFC*

## 502.08 – A Ring-'Rain' influence for Saturn's Cloud Albedo and Temperatures? Evidence Pro or Con from Voyager, HST, and Cassini

J. E. P. Connerney [*Geophys. Res. Lett*, **13**, 773-776, 1986] pointed out that 'latitudinal variations in images of Saturn's disk, upper atmospheric temperatures, and ionospheric electron densities are found in magnetic conjugacy with features in Saturn's ring plane', and proposed 'that these latitudinal variations are the result of a variable influx of water, transported along magnetic field lines from sources in Saturn's ring plane'. Observations of $H_3^+$ support a ring-ionosphere connection [O'Donoghue et al., *Nature* **496**, 7444, 2013]. What about cloud albedo and temperature? Connerney attributed a hemispheric asymmetry in haze and temperature to an asymmetry in water flux and predicted that 'the presently-observed north-south asymmetry (upper tropospheric temperatures, aerosols) will persist throughout the Saturn year'. We can now test these ideas with data from the Cassini mission, from the Hubble Space Telescope, and from ground-based observations. Analyses of ground-based images and especially Hubble data established that the hemispheric asymmetry of the aerosol population does change, and seasonal effects are dominant, although non-seasonal variations are also observed [Karkoschka and Tomasko, Icarus 179, 195-221, 2005]. Upper tropospheric temperatures also vary as expected in response to seasonal forcing [Fletcher et al., *Icarus* **208**, 337-352, 2009]. Connerney also identified dark bands in Voyager Green-filter images on magnetic conjugacy with the E ring and edges of the A and B rings. In Cassini Green-filter images there is some correspondence between dark bands and ring features in magnetic conjugacy, but collectively the correlation is not strong. Cassini 727-nm methane band images do not suggest depletion of aerosols in the upper troposphere at ring edge magnetic conjugacy latitudes as proposed by Connerney. We conclude that ring rain does not have a significant influence on upper tropospheric aerosols and temperatures on Saturn. Part of this work was performed by the Jet Propulsion Lab, Calif. Institute of Technology.

**Author(s): Robert A. West[1]**, Liming Li[2]
**Institution(s):** *1. JPL, 2. Univ. of Houston*

## 502.09D – Determining the vertical extent of Jupiter's Great Red Spot with the Juno gravity measurements

The NASA *Juno* mission is due to arrive at Jupiter in July 2016. We explore the possibility of inferring the depth of Jupiter's biggest vortex, the Great Red Spot (GRS), by determining its gravitational signature with the onboard gravity experiment, considering different possible scale heights for the vortex. We estimate the strength of the gravity signal coming from the vortex using an idealized dynamical model for the atmosphere of the giant planet. The gravity anomaly is then compared to the expected accuracy in the retrieval of the surface gravity at the GRS location obtained with numerical simulations of the Doppler data inversion based on the expected trajectory of the spacecraft. Starting from observations of the planet's velocity vectors at the cloud level, we propagate the profiles along coaxial cylinders parallel to the spin axis and explore a wide range of decay scale heights in the radial direction. Assuming the large scale vortex dynamics are geostrophic, and therefore thermal wind balance holds, the density anomaly distribution due to Jupiter's winds can be derived from the velocity maps. The novelty of this approach is in the integration of thermal wind relations over a three-dimensional grid, and in the inclusion of the observed meridional velocity as measured during the Cassini flyby of Jupiter. The introduction of longitudinal perturbations to the mean zonal flows gives rise to fluctuations in the tesseral spherical harmonics of Jupiter's gravitational potential. We show that the deeper the penetration of the jets, the stronger is the gravity signal coming from the GRS. On the other hand, the larger the mass involved in the planet's atmospheric motion, the higher are the degree and order of the spherical harmonic expansion of Jupiter's gravity field needed to fit the simulated Doppler data. We show that the mass anomaly associated with the Great Red Spot is detectable by the Juno gravity experiment if the winds penetrate at depth of 2,000 km below the cloud level of Jupiter and that the large mass involved with deep winds does not render much the ability to measure the feature.

**Author(s): Marzia Parisi[2]**, Eli Galanti[2], Stefano Finocchiaro[1], Luciano Iess[1], Yohai Kaspi[2]
**Institution(s):** *1. Sapienza Università di Roma, 2. Weizmann Institute of Science*

## 503 – Comet 67P/C-G -- Coma and Environment

### 503.01 – One year at the comet: highlights from the ROSINA instruments on the composition and evolution of the cometary coma

After one year in the close vicinity of comet 67P/Churyumov-Gerasimenko we report on the most surprising results from the Rosetta Orbiter Sensor for Ion and Neutral Analysis (ROSINA) on Rosetta which is analysing the volatile composition of the cometary coma since more than 15 months. Several species like $N_2$ and Ar were detected for the first time in a cometary coma, others have been detected before in long period, but not in Jupiter family comets. There are significant amounts of long carbon chain molecules. Many of them are probably related to dust. We will give an overview on the inventory of volatile and less volatile species. The coma is quite heterogeneous and the relative abundances vary by factors between summer and winter hemisphere. The evolution of the abundances with heliocentric distances and solar illumination will be discussed.

**Author(s): Kathrin Altwegg[8]**, Hans Balsiger[8], Ursina Calmonte[8], Sébastien Gasc[8], Myrtha Hässig[8], Léna LeRoy[2], Annette Jäckel[8], Martin Rubin[8], Peter Wurz[8], Chia-Yu Tzou[8], Urs Mall[5], Björn Fiethe[7], Johan de Keyser[1], Jean-Jacques Berthelier[4], Henri Rème[3], Tamas Gombosi[9], Steven Fuselier[6]
**Institution(s):** *1. BIRA, 2. Center for Space and Habitability, 3. IRAP, 4. LATMOS, 5. Max-Planck Insitut für Sonnenphysik, 6. SwRI, 7. Technische Universität Braunschweig, 8. University of Bern, 9. University of Michigan*

### 503.02 – Comet 67P Nucleus-Coma Interaction and Coma Structure Observed with Rosetta/MIRO

The Microwave Instrument on the Rosetta Orbiter (MIRO), operating at frequencies near 190 GHz and 562 GHz, has been observing Comet 67P nucleus thermal emissions and coma molecular lines since May 2014. As Comet 67P approaches perihelion in its orbit around the Sun, MIRO witnesses that the nucleus heats up and emits more volatiles, creating a dense, complex, and rich coma structure. In order to study nucleus-coma interactions and coma structure and evolution, MIRO has used specially designed scan patterns called “Inner Coma Map” and “Nucleus Gas Emission”, which cover the nucleus, limb, and inner coma region in detail. In this paper, we will present the MIRO molecular line measurements with those scan patterns from January 2015 to August 2015. We have analyzed the line measurements with a non local-thermal-equilibrium molecular radiative transfer model and an optimal estimation method in order to retrieve nucleus and coma parameters such as outgassing rate, column density, expansion velocity, and gas kinetic temperature. Along with the line analysis retrieval results, we will discuss the implication of the results on nucleus-coma interactions, coma structure, and their temporal evolutions.

**Author(s): Seungwon Lee[1]**, Paul von Allmen[1], Samuel Gulkis[1], Mathieu Choukroun[1], Mark Hofstadter[1], Margaret A Frerking[1], Crovisier Jacques[3], Gerhard Beaudin[2]
**Institution(s):** *1. Jet Propulsion Laboratory, 2. LERMA, Observatoire de Paris, 3. LESIA-Observatoire de Paris*

### 503.03 – Observed changes in the physical environment and chemistry in the inner coma of 67P/Churyumov-Gerasimenko

The Optical, Spectroscopic, and Infrared Remote Imaging System (OSIRIS) on board Rosetta consists of two bore-sighted cameras (Keller et al. 2007). Its Wide Angle Camera includes narrow-band filters to image gaseous emission by CS, OH, NH, CN, $NH_2$, Na, and [O I].
OSIRIS monitored gas about once every two weeks for heliocentric distances greater than 2 AU and weekly afterward. Images were calibrated using the OSIRIS pipeline (Tubiana et al. 2015), and further processed to remove the continuum flux and the emission from other molecules with lines that fall within the narrowband filters’ passbands.
Many collimated jets are visible in the continuum images (Lara et al. 2015; Lin et al. 2015). Those jets are not present in the gas images. The morphology of the gas images is either focused in a projected cone (OI, CN) or diffuse and roughly isotropic (OH, NH, CS, $NH_2$). We interpret the first as the signature of prompt emission (where fragmentation of a molecule released from the nucleus directly produces a radical in an excited state), and the second as that of excitation of fragments species after they were formed.
Surprisingly, up to the spring of 2015 all measured surface brightnesses are more than 10x higher than can be accounted for by formation and excitation processes as understood from remote sensing of comets. This changed in the summer of 2015 and current measurements are consistent with photodissociation and fluorescence rates. This change reflects the transition of 67P from a distant comet with extremely low gas production rates to conditions under which comets are normally observed.

**Author(s): Dennis Bodewits[5]**, Luisa M. Lara[3], Fiorangela LaForgia[6], Michael F. A'Hearn[5], Joerg Knollenberg[1], Monica Lazzarin[6], Zhing-Yi Lin[2], Xian Shi[4]
**Institution(s):** *1. Deutsches Zentrum für Luft- und Raumfahrt , 2. Institute for Space Science, National Central University, 3. Instituto de Astrofisica de Andalucia-CSIC, 4. Max-Planck Institut für Sonnensystemforschung, 5. University of Maryland, 6. University of Padova*

### 503.04 – Water and carbon dioxide investigation in the inner coma of 67P/Churyumov-Gerasimenko

The study of 67P/CG coma environment is one of the primary scientific goals of the VIRTIS experiment aboard ESA Rosetta mission.
In the present work, results of 74 observations acquired by VIRTIS-M IR channel in the 1-5 µm spectral range from 8 to 14 April 2015 are discussed. In this time, 67P/CG was at heliocentric distance of 1.9 AU, and the coma activity was monitored for about 10 full comet rotations. This allows one to tentatively correlate gas distribution with active areas on the nucleus and to disentangle gas emissions from dust.
Vibrational emission lines of $H_2O$ and $CO_2$ at 2.67 and 4.27 µm, respectively, are identified by VIRTIS-M imaging channel and mapped from the surface up to about 10 km altitude with a spatial resolution of approximately 40 m/px.
The maximum $H_2O$ emission is mainly concentrated above Aten-Babi and Seth-Hapi active regions, which are located on the neck connecting the two principal lobes. The $CO_2$ column density is quite poor in the neck region, while diffuse emission is clear above the small and great lobe regions. These observations confirm the anti correlation between these two main species, as already noticed by Bockelée-Morvan et al. (2015) and Hässig et al. (2014). Column density of both species decreases with altitude with the CO2 distribution decreasing more rapidly than the H2O. The $H_2O/CO_2$ ratio, which increases with the altitude, varies from 18.7 close to the nucleus to 30.8 at 2-3 km above the nucleus. These values refer to the equatorial region, calculated considering all the longitudes. Gas emission is maximum in the afternoon quadrant, from 12 LST to 18 LST.
VIRTIS-M has revealed with unprecedented spatial resolution the distribution of gaseous species around a cometary nucleus and correlated the emissions with surface-active areas, altitude above the nucleus and local time. Our study confirms the asymmetric distribution of carbon dioxide, which has a more uniform distribution above the comet's nucleus than water vapour (Hässig et al. 2014; Bockelée-Morvan et al. 2015; Capaccioni et al. 2015), and improves our knowledge about the spatial and temporal distribution of the gases in the lower coma.

**Author(s): Alessandra Migliorini[1]**, Giuseppe Piccioni[1], Fabrizio Capaccioni[1], Gianrico Filacchione[1], Dominique Bockelée-Morvan[2], Stefan Erard[2], Cedric Leyrat[2], Michael Combi[3], Nicolas Fougere[3], Maria Cristina De Sanctis[1]
**Institution(s):** *1. IAPS-INAF, 2. LESIA - Observatoire de Paris, 3. Space Physics Research Laboratory, University of Michigan*

### 503.05 – Rosetta-Alice Observations of the Evolution of the CO Coma of Comet 67P/Churyumov-Gerasimenko During Perihelion

*Alice* is a lightweight, low-power far-ultraviolet (700 – 2050 Å) spectrograph onboard *Rosetta* designed for *in situ* imaging spectroscopy of the cometary coma during the rendezvous with comet 67P/Churyumov-Gerasimenko. We initially reported on spectra obtained following orbit insertion in August 2014 that showed multiplets of atomic hydrogen, oxygen, and carbon concentrated above the limb of the comet. From the relative intensities of these multiplets, we identified photoelectron impact dissociative excitation of $H_2O$ and $CO_2$ as the source of the observed atomic emissions. Variations in the relative intensities were interpreted in terms of variations in the molecular abundances. Emission from CO via resonance fluorescence in the Fourth Positive Band system was observed only sporadically. Beginning in July 2015, as the comet approached perihelion on 13 August 2015, the CO emission bands became a strong persistent feature of the observed spectrum, in addition to the atomic multiplets. The CO emissions exhibit a very strong sunward/anti-sunward asymmetry as well as a brightness variation with rotational phase of the comet. CO column densities are derived using the fluorescence model of Lupu et al. (ApJ 670, 1473, 2007) and compared with the predictions of DSMC models and with concurrent measurements of $H_2O$ and $CO_2$ column densities. The long term evolution of the CO coma through the comet's perihelion passage will be presented.

**Author(s): Paul D. Feldman[1]**, Michael F. A'Hearn[5], Jean-Loup Bertaux[3], Lori M. Feaga[5], Joel Wm. Parker[4], Eric Schindhelm[4], Andrew J. Steffl[4], S. Alan Stern[4], Harold A. Weaver[2]
**Institution(s):** *1. Johns Hopkins Univ., 2. Johns Hopkins Univ. Applied Physics Laboratory, 3. LATMOS, 4. Southwest Research Institute, 5. University of Maryland*

### 503.06 – Comet 67P/Churyumov-Gerasimenko's Increasing Atomic Sulfur Abundance Observed by *Rosetta Alice*

*Alice*, NASA's lightweight and low-power far-ultraviolet (FUV) imaging spectrograph onboard ESA's comet orbiting spacecraft *Rosetta* (Stern et al. 2007), is continuing its characterization of the nucleus and coma of the Jupiter family comet 67P/Churyumov-Gerasimenko (C-G) as it approaches and recedes from perihelion. With a spectral range from 700-2050 Å, *Alice* has the ability to detect the atomic sulfur multiplets at 1429 Å, 1479 Å and 1814 Å. Sulfur in C-G's coma is most likely a dissociation product of $CS_2$ and OCS, but could also be produced after a secondary dissociation from $H_2S$ and $SO_2$, all molecular species measured in C-G's coma by *ROSINA*, the *Rosetta* orbiter's mass spectrometer.
Due to low abundances, *Alice* did not detect sulfur atoms at C-G until May 2015 when the comet was at ~1.7 AU and still 3 months from perihelion. Now, sulfur is ubiquitous in *Alice* observations above the limb of the nucleus. There is evidence that there is not a strong dependence of the abundance of sulfur on the distance from the nucleus in the pre-perihelion radial profiles of the gas, which may be indicative of the parent molecule and its distribution. This will be investigated further. The evolution of the presence of the three sulfur multiplets, their relative abundances and excitation processes, and behavior pre- and post-perihelion will be presented.

**Author(s): Lori M. Feaga[6]**, Paul D. Feldman[1], Michael F. A'Hearn[6], Jean-Loup Bertaux[3], Brian A. Keeney[7], Matthew M. Knight[4], John Noonan[5], Joel Wm. Parker[5], Eric Schindhelm[5], Andrew J. Steffl[5], S. Alan Stern[5], Ronald J. Vervack[2], Harold A. Weaver[2]
**Institution(s):** *1. Johns Hopkins University, 2. Johns Hopkins University Applied Physics Lab, 3. LATMOS, CNRS/UVSQ/IPSL, 4. Lowell Observatory, 5. Southwest Research Institute, 6. Univ. of Maryland, 7. University of Colorado*

### 503.07 – Study of the characteristics of the grains in the coma background and in the jets in comet 67P/C-G, as observed by VIRTIS-M onboard of the Rosetta mission

We report observations of the coma of the comet 67P/C-G performed in the near-IR by VIRTIS-M during the escort phase in April 2015. We selected observations performed when the spacecraft was at about 150 km from the nucleus, in order to cover the greatest part of the coma.
We have chosen observations: **a)** with a diffuse coma without any evident strong jets and **b)** with strong jets originating from the "neck" region of the nucleus.
We analyzed the in changes intensity and spectral behavior of the coma along the projected nucleocentric distance, for both the diffuse coma and for the jets.
The results show that:
- The emission of the grains in the diffuse coma is going as 1/rho in the FoV of VIRTIS, (about 2 km), suggesting the absence of grain fragmentation or sublimation. In the region close to the surface, within about 400 m, there is an increase of the emission, which is probably due to instrumental scattered light from the nucleus that can hide the effects due to the grains acceleration.
- Also for the grains in the jets there is no evidence of fragmentation or sublimation in the spectral region where the scattering of the solar radiation is the mechanism of emission. Instead in the thermal region there are strong variations between the regions close to the nucleus and the farther ones.

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**Author(s): Gian-Paolo Tozzi[3]**, G. Rinaldi[3], U. Fink[5], L. Doose[5], F. Capaccioni[3], G. Filacchione[3], D. Bockelée-Morvan[4], S. Erard[4], C. Leyrat[4], G. Arnold[2], M. Blecka[6], M. T. Capria[3], M. Ciarniello[3], M. Combi[7], S. Faggi[3], P. Irwin[1], A. Migliorini[3], E. Paolomba[3], G. Piccioni[3], F. Tosi[3]
**Institution(s):** *1. Departement of Physics, Oxford University, 2. DLR, 3. INAF, 4. LESIA-Observatoire de Paris, 5. LPL, 6. Space Research Centre, PAS, 7. SPRL, The University of Michigan*

### 503.08 – COSIMA - In-situ dust particles measurements in the inner coma of comet 67P/Churyumov-Gerasimenko

COSIMA, the COmetary Secondary Ion Mass Analyzer, is one of the three in-situ dust instruments onboard the Rosetta spacecraft [1]. Since August 2014, Rosetta has been escorting the comet 67P/Churyumov-Gerasimenko on its journey toward the inner solar system.
COSIMA is collecting cometary dust particles by exposing metal targets in the inner coma, from 10 to hundreds of kilometers off the cometary nucleus [2]. Already several thousands of dust particles have been collected. The targets are imaged with the microscope COSISCOPE and some collected particles are then analyzed by SIMS (Secondary Ion Mass Spectrometry). The mass spectra contain positive and negative ions revealing components of the grains originating from selected surface areas. Dust characteristics

will be presented and discussed.
[1] Kissel et al. (2007), Sp. Sci. Rev. 128, 82-867. [2] Schulz et al. (2015), Nature, 518, 216-218.

**Author(s): Anais Bardyn[16]**, Martin Hilchenbach[19], Christelle Briois[14], Jochen Kissel[19], Andreas Koch[27], Yves Langevin[8], Rita Schulz[4], Johan Silen[5], Kathrin Altwegg[20], Luigi Colangeli[4], Herve Cottin[16], Cecile Engrand[2], Henning Fischer[19], Albrecht Glasmachers[25], Eberhard Grün[18], Gerhard Haerendel[17], Hartmut Henkel[27], Herwig Höfner[17], Klaus Hornung[24], Elmar K. Jessberger[11], Harry Lehto[26], Kirsi Lehto[15], Francois Raulin[16], Lena Le Roy[1], Jouni Rynö[6], Wolfgang Steiger[21], Thomas Stephan[23], Laurent Thirkell[14], Roger Thomas[14], Klaus Torkar[12], Kurt Varmuza[13], Karl-Peter Wanczek[10], Nicolas Altobelli[22], Donia Baklouti[8], Nicolas Fray[16], Pedro Lacerda[19], Nicolas Ligier[8], ZhongYi Lin[7], Philippe Martin[14], Sihane Merouane[19], François-Régis Orthous-Daunay[9], John Paquette[19], Claire Revillet[14], Sandra Siljeström[3], Oliver Stenzel[19], Boris Zaprudin[26]
**Institution(s):** *1. Center for Space and Habitability (CSH), University of Bern, 2. Centre de Sciences Nucléaires et de Sciences de la Matière - CSNSM, CNRS/IN2P3-Univ. Paris Sud, 3. Department of Chemistry, Materials and Surfaces, SP Technical Research Institute of Sweden, 4. ESA - ESTEC, 5. Finnish Meteorological Institute, Climate Research, 6. Finnish Meteorological Institute, Observation services, 7. Graduate Institute of Astronomy, 8. Institut d'Astrophysique Spatiale, CNRS / Université Paris Sud, 9. Institut de Planétologie et d'Astrophysique de Grenoble, UMR 5274, Univ. Grenoble Alpes, CNRS, 10. Institut für Anorganische und Physikalische Chemie, Universität Bremen, 11. Institut für Planetologie Universität Münster, 12. Institut für Weltraumforschung, Österreichische Akademie der Wissenschaften, 13. Institute of statistics and mathematical methods in economics, 14. Laboratoire de Physique et Chimie de l'Environnement et de l'Espace, CNRS / Université d'Orléans, 15. Laboratory of Molecular Plant Biology, Dept. of Biochemistry, PharmaCity, 16. LISA, UMR CNRS 7583, Université Paris Est Créteil et Université Paris Diderot, Institut Pierre Simon Laplace, 17. Max-Planck-Institut für extraterrestrische Physik, 18. Max-Planck-Institut für Kernphysik, 19. Max-Planck-Institut für Sonnensystemforschung, 20. Physikalisches Institut, Universität Bern,, 21. RC Seibersdorf Research GmbH Business Field Aerospace Technology, 22. Solar System Science Operation Division, ESA-ESAC, 23. The University of Chicago, Department of the Geophysical Sciences, 24. Universität der Bundeswehr LRT-7, 25. Universität Wuppertal, 26. University of Turku, Department of Physics and Astronomy, Tuorla Observatory, 27. von Hoerner und Sulger GmbH*

### 503.09 – Three-dimensional kinetic modeling of the neutral and charged dust in the coma of Rosetta's target comet 67P/Churyumov-Gerasimenko

Rosetta is the first mission that escorts a comet along its way through the Solar System for an extended amount of time. As a result, the target of the mission, comet 67P/Churyumov-Gerasimenko, is an object of great scientific interest.
Dust ejected from the nucleus is entrained into the coma by the escaping gas. Interacting with the ambient plasma the dust particles are charged by the electron and ion collection currents. The photo and secondary emission currents can also change the particle charge. The resulting Lorentz force together with the gas drag, gravity, and radiation pressure define the dust particle trajectories.
At altitudes comparable to those of the Rosetta trajectory, direction of a dust particle velocity can be significantly different from that in the innermost vicinity of the coma near the nucleus. At such altitudes the angular distribution of the dust grains velocity has a pronounced tail-like structure. This is consistent with Rosetta's GIADA dust observations showing dust grains moving in the anti-sunward direction.
Here, we present results of our model study of the neutral and charged dust in the coma of comet 67P/Churyumov-Gerasimenko, combining the University of Michigan AMPS kinetic particle model and the BATSRUS MHD model. Trajectories of dust particles within the observable size range of Rosetta's GIADA dust instrument have been calculated accounting for the radiation pressure, gas drag, the nucleus gravity, the Lorentz force, and the effect of the nucleus rotation. The dust grain electric charge is calculated by balancing the collection currents at the grain's location. We present angular velocity distribution maps of these charged dust grains for a few locations representative of Rosetta's trajectory around the comet.
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**Author(s): Valeriy Tenishev[2]**, Dmitry Borovikov[2], Michael R Combi[2], Nicolas Fougere[2], Zhenguang Huang[2], Andre Bieler[2], Kenneth Hansen[2], Gabor Toth[2], Xianzhe Jia[2], Yinsi Shou[2], Tamas Gombosi[2], Martin Rubin[3], Alessandra Rotundi[1], Vincenzo Della Corte[1]
**Institution(s):** *1. INAF Istituto di Astrofisica e Planetologia Spaziali, 2. Univ. of Michigan, 3. University of Bern*

## 504 – Extrasolar Planets: Giant Planet Atmospheres

### 504.01 – Saturn as a Transiting Exoplanet

Previous investigations of exoplanet atmospheres have not targeted those resembling the gas giant planets in our solar system. These types of exoplanets are too cold to be directly imaged or observed in emission, and their low transit probabilities and frequencies make characterization via transmission spectroscopy a challenging endeavor. However, studies of cold giant exoplanets would be highly valuable to our understanding of planet formation and migration and could place the gas giant members of our own solar system in a greater context. Here, we use solar occultations observed by the Visual and Infrared Mapping Spectrometer aboard the *Cassini* Spacecraft to extract the 1 to 5 μm transmission spectrum of Saturn, as if it were a transiting exoplanet. We detect absorption features from several molecules despite the presence of ammonia clouds. Self-consistent exoplanet atmosphere models show good agreement with Saturn's transmission spectrum but fail to reproduce the largest feature in the spectrum. We also find that atmospheric refraction determines the minimum altitude that could be probed during mid-transit of a Saturn-twin exoplanet around a Sun-like star. These results suggest that transmission spectroscopy of cold, long-period gaseous exoplanets should be possible with current and future observatories.

**Author(s): Paul A. Dalba[1]**, Philip S. Muirhead[1], Jonathan J. Fortney[3], Matthew M. Hedman[4], Philip D. Nicholson[2], Mark J. Veyette[1]
**Institution(s):** *1. Boston University, 2. Cornell University, 3. University of California, Santa Cruz, 4. University of Idaho, Moscow*

### 504.02D – Transmission spectral properties of clouds for hot Jupiter exoplanets

Clouds play an important role in the atmospheres of planetary bodies. It is expected that, like all the planetary bodies in our solar system, exoplanet atmospheres will also have substantial cloud coverage, and evidence is mounting for clouds in a number of hot Jupiters. To better characterise planetary atmospheres, we need to consider the effects these clouds will have on the observed broadband transmission spectra. Here we examine the expected cloud condensate species for hot Jupiter exoplanets and the effects of various grain sizes and distributions on the resulting transmission spectra from the optical to infrared, which can be used as a broad framework when interpreting exoplanet spectra. We note that significant infrared absorption features appear in the computed transmission spectrum, the result of vibrational modes between the key species in each condensate, which can potentially be very constraining. While it may be hard to differentiate between individual condensates in the broad transmission spectra, it may be possible to discern different vibrational bonds, which can distinguish between cloud formation scenarios, such as condensate clouds or photochemically generated species. Vibrational mode features are shown to be prominent when the clouds are composed of small sub-micron sized particles and can be associated with an accompanying optical scattering slope. These infrared features have potential implications for future exoplanetary atmosphere studies conducted with JWST, where such vibrational modes distinguishing condensate species can be probed at longer wavelengths.

**Author(s): Hannah Wakeford[1]**, David Kent Sing[2]
**Institution(s):** *1. NASA GSFC, 2. University of Exeter*

### 504.03 – Exploring Equilibrium Chemistry for Hot Exoplanets

It has been established that equilibrium chemistry is usually achieved deep in the atmosphere of hot Jovians where timescales are short (Line and Young 2013). Thus, equilibrium chemistry has been used as a starting point (setting initial conditions) for evaluating disequilibrium processes. We explore parameters of setting these initial conditions including departures from solar metallicity, the number of species allowed in a system, the types of species allowed in a system, and different thermodynamic libraries in an attempt to create a standard for evaluating equilibrium chemistry. NASA's open source code Chemical Equilibrium and Applications (CEA) is used to calculate model planet abundances by varying the metallicity, in the pressure regime of 0.1 to 1 bar. These results are compared to a variety of exoplanets (Teq between 600 and 2100K) qualitatively by color maps of the dayside with different temperature redistributions. Additionally, CEA (with an updated thermodynamic library) is validated with the thermochemical model presented in Venot et al. (2012) for HD 209458b and HD 189733b. This same analysis has then been extended to the cooler planet HD 97658b. Spectra are generated from both models' abundances using the open source code transit (https://github.com/exosports/transit) using the opacities of 15 molecules. We make the updated CEA thermodyanamic library and supporting Python scripts to do the CEA analyses available open source. This work was supported by NASA Planetary Atmospheres grant NNX12AI69G.

**Author(s): Sarah Blumenthal3**, Joseph Harrington3, Avi Mandell[2], Eric Hébrard[2], Olivia Venot[1], Patricio Cubillos3, Ryan Challener3
**Institution(s):** *1. Katholieke Universiteit Leuven, 2. NASA Goddard Space Flight Center, 3. University of Central Florida*

### 504.04D – Microphysics of Exoplanet Clouds and Hazes

Clouds and hazes are ubiquitous in the atmospheres of exoplanets. However, as most of these planets have temperatures between 600 and 2000 K, their clouds and hazes are likely composed of exotic condensates such as silicates, metals, and salts. We currently lack a satisfactory understanding of the microphysical processes that govern the distribution of these clouds and hazes, thus creating a gulf between the cloud properties retrieved from observations and the cloud composition predictions from condensation equilibrium models. In this work we present a 1D microphysical cloud model that calculates, from first principles, the rates of condensation, evaporation, coagulation, and vertical transport of chemically mixed cloud and haze particles in warm and hot exoplanet atmospheres. The model outputs the equilibrium number density of cloud particles with altitude, the particle size distribution, and the chemical makeup of the cloud particles as a function of altitude and particle mass. The model aims to (1) explain the observed variability in “cloudiness” of individual exoplanets, (2) assess whether the proposed cloud materials are capable of forming the observed particle distributions, and (3) examine the role clouds have in the transport of (cloud-forming) heavy elements in exoplanet atmospheres.

**Author(s): Peter Gao[1]**, Björn Benneke[1], Heather A. Knutson[1], Yuk L. Yung[1]
**Institution(s):** *1. Caltech*

### 504.05 – The Effect of Photochemistry and Quenching on the Atmospheric Composition of Young Directly Imaged Giant Planets

The last decade has seen significant progress on the direct detection and characterization of young, self-luminous giant planets at wide orbital separation from their host stars. Several of these planets show evidence for disequilibrium processes like transport-induced quenching in their atmospheres, which affects the relative abundances of methane and carbon monoxide and has other compositional consequences. Photochemistry is also potentially important on many of these planets, despite their large orbital distance, because the young host stars often have prodigious UV output. Disequilibrium chemical processes such as the above can alter the expected spectroscopic signatures of the planets and potentially confuse determinations of bulk elemental ratios, which provide important insights into planet-formation mechanisms. We use a thermochemical and photochemical kinetics and transport model to investigate the effects of photochemistry and quenching on young, directly imaged planets. Results for specific exoplanets such as the HR 8799 planets and 51 Eri b will be presented, as will more general trends as a function of planet mass, orbital distance, bulk atmospheric abundances, and stellar properties.

**Author(s): Julianne I. Moses3**, Michael R Line5, Channon Visscher[1], Mark S Marley[2], Jonathan J Fortney5, Nikole K Lewis4, Michael J Wolff3
**Institution(s):** *1. Dordt College, 2. NASA Ames Research Center, 3. Space Science Institute, 4. Space Telescope Science Institute, 5. University of California - Santa Cruz*

### 504.06 – WASP-12b According to the Bayesian Atmospheric Radiative Transfer (BART) Code

We present the Bayesian Atmospheric Radiative Transfer (BART) code for atmospheric property retrievals from transit and eclipse spectra, and apply it to WASP-12b, a hot (~3000 K) exoplanet with a high eclipse signal-to-noise ratio. WASP-12b has been controversial. We (Madhusudhan et al. 2011, Nature) claimed it was the first planet with a high C/O abundance ratio. Line et al. (2014, ApJ) suggested a high $CO_2$ abundance to explain the data. Stevenson et al. (2014, ApJ, atmospheric model by Madhusudhan) add additional data and reaffirm the original result, stating that $C_2H_2$ and HCN, not included in the Line et al. models, explain the data. We explore several modeling configurations and include Hubble, Spitzer, and ground-based eclipse data.
BART consists of a differential-evolution Markov-Chain Monte Carlo sampler that drives a line-by-line radiative transfer code through the phase space of thermal- and abundance-profile parameters. BART is written in Python and C. Python modules generate atmospheric profiles from sets of MCMC parameters and integrate the resulting spectra over observational bandpasses, allowing high flexibility in modeling the planet without interacting with the fast, C portions that calculate the spectra. BART's shared memory and optimized opacity calculation allow it to run on a laptop, enabling classroom use. Runs can scale constant abundance profiles, profiles of thermochemical equilibrium abundances (TEA) calculated by the included TEA code, or arbitrary curves. Several thermal profile parameterizations are available. BART is an open-source, reproducible-research code. Users must release any code or data modifications if they publish results from it, and we encourage the community to use it and to participate in its development via http://github.com/ExOSPORTS /BART.
This work was supported by NASA Planetary Atmospheres grant NNX12AI69G and NASA Astrophysics Data Analysis Program grant NNX13AF38G. J. Blecic holds a NASA Earth and Space Science Fellowship.

**Author(s): Joseph Harrington4**, Patricio E. Cubillos4, Jasmina Blecic4, Ryan C. Challener4, Patricio M. Rojo3, Nate B. Lust[1], M. Oliver Bowman[2], Sarah D. Blumenthal4, Andrew SD Foster4, A. J. Foster4
**Institution(s):** *1. Princeton University, 2. UCLA, 3. Universidad de Chile, 4. University of Central Florida*

### 504.07 – HST hot Jupiter transmission spectral survey: The atmospheric circulation of a large hot Jupiter sample

Even as we move towards characterizing smaller and cooler exoplanets, hot Jupiters continue to be the best transiting planets for probing the atmospheric properties of exoplanets and refining current theory. Here we present results from a comprehensive atmospheric circulation study of nine transiting hot Jupiters that probe a wide range of planetary properties, including orbital distance, rotation rate, mass, radius, gravity and stellar insolation. We utilize these circulation models to aid in the interpretation of transmission spectra obtained using the Space Telescope Imaging Spectrograph (STIS) and Wide Field Camera 3 (WFC3) as a part of a large Hubble Space Telescope (HST) transmission spectral survey. These observations have shown a range of spectral behavior over optical and infrared wavelengths, suggesting diverse cloud and haze properties in their atmospheres. Our "grid" of models recovers trends shown in other parametric studies of hot Jupiters, particularly increased day-night temperature contrast with increasing equilibrium temperature and equatorial superrotation. Furthermore, we show that three-dimensional variations in temperature, particularly across the western and eastern terminators and from the equator to the pole, can vary by hundreds of Kelvin. This can result in vastly different cloud properties across the limb, which can lead to variations in transmission spectra. Finally, we comment on prospects with the James Webb Space Telescope (JWST) to further characterize hot Jupiters out to longer wavelengths.

**Author(s): Tiffany Kataria[5]**, David K. Sing[5], Nikole K. Lewis[2], Jonathan J. Fortney[4], Mark S. Marley[1], Adam P. Showman[3]
**Institution(s):** *1. NASA Ames Research Center, 2. Space Telescope Science Institute, 3. University of Arizona, 4. University of California at Santa Cruz, 5. University of Exeter*

### 504.08 – Structure and Evolution of Internally Heated Hot Jupiters

The transit radii of many close-in extrasolar giant planets, or "hot Jupiters," are systematically larger than those expected from models considering only cooling from an initial high-entropy state. Though these planets receive strong irradiation, with equilibrium temperatures of 1000-2500 Kelvin, the absorption of stellar incident flux in the upper atmosphere alone cannot explain these anomalous radii. More promising mechanisms involve irradiation-driven meteorological activity, which penetrates much deeper into the planet than direct stellar heating. This circulation can lead to large-scale mixing and downward transport of kinetic energy, both processes whereby a fraction of the stellar incident power is transported downwards to the interior of the planet. Here we consider how deposition of heat at different pressure levels or structural locations within a planet affects the resulting evolution. To do so, we run global gas giant evolutionary models with with the stellar structure code MESA including additional energy dissipation. We find that relatively shallow atmospheric heating alone can explain the transit radii of the hot Jupiter sample, but heating in the convective zone is an order of magnitude more efficient regardless of exact location. Additionally, a small difference in atmospheric heating location can have a significant effect on radius evolution, especially near the radiative-convective boundary. The most efficient location to heat the planet is at the radiative-convective boundary or deeper. We expect that shear instabilities at this interface may naturally explain energy dissipation at the radiative-convective boundary, which typically lies at a pressure of ~1 kilobar after 5 Gyr for a planet with the mass and incident stellar flux of HD 209458b. Hence, atmospheric processes are most efficient at explaining the bloated radii of hot Jupiters if they can transport incident stellar power downwards to the top of the inner convective zone.

**Author(s): Thaddeus D Komacek[1]**, Andrew N Youdin[1]
**Institution(s):** *1. University of Arizona*

## 505 – Mars's Atmosphere

### 505.01 – How relevant is heterogeneous chemistry on Mars? Strong tests via global mapping of water and ozone (sampled via $O_2$ dayglow)

Ozone and water are powerful tracers of photochemical processes on Mars. Considering that water is a condensable with a multifaceted hydrological cycle and ozone is continuously being produced / destroyed on short-time scales, their maps can test the validity of current 3D photochemical and dynamical models. Comparisons of modern GCM models (e.g., Lefèvre et al. 2004) with certain datasets (e.g., Clancy et al. 2012; Bertaux et al. 2012) point to significant disagreement, which in some cases have been related to heterogeneous (gas-dust) chemistry beyond the classical gas-gas homogeneous reactions.
We address these concerns by acquiring full 2D maps of water and ozone (via $O_2$ dayglow) on Mars, employing high spectral infrared spectrometers at ground-based telescopes (CRIRES/VLT and CSHELL/NASA-IRTF). By performing a rotational analysis on the $O_2$ lines, we derive molecular temperature maps that we use to derive the vertical level of the emission (e.g., Novak et al. 2002). Our maps sample the full observable disk of Mars on March/25/2008 (Ls=50°, northern winter) and on Jan/29/2014 (Ls=83°, northern spring). The maps reveal a strong dependence of the $O_2$ emission and water burden on local orography, while the temperature maps are in strong disagreement with current models. Could this be the signature of heterogeneous chemistry? We will present the global maps and will discuss possible scenarios to explain the observations.
This work was partially funded by grants from NASA's Planetary Astronomy Program (344-32-51-96), NASA's Mars Fundamental Research Program (203959.02.02.20.29), NASA's Astrobiology Program (344-53-51), and the NSF-RUI Program (AST-805540). We thank the administration and staff of the European Southern Observatory/VLT and NASA-IRTF for awarding observing time and coordinating our observations.
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**Author(s): Geronimo Luis Villanueva[2]**, Michael J Mumma[2], Robert E Novak[1]
**Institution(s):** *1. Iona College, 2. NASA-Goddard Space Flight Center*

### 505.02 – Investigating SEP and Auroral Consequences of the Magnetic Topology Near Mars

The diffuse UV aurora at Mars, discovered by MAVEN's IUVS, has been shown to be caused by solar energetic electrons observed by MAVEN's SEP detector, but the spatial patterns of these emissions are still under study. In the meantime, BATS-R-US models of the Mars-solar wind interaction have been shown to describe the in-situ plasma and field observations well, to first order. We use a set of nominal simulations together with a few case study results to examine the geometry of the magnetic field line footpoints that are 'open'-or connected to the interplanetary field- in these models. In addition, the subset of these that are directly connected to the Sun via the upstream magnetic field are identified. We use these results for comparisons with the reported diffuse auroral occurrence map, and to describe what can happen during the passage of an ICME. We also consider the potential use of these field line tracings for understanding the geometry of the SEP ion 'shadowing' at the MAVEN orbital period.

**Author(s): Janet Luhmann5**, Christina O. Lee5, Rob Lillis5, Davin Larson5, David L. Mitchell5, Shannon M. Curry5, Takuya Hara5, Jack Connerney4, Jared Espley4, Nick Schneider3, Chuanfei Dong[1], Yingjuan Ma[2], Bruce M. Jakosky3
**Institution(s):** *1. AOSS University of Michigan, 2. IGPP UCLA, 3. LASP University of Colorado, 4. NASA GFSC, 5. SSL, University of California, Berkeley*

### 505.03 – Impacts of an Interplanetary Coronal Mass Ejection and the Crustal Magnetic Fields to the Martian hot O corona

An interplanetary coronal mass ejection (ICME) is a large amount of mass entrained in the heliospheric magnetic field and propagating outward from the Sun into the interplanetary medium. Upon arrival at Mars, ICMEs interact with its upper atmosphere and ionosphere, causing important impacts in the planetary environment. In March 2015, a strong solar event was observed and associated with a major ICME. The major ICME events aroused a chain of events on Mars, which were detected by the instruments onboard Mars Atmosphere and Volatile EvolutioN (MAVEN). The consequences in the upper atmosphere are directly related to the important processes that lead to the atmospheric escape. We report here our examinations of the impacts of the March 8$^{th}$ ICME event on the Martian hot O corona by using our 3D framework, which couples the Mars application of the Adaptive Mesh Particle Simulator (M-AMPS), the Mars Global Ionosphere-Thermosphere Model (M-GITM), and the Mars multi-fluid MHD (MF-MHD) model. Also, we present the effects of the crustal magnetic fields on the structure of the hot O corona to study the interesting signatures of the crustal magnetic fields. Due to the minimal impacts of the ICME deep in the thermosphere and ionosphere, where the maximum production of hot O occurs, our model results showed a stable hot O corona during and after the peak ICME event. However, the structure of the corona was affected by the existence of the crustal magnetic fields with a decrease in escape rate.

**Author(s): Yuni Lee[1]**, Michael Combi[1], Valeriy Tenishev[1], Stephen Bougher[1]
**Institution(s):** *1. University of Michigen*

### 505.04 – A Comet Engulfs Mars: MAVEN observations of Comet Siding Spring's Effects on the Martian Magnetosphere

The nucleus of Comet C/2013 A1 (Siding Spring) passed within 135,000 km of Mars on Oct. 19, 2014. Thus the cometary coma and the plasma it produces washed over Mars for several hours producing significant effects in the martian magnetosphere and upper atmosphere. We present observations from MAVEN's particles and fields instruments that show the martian magnetosphere was severely distorted during the comet's passage. We note four specific major effects: 1) a variable induced magnetospheric boundary, 2) a strong rotation of the magnetic field as the comet approached, 3) severely distorted and disordered ionospheric fields during the comet's closest approach, and 4) unusually strong magnetosheath turbulence lasting hours after the comet left. We argue that the comet had effects comparable to a large solar storm (in terms of incident energy) and so was a fascinating opportunity to explore atmospheric escape, MAVEN's primary science objective.

**Author(s): Jared R. Espley5**, Gina A DiBraccio5, Jack Connerney5, David Brain4, Jacob Gruesbeck5, Yasir Soobiah5, Jasper Halekas3, Michael Combi[1], Janet Luhmann[6], Yingjuan Ma[2], Yingdong Jia[2], Bruce Jakosky4
**Institution(s):** *1. Atmospheric, Oceanic and Space Sciences Department, University of Michigan, 2. Department of Earth Planetary and Space Sciences, UCLA, 3. Department of Physics and Astronomy, University of Iowa, 4. Laboratory for Atmospheric and Space Physics, University of Colorado, 5. NASA Goddard Space Flight Center, 6. Space Sciences Laboratory, University of California*

### 505.05 – Mars Exospheric Temperature Trends as Revealed by MAVEN NGIMS Measurements

The Martian dayside upper thermosphere and exosphere temperatures (Texo) have been the subject of considerable debate and study since the first Mariner ultraviolet spectrometer (UVS) measurements (1969–1972), up to recent Mars Express SPICAM UVS measurements (2004–present) (e.g., see reviews by Stewart 1987; Bougher et al. 2000, 2014; Müeller-Wodarg et al. 2008; Stiepen et al. 2014). Prior to MAVEN, the Martian upper atmosphere thermal structure was poorly constrained by a limited number of both in-situ and remote sensing measurements at selected locations, seasons, and periods scattered throughout the solar cycle. Nevertheless, it is recognized that the Mars orbit eccentricity determines that both the solar cycle and seasonal variations in upper atmosphere temperatures must be considered together. The MAVEN NGIMS instrument measures the neutral composition of the major gas species (e.g. He, N, O, CO, $N_2$, $O_2$, NO, Ar and $CO_2$) and their major isotopes, with a vertical resolution of ~5 km for targeted species and a target accuracy of <25% for most of these species (Mahaffy et al. 2014; 2015). Corresponding temperatures can now be derived from the neutral scale heights (especially $CO_2$, Ar, and $N_2$) (e.g. Mahaffy et al. 2015; Bougher et al. 2015). Texo mean temperatures spanning ~200 to 300 km are examined for both Deep Dip and Science orbits over 11-February 2015 (Ls ~ 290) to 14-July 2015 (Ls ~ 12). During these times, dayside sampling below 300 km occurred from the dusk terminator, across the dayside, and approaching the dawn terminator. NGIMS temperatures are investigated to extract spatial (e.g. SZA) and temporal (e.g. orbit-to-orbit, seasonal, solar rotational) variability and trends over this sampling period. Solar and seasonal driven trends in Texo are clearly visible, but orbit-to-orbit variability is significant, and demands further investigation to uncover the major drivers that are responsible.

**Author(s): Stephen W. Bougher4**, Kirk Olsen4, Kali Roeten4, Jared Bell[2], Paul Mahaffy[1], Mehdi Benna[1], Meredith Elrod[1], Bruce Jakosky3
**Institution(s):** *1. Goddard Space Flight Center, 2. National Institute for Aerospace, 3. Univ. Colorado, 4. Univ. of Michigan*

### 505.06 – MAVEN data-model comparison of the response of heavy pick-up ions during extreme conditions at Mars

MAVEN has observed multiple interplanetary coronal mass ejection (ICME) events at Mars, showing dramatic enhancements of heavy ion precipitation into the upper atmosphere. Heavy ion precipitation is the primary driver of sputtering, which is believed to be one of the main channels for atmospheric erosion during earlier epochs of our solar system when the solar activity and EUV intensities were much higher than the present day. Using MAVEN observations of extreme solar wind events, we simulate atmospheric precipitation using fluid and kinetic models and compare with MAVEN observations. The fluid model reproduces the observed features in the solar wind density, velocity and magnetic field seen along the MAVEN orbit during the March 8th ICME event, and the subsequent precipitation shows strong agreement with other published predictions of sputtering in extreme conditions.

**Author(s): Shannon Curry3**, Janet G. Luhmann3, Chuanfei D. Dong[6], David Brain4, Francois Leblanc[1], Ronan Modolo[1], Jasper Halekas5, James McFadden3, Jack Connerney[2], Jared Espley[2], David Mitchell3, Davin Larson3, Takuya Hara3, Bruce Jakosky4
**Institution(s):** *1. LATMOS, UVSQ, 2. NASA Goddard Space Flight Center, 3. UC Berkeley, Space Sciences Laboratory, 4. University of Colorado, LASP, 5. University of Iowa, 6. University of Michigan*

### 505.07 – Initial Results from the MAVEN IUVS Echelle Channel

The study of the evolution of water on Mars includes understanding the high D/ H ratio in the atmosphere and surface water today, believed to be linked to the historic loss of a large volume of primordial water (the lighter H escapes faster than the heavier D). Toward this end, the IUVS instrument on MAVEN contains the first echelle spectrograph to be sent to another planet. The system has a novel optical design to enable long-aperture measurements of emission lines in the absence of continuum, intended primarily to measure the H and D Ly α emission lines and thereby the D/H ratio from the martian upper atmosphere. The system also detects the OI 1304 triplet with the three component lines well resolved. The specific scientific goal of the echelle channel is to measure the H and D Ly α emissions, and to discover how the H and D densities, temperatures, and escape fluxes vary with location, season, topography, etc. Recent IR observations indicate large variations in the D/H ratio in the lower atmosphere from location to location, and possibly seasonal changes [Villanueva *et al.* 2015]. HST and MEX measurements of the H corona of Mars show large (order of magnitude) changes in the H exosphere and escape flux with changing seasons and/or heliospheric distance [Clarke *et al.* 2014; Chaffin *et al.* 2014]. Early results from the echelle channel regarding how these parameters apply to martian deuterium will be presented.

**Author(s): John T. Clarke[1]**, Majd Mayassi[1], William McClintock[2], Nick Schneider[2], Justin Deighan[2], Ian Stewart[2], Greg Holsclaw[2], Bruce Jakosky[2]
**Institution(s):** *1. Boston Univ., 2. Univ of Colorado*

### 505.08 – Mars atmospheric escape constrained using MAVEN IUVS coronal observations

Every planetary atmosphere is capped by a corona: an extended, extremely tenuous region where collisions are negligible and particles follow ballistic trajectories. At Mars, the corona is especially extended due to the low gravity of the planet, and a large number of coronal particles are on escaping trajectories. Such escape has played a critical role in the history of the Mars system, likely removing a substantial fraction of the water initially present on the planet, but the mechanism and magnitude of this escape remains poorly constrained. Currently in orbit at Mars, MAVEN's Imaging Ultraviolet Spectrograph (IUVS) is mapping the distribution of oxygen and hydrogen above 200 km at a high spatial and temporal cadence, revealing a dynamic corona in unprecedented detail. Results will be presented demonstrating that the H in the corona is not spherically symmetric in its distribution, and can potentially be used as a tracer of thermospheric general circulation; and that non-thermal "hot" O (in contrast with more spatially confined "cold" thermal O) is ionospherically sourced with a characteristic energy of 1.1 eV and responds to solar EUV forcing. These results will be interpreted in terms of their impact on our current understanding of how atmospheric escape operates today. We will also discuss how these processes may have acted in the past to deplete Mars' initial water inventory, potentially altering the redox balance of the planet and atmosphere through differential escape of H and O.

**Author(s): Michael S. Chaffin5**, Justin Deighan5, Jean-Yves Chaufray3, Sonal Jain5, Ian Stewart5, Bill McClintock5, Matteo Crismani5, Arnaud Stiepen[2], Greg Holsclaw5, John Clarke[1], Franck Montmessin3, Frank Eparvier5, Ed Thiemann5, Phil Chamberlain4, Nick Schneider5, Bruce Jakosky5
**Institution(s):** *1. Boston University, 2. Laboratoire de Physique Atmosphérique et Planétaire (LPAP), 3. LATMOS/IPSL, 4. NASA Goddard, 5. University of Colorado*

### 505.09 – Structure and variability of the Martian upper atmosphere: Ultraviolet dayglow observations by MAVEN/IUVS

Mars has been studied extensively at ultraviolet wavelengths starting from Mariner 6 and 7, Mariner 9, and more recently by SPICAM aboard Mars Express. The results from these measurements reveal a large variability in the composition and structure of the Martian upper atmosphere. However, due to the lack of simultaneous measurements of energy input (such as solar electromagnetic and particle flux), and limitations in the observation geometry and data itself, this variability is still not fully understood.
We report a comprehensive study of Mars dayglow observations by the Imaging Ultraviolet Spectrograph (IUVS) aboard the Mars Atmosphere and Volatile EvolutioN (MAVEN) satellite, focusing on vertical and global upper atmospheric structure and seasonal variability. The dayglow emission spectra show features similar to previous UV measurements at Mars. IUVS has detected a second, low-altitude peak in the emission profile of OI 297.2 nm, confirming the prediction that the absorption of solar Lyman alpha emission is an important energy source there. We find a significant drop in thermospheric scale height and temperature between Ls = 218° and Ls = 337 - 352°, attributed primarily to the decrease in solar activity and increase in heliocentric distance. The $CO_2^+$ UVD peak intensity is well correlated with simultaneous observations of solar 17 - 22 nm irradiance at Mars by Extreme Ultraviolet Monitor (EUVM) aboard MAVEN. Variations of the derived $CO_2$ density also exhibit significant persistent global structure with longitudinal wavenumbers 1, 2 and 3 in a fixed local solar time frame, pointing to non-migrating atmospheric tides driven by diurnal solar heating. We will present and discuss the variability in Martian UV dayglow, its dependence on solar EUV flux, and the importance of IUVS observations in our current understanding of Mars' thermosphere.

**Author(s): Justin Deighan3**, Sonal K. Jain3, Daniel Y. Lo5, A. Ian F. Stewart3, Nicholas M. Schneider3, Arnaud Stiepen3, J. Scott Evans[2], Michael H. Stevens[6], Roger V. Yelle5, Scott L. England7, Michael Scott Chaffin3, Matteo Crismani3, William E. McClintock3, John T. Clarke[1], Greg M. Holsclaw3, Franck Lefevre4, Franck Montmessin4, Edward M.B. Thiemann3, Frank Eparvier3, Bruce M. Jakosky3
**Institution(s):** *1. Center for Space Physics, Boston University, 2. Computational Physics, Inc., 3. Laboratory for Atmospheric and Space Physics, University of Colorado, 4. LATMOS/CNRS, 5. Lunar and Planetary Laboratory, University of Arizona, 6. Naval Research Laboratory, 7. Space Sciences Laboratory, University of California*

## 506 – Comets: Physical Characteristics, Dynamics, and Composition

### 506.01D – Comets as natural laboratories: Interpretations of the structure of the inner heliosphere

Much has been learnt about the heliosphere's structure from in situ solar wind spacecraft observations. Their coverage is however limited in time and space. Comets can be considered to be natural laboratories of the inner heliosphere, as their ion tails trace the solar wind flow. Solar wind conditions influence comets' induced magnetotails, formed through the draping of the heliospheric magnetic field by the velocity shear in the mass-loaded solar wind. I present a novel imaging technique and software to exploit the vast catalogues of amateur and professional images of comet ion tails. My projection technique uses the comet's orbital plane to sample its ion tail as a proxy for determining multi-latitudinal radial solar wind velocities in each comet's vicinity. Making full use of many observing stations from astrophotography hobbyists to professional observatories and spacecraft, this approach is applied to several comets observed in recent years. This work thus assesses the validity of analysing comets' ion tails as complementary sources of information on dynamical heliospheric phenomena and the underlying continuous solar wind.
Complementary velocities, measured from folding ion rays and a velocity profile map built from consecutive images, are derived as an alternative means of quantifying the solar wind-cometary ionosphere interaction, including turbulent transient phenomena such as coronal mass ejections. I review the validity of these techniques by comparing near-Earth comets to solar wind MHD models (ENLIL) in the inner heliosphere and extrapolated measurements by ACE to the orbit of comet C/2004 Q2 (Machholz), a near-Earth comet. My radial velocities are mapped back to the solar wind source surface to identify sources of the quiescent solar wind and heliospheric current sheet crossings. Comets were found to be good indicators of solar wind structure, but the quality of results is strongly dependent on the observing geometry.

**Author(s): Yudish Ramanjooloo2**, Geraint H. Jones1, Andrew J. Coates1, Mathew J. Owens3
**Institution(s):** *1. University College London (MSSL), 2. University of Hawaii, 3. University of Reading (Dept of Meteorology)*

### 506.02D – Five years of comet narrow band photometry and imaging with TRAPPIST

TRAPPIST is a 60-cm robotic telescope in La Silla Observatory [1] mainly dedicated to the study of exoplanets and comets. The telescope is equipped with a set of narrow band cometary filters designed by the NASA for the Hale-Bopp observing campaign [2]. Since its installation in 2010, we gathered a high quality and homogeneous data set of more than 30 bright comets observed with narrow band filters. Some comets were only observed for a few days but others have been observed weekly during several months on both sides of perihelion. From the images, we derived OH, NH, CN, $C_2$, and $C_3$ production rates using a Haser [3] model in addition to the Afρ parameter as a proxy for the dust production. We computed production rates ratios and the dust color for each comet to study their composition and followed the evolution of these ratios and colors with the heliocentric distance.
The TRAPPIST data set, rich of more than 10000 images obtained and reduced in an homogeneous way, allows us to address several fundamental questions such as the pristine or evolutionary origin of composition differences among comets. The evolution of comet activity with the heliocentric distance, the differences between species, and from comet to comet, will be discussed. Finally, the first results about the one year campaign on comet C/2013 US10 (Catalina) and our recent work on the re-determination of Haser scalelengths will be presented.

[1] Jehin et al., The Messenger, 145, 2-6, 2011
[2] Farnham et al., Icarus, 147, 180-204, 2000
[3] Haser, Bulletin de l'Académie Royal des Sciences de Belgique,63, 739, 1957

**Author(s): Cyrielle Opitom1**, Emmanuel Jehin1, Jean Manfroid1, Damien Hutsemékers1, Michaël Gillon1, Pierre Magain1
**Institution(s):** *1. University of Liège*

### 506.03 – Daughter Species Abundances in Comet C/2014 Q2 (Lovejoy)

We present analysis of high spectral resolution optical spectra of C/2014 Q2 (Lovejoy) acquired with the Tull Coude spectrometer on the 2.7-meter Harlan J. Smith Telescope at McDonald Observatory and the ARCES spectrometer mounted on the 3.5-meter Astrophysical Research Consortium Telescope at Apache Point Observatory. Both Tull Coude and ARCES provide high spectral resolution (R=30,000-60,000) and a large spectral range of approximately 3500-10000 Angstroms. We obtained two observation epochs, one in February 2015 at a heliocentric distance of 1.3 AU, and another in May 2015 at a heliocentric distance of 1.9 AU. Another epoch in late August 2015 at a heliocentric distance of 3.0 AU is scheduled. We will present production rates of the daughter species CN, $C_3$, CH, $C_2$, and $NH_2$. We will also present $H_2O$ production rates derived from the [OI]6300 emission, as well as measurements of the flux ratio of the [OI]5577 Angstrom line to the sum of the [OI]6300 and [OI]6364 Angstrom lines (sometimes referred to as the oxygen line ratio). This ratio is indicative of the $CO_2$ abundance of the comet. As we have observations at several heliocentric distances, we will examine how production rates and mixing ratios of the various species change with heliocentric distance. We will compare our oxygen line measurements to observations of $CO_2$ made with Spitzer, as well as our other daughter species observations to those of candidate parent molecules made at IR wavelengths.

**Author(s): Adam McKay3**, Anita Cochran3, Neil Dello Russo1, Michael Kelley2
**Institution(s):** *1. Johns Hopkins Applied Physics Laboratory, 2. University of Maryland, 3. University of Texas Austin*

### 506.04 – A Comprehensive Near-Infrared Spectral Survey of comet C/2014 Q2 (Lovejoy): 0.9-2.5 µm

In February 2015, we acquired a comprehensive high resolution spectral survey of comet C/2014 Q2 (Lovejoy) in the 0.9-2.5 µm range, with GIANO - the near-IR spectrograph on TNG (the Italian Telescopio Nazionale Galileo in Canary Island, ES). We detected emission from multiple ro-vibrational bands of $H_2O$, the red system of CN, and many other features whose precursors are now being identified. We also searched for overtone lines of other volatiles (e.g., $CH_4$, CO, and $C_2$) along with OH prompt and fluorescent emissions, and atomic carbon prompt emission at 9823/9850 Å. These species are relevant to astrobiology, owing to questions regarding the origin of water and organics on terrestrial planets.
Comets are the most pristine bodies in the solar system and water is the most abundant constituent of cometary ice – its production rate is used to quantify cometary activity. Along with the water production rate, the newly discovered water bands offer the opportunity to measure the ortho-para ratio and nuclear spin temperature with high accuracy in a single instrument setting, thereby eliminating many sources of systematic error and permitting comparisons amongst comets. This can clarify the nature and meaning of the spin temperature in the cosmic context. High-resolution spectroscopy in the infrared (2.7 - 5 µm) is a well-established powerful tool for quantifying abundances of trace compounds and water in cometary comae. Implementing this approach in the near-IR region (0.9-2.5 µm) will extend this capability to new band systems and will also reduce thermal noise significantly.
These observations open new pathways for cometary science in the near-infrared spectral range (0.9-2.5 µm) and establish the feasibility of astrobiology-related scientific investigations with future high resolution IR spectrographs on 30-m class telescopes, e.g., the HIRES spectrograph on the E-ELT telescope. This work is part of Sara Faggi's Ph.D. thesis project.

**Author(s): Sara Faggi1**, Geronimo Luis Villanueva2, Michael J Mumma2, John Robert Brucato1, Gian-Paolo Tozzi1, Ernesto Oliva1
**Institution(s):** *1. INAF Osservatorio Astrofisico di Arcetri, 2. NASA Goddard Space Flight Center*

### 506.05 – The distribution and excitation of $CH_3OH$ in comet C/2012 K1 (PanSTARRS) from ALMA

We present measurements of spatially and spectrally resolved $CH_3OH$ emission from the coma of comet C/2012 K1 (PanSTARRS) observed using the Atacama Large Millimeter/submillimeter Array (ALMA) in June 2014. The CH3OH emission is centrally peaked, with a spatial profile consistent with production from the sublimation of ices from the nucleus. From the detection of multiple lines of $CH_3OH$ in the J=7-6 and K=3-2 bands around 339 and 252 GHz, respectively, the line-of-sight average rotational excitation temperatures ($T_{rot}$) have been derived as a function of spatial position across the coma. At the $CH_3OH$ peak, we find Trot=92 K, falling to about 40 K at a distance of 1000 km. The temperature does not fall monotonically but shows a double-peaked structure, indicative of a heating source at distances >=500 km from the nucleus.

**Author(s): Stefanie N. Milam2**, Martin A Cordiner2, Jeremie Boissier1, Steven B Charnley2, Anthony Remijan3, Michael Mumma2, Geronimo Villanueva2, Lucas Paganini2, Dominique Bockelee-Morvan5, Jacques Crovisier5, Nicolas Biver5, Boncho Bonev2, Yi-Jehng Kuan4, Dariuz Lis5
**Institution(s):** *1. Institut de Radioastronomie Millimetrique, 2. NASA Goddard Space Flight Center, 3. National Radio Astronomy Observatory, 4. National Taiwan Normal University, 5. Observatoire de Paris*

### 506.06 – Spatial-Spectral Studies of Cometary Volatiles and the Physical Environment of Inner Cometary Atmospheres

How is water released in comets - directly from the nucleus versus sublimation from icy grains in the coma? How common and how prevalent are icy grains as a source of gas-phase water (and other

volatiles) among the active comet population? These questions are being addressed through synergy between spatial-spectral studies of native volatiles in comets and the physical models tested against them. This synergy is extending the state-of-the-art in both domains. Ground-based near-IR spectroscopy (Keck, NASA IRTF, and ESO VLT) allowed measurements of spatially resolved inner coma temperatures and column densities for H2O – the most abundant volatile in the coma. These measurements motivated the inclusion of new physics in the models. The evolved models now open new questions and trigger improvement in the accuracy of measured temperature profiles, most recently extended to other molecules (HCN in the near-IR) and to other wavelength domains (CH3OH, through ALMA; S. Milam et al., this meeting). The net result is deeper quantitative insight into the competition among processes that cause heating and cooling of the coma and into the prevalent mechanism(s) for release of native volatiles in the gas phase.
The same inner-coma modeling formalisms are used to interpret both the environment of Rosetta's mission target (67P/Churyumov–Gerasimenko) and those from the ground-based observations reported here (Combi et al. 2015, LPSC, #1714; Fougere et al., this meeting). While ground-based spectroscopy offers less detail than in-situ missions, it can probe the comae of many comets that may differ greatly from one another and from Rosetta's target, thereby assessing the extent to which the inner-coma environment of 67P is unique, and how it relates to other comets.
We gratefully acknowledge support from NASA Planetary Atmospheres, Solar System Workings, Planetary Astronomy, and Astrobiology programs, and from NSF Astronomy and Astrophysics Research Grants program.

**Author(s): Boncho P. Bonev[1]**, Nicolas Fougere3, Geronimo L. Villanueva[1], Michael J. Mumma[2], Michael R. Combi3, Michael A. DiSanti[2], Lucas Paganini[1], Martin Cordiner[1], Erika L. Gibb4, Stefanie N. Milam[2]
**Institution(s):** *1. Catholic University of America, 2. NASA Goddard Center for Astrobiology, 3. University of Michigan, 4. University of Missouri - St. Louis*

### 506.07 – Lightcurves and revised masses of the large particles at comet 103P/Hartley 2

Comet 103P/Hartley 2 is a hyperactive comet. Such comets have nuclei with surface areas comparable to the surface area required to sustain their water production rates, implying the surface is near 100% active. However, images of the nucleus and inner coma by the *Deep Impact Flyby* spacecraft show signficant localized activity, dominated by a single strong active area (A'Hearn et al. 2011, Science 332, 1396). This active area seems to be driven by carbon dioxide ice sublimation, which releases water ice into the coma (Protopapa et al. 2014, Icarus 238, 191). It has been hypothesized that this water-ice-rich material is the origin of the comet's hyperactivity, but this has not yet been definitively demonstrated.
The Deep Imact spacecraft also imaged thousands of point sources surrounding the nucleus of the comet (A'Hearn et al. 2011). These sources are particles ejected by the comet, the largest of which is estimated to have a radius between 30 and 400 cm. The wide range in the radius estimate is due to the unknown photometric properties of the particles. If the particles are icy, they may contribute a significant fraction of the comet's water production rate (Kelley et al. 2013, Icarus 222, 634).
To better elucidate the physical properties of the particles, we generated particle lightcurves, based on the identifications of Hermalyn et al. (2013, Icarus 222, 625) and a an independent (manual) particle search. We find no clear correlation with time or phase angle, suggesting the lightcurves are primarily driven by particle shape rather than sublimation, fragmentation, or phase effects. Three lightcurves are double-peaked, indicating rotation periods near 75 to 300 s. At least one other lightcurve suggests a rotation period of order 20 s.
We also present corrections to the analysis of Kelley et al. (2013) that decrease the total large particle population mass estimates by two orders of magnitude. Despite the revision, the large particles may still account for the comet's hyperactivity if they are more like the low-albedo, ice-rich nucleus rather than high-albedo icy grains. However, an understanding of the large particle production rate is needed before definitive statements may be made.

**Author(s): Michael S. Kelley[2]**, Tony L. Farnham[2], Brendan Hermalyn[1], Dennis Bodewits[2], Michael F. A'Hearn[2]
**Institution(s):** *1. NASA Ames Research Center, 2. Univ. of Maryland*

### 506.08 – Volatile Abundance and Distribution in the Tempel 1 Ejecta Cloud

On 4 Jul 2005 the Deep Impact Impactor Spacecraft collided with comet Tempel 1, creating an ejecta cloud that was observed by the Deep Impact Flyby Spacecraft (DIF) as well as Earth and space based observatories. The High Resolution Instrument Infrared Spectrometer (HRI-IR) onboard DIF acquired several spectral scans of this ejecta cloud in the minutes immediately after impact. HRI-IR has a spectral range of 1.05 to 4.85 microns. This spectral range allows for water vapor, water ice, organics, $CO_2$ and CO to be detected simultaneously, if each species is sufficiently abundant. We present an analysis of the quantity and spatial distribution of water, organics and $CO_2$ in the Tempel 1 ejecta cloud. Variation in abundance, either absolute or relative, will be compared to morphological features in the ejecta cloud present in visible images acquired by the Medium and High Resolution Imagers onboard DIF. The composition of the ejecta cloud will also be compared with that of the 2 Jul 2005 natural outburst and quiescent activity levels at Tempel 1.

**Author(s): Mark J. Moretto[1]**, Lori M. Feaga[1], Michael F. A'Hearn[1], Silvia Protopapa[1], Jessica M. Sunshine[1], Tony L. Farnham[1]
**Institution(s):** *1. University of Maryland*

### 506.09 – A Preliminary Analysis of Cometary Dust in the 1st Year of the NEOWISE Restarted Mission

As some of the most pristine objects in the Solar System, comets present an opportunity to understand the mechanics and chemistry of the planetary formation era. By studying a large number of comets in different dynamical classes, we can better understand the ensemble properties of the different classes, and begin to characterize the evolution that may have occurred since their formation.
In late 2013, the WISE spacecraft was brought out of hibernation, and renamed NEOWISE with a renewed goal to detect and characterize small bodies using its 3.4 and 4.6-micron bands. Survey operations began in December 2013 [1], and the first year of data was publicly released in March 2015 [2]. During the course of the first year of the restarted mission, over 60 comets were serendipitously detected by NEOWISE at heliocentric distances between ~1-7.5 AU, including 3 newly discovered comets. The comets detected were split roughly evenly between short-period and long-period comets, and many displayed extended dust structures. Several of the comets were detected multiple times over the course of the year, and some were also seen during the prime WISE mission. This long baseline allows for an intriguing analysis of long-term cometary behavior.
NEOWISE has sampled the behavior of these comet dynamical sub-types over the thermal infrared and near-infrared reflected-light regimes, where effects from different particle size ranges of dust may dominate the morphologies and observed fluxes. We present a preliminary analysis of the cometary dust seen in these data, including dynamical models to constrain the sizes and ages of the dust particles. We discuss how these results compare to those obtained for the comets seen in the 12 and 22-micron WISE prime mission data.
**Acknowledgments:** This publication makes use of data products from (1) WISE, which is a joint project of UCLA and JPL/Caltech, funded by NASA; and (2) NEOWISE, which is a project of JPL/Caltech, funded by the Planetary Science Division of NASA. EK, RS, and SS gratefully acknowledge support from the NASA Postdoctoral Program. **References:** [1] Mainzer, A. et al., 2014, ApJ, 792:1; [2] Cutri, R. et al., 2015, http://wise2.ipac.caltech.edu /docs/release/neowise/expsup/

**Author(s): Emily A. Kramer[2]**, James M Bauer[2], Yanga R Fernández[4], Amy K Mainzer[2], Tommy Grav[3], Joseph R Masiero[2], Carolyn R Nugent[1], Sarah Sonnett[2], Roc Cutri[1], Rachel Stevenson[2]
**Institution(s):** *1. Infrared Processing and Analysis Center, 2. Jet Propulsion Laboratory, 3. Planetary Science Institute, 4. University of Central Florida*

### 506.10 – Is comet 19P/Borrelly changing its spin state?

We observed comet 19P/Borrelly from September 6-12 and October 9-14, 2014 at the SOAR telescope in Chile. The comet was at heliocentric and geocentric distances of 2.9 AU and 2.2 AU in September, and of 2.7 AU and 2.4 AU in October. We carried out lightcurve observations to derive an accurate rotation period to be compared with that derived by Mueller et al. (2010; Icarus 209, 745) from observations of the 2000/2001 apparition.
The ultimate goal for these and lightcurve observations of other comets is to derive changes in the rotation period to test whether the changes are really independent of the active fraction as seen for four other comets (Samarasinha and Mueller 2013; ApJL 775, article id. L10). Establishing such a correlation will enable the prediction of rotational changes for other comets as well. It will also have far reaching implications for nuclear activity and its characteristics, as well as for understanding the reaction torques due to outgassing.
We gratefully acknowledge support for this work from NASA PAST grant NNX14AG73G.

**Author(s): Beatrice E. A. Mueller[1]**, Nalin H Samarasinha[1]
**Institution(s):** *1. Planetary Science Institute*

### 506.11 – 322P/SOHO 1: Sunskirting Comet or Asteroid?

Comet 322P/SOHO 1 (P/1999 R1) is a unique object: a short period comet (P = 3.99 yr) on a “sunskirting orbit” (q = 0.053 AU, or ~11 solar radii) with no dynamical linkage to any other known comets. 322P was discovered in SOHO images in 1999, and has been seen by SOHO on every subsequent orbit: 2003, 2007, and 2011 (it is expected to be observed by SOHO again during its next perihelion passage in 2015 September). During this time it has not displayed an obvious coma or tail in SOHO images, but has exhibited a non-asteroidal lightcurve that strongly suggests the presence of an unresolved coma. Equilibrium temperatures during these observations exceed 1000 K, so it is unclear if 322P is active due to sublimation of volatile ices like a typical comet or if it is an otherwise inactive object that is losing material through more exotic processes such as sublimation of refractory materials or thermal fracturing. Due to the very large uncertainty in orbits derived from SOHO observations and 322P’s assumed small size, 2015 was the first reasonable opportunity to recover it at large heliocentric distance and attempt to determine its heritage: traditional comet or asteroid. We recovered 322P on 2015 May 22 with the VLT and observed it again on five epochs in June and July with Spitzer, the VLT, and the Discovery Channel Telescope. These are the first successful observations of any SOHO-discovered short period comet at traditional cometary distances. 322P appeared pointlike in all images (heliocentric distances from 2.1 to 1.2 AU), implying an inactive object having a diameter of a few hundred meters. We will report on these observations, focusing on constraining properties of 322P such as activity level, color, and albedo that may help us deduce whether or not it is of a cometary or asteroidal origin.

**Author(s): Matthew M. Knight[1]**, Alan Fitzsimmons[2], Michael S. P. Kelley[4], Colin Snodgrass[3]
**Institution(s):** *1. Lowell Observatory, 2. Queen's University Belfast, 3. The Open University, 4. University of Maryland*

## 507 – Origins of Planetary Systems

### 507.01D – Collisional properties and dynamical accretion of centimeter-sized protoplanetesimals

The seeds of planetesimals that formed in the turbulent gaseous environment of the nascent protoplanetary disk have many barriers to overcome in their growth from millimeter to meter-sized and larger objects, such as collisional disruption and orbital decay. Centimeter-sized agglomerates can be weakly bound and quite fragile and at these sizes self-gravity is almost non-existent. Electrostatic surface forces such as van der Waal’s forces play a critical role in holding loosely bound rubble-piles together. We wish to further understand the mechanical, material, collisional properties, and outcomes of collisions between cm-sized rubble-piles at low speeds that may lead to accretion. The collisional outcomes can be determined by a set of definable collision parameters, and experimental constraints on these parameters will improve formation models for planetesimals. We have carried out a series of laboratory microgravity collision experiments of small aggregates to determine under what conditions collisional growth can occur using mm-sized silica beads and $SiO_2$ dust as simulants. In our free-fall chambers we obtain collision velocities ranging from 1 to 200 cm $s^{-1}$ for 1-2 cm aggregates with pressures ~0.1 mbars. We measure coefficients of restitution, sticking thresholds, and fragmentation thresholds, then compare the results of our experiments with numerical simulations using a collisional N-body code. We find that cm-sized agglomerates made up of mm-sized particles (or of mm-sized aggregates of micron sized $SiO_2$ dust) are very weakly bound and require high porosity and internal cohesion to avoid fragmentation in agreement with both simulations and collision experiments. The velocity threshold for sticking is found to be near 7 cm $s^{-1}$, far from the fragmentation threshold of ~1 m $s^{-1}$ for cm-sized bodies. Quiescent regions in the mid-plane of the disk may cultivate abnormally low relative velocities permitting sticking to occur (~1 cm $s^{-1}$), however, without a well-defined path to formation it is difficult to determine whether collisional accretion as a mechanism can overcome low thresholds for sticking and fragmentation. We discuss this research’s implications to both the meter-barrier and planetesimal formation.

**Author(s): Akbar Whizin3**, Joshua E Colwell3, Jürgen Blum[1], Mark C Lewis[2]
**Institution(s):** *1. Technische Universität Braunschweig, 2. Trinity University, 3. University of Central Florida*

### 507.02 – Global Evolution of Solids in the Nebula: the Role of Porosity in Particle Growth and Radial Migration

Primitive chondrite parent bodies apparently accreted over several Myr during which time the nebula gas is expected to have evolved significantly. The extended range of radioisotope ages observed for primitive body formation can then best be explained if the nebula were weakly turbulent; this environment frustrates planetesimal formation but millimeter-to-meter-size particles can grow by sticking, and possibly undergo substantial inward radial migration, before being destroyed by mutual collisions or evaporating in a warmer environment. This migration can lead to a significant redistribution of the nebula condensibles relative to the evolving gas, challenging the popular concepts of "minimum mass nebula" and "local cosmic abundance". Moreover, as drifting particles transform from solid to vapor at "evaporation fronts", they can fundamentally change the nebula chemical and isotopic composition. Yet, the problem of primary accretion remains complicated, because although even moderate turbulence can extend the period of accretion over those implied by the meteorite record, it may do so too well. Estrada et al. (2015, submitted to ApJ, arXiv:1506.01420) have found that particle sizes are so readily restricted by the combination of bouncing, fragmentation and radial drift over the range of models studied that much of the nebula solids can be removed from the outer portions of the disk and become concentrated in the inner regions in relatively short timescales, where they may eventually be lost altogether. The rapid clearing of the outer disk is due to growth not being fast enough to overcome the radial drift barrier. However, only solid particles were considered. Fractal growth by low velocity sticking of small monomers will cause the particles to have a much lower density than the monomers themselves. Coupled with the stickiness and strength of icy particles, we expect that these fluffy aggregates can grow large, but maintain low relative velocities, allowing for continued growth without compaction. Here we assess whether the consideration of particle porosity, particularly outside the snow line, may allow for particles to overcome the radial drift barrier and potentially grow into larger bodies.

**Author(s): Paul R. Estrada[2]**, Jeffrey N. Cuzzi[1]
**Institution(s):** *1. NASA Ames Research Center, 2. SETI Institute*

### 507.03D – Planetary growth by the accretion of pebbles

Pebbles, approximately cm-sized solids that drift through a protoplanetary disc, provide a reservoir of material that can be efficiently accreted by planetary embryos due to the dissipating effect of gas drag (Lambrechts & Johansen, 2012).
Here, we will highlight the robust implications of pebble accretion on the formation of planets throughout the protoplanetary disc.
In the outer disc, icy pebbles form by coagulation and consequently start drifting inwards. Nevertheless, we find that the pebble surface densities are sufficiently high to form giant planets on wide orbits, before the gas disc disperses after a few Myr (Lambrechts & Johansen, 2014). Growth is only halted when cores reach sizes of around 10 Earth masses, when their gravity creates pressure bumps trapping the inwards drifting pebbles.This accretion cutoff triggers the attraction of a massive gaseous envelope. Additionally, the fast growth of giant planets prevents the loss of the cores by type-I migration (Lambrechts et al 2014, Bitsch et al 2015).
Closer to the star, interior to the ice line, pebble accretion takes on a different form. There, chondrule-sized particles lead to the formation of much smaller, Mars-sized embryos, before the pebble flux is terminated by the growth of the gas giants (Morbidelli et al, 2015). We will also discuss ongoing work on the conditions under which much larger Super-Earths can form.

**Author(s): Michiel Lambrechts[2]**, Anders Johansen[1], Bertram Bitsch[1], Alessandro Morbidelli[2]
**Institution(s):** *1. Lund University, 2. Observatoire de la Côte d'Azur*

### 507.04 – Early Solar System Leftovers: Testing Solar System Formation Models

One of the most intriguing predictions of the Grand Tack model is the presence of volatile poor objects in the Oort cloud that were swept from the region where the terrestrial planets formed. This volatile-poor material is represented today by ordinary chondrites, enstatite chondrites and differentiated planetesimals. These are the main constituents of the S-type asteroids that reside in the inner Solar system. According to the Grand Tack model, the fraction of S-type material in cometary orbits should be around 0.1-0.2%.
Recent Pan-STARRS 1 discoveries of objects on long-period comet orbits that are minimally active while at small perihelia have suggested the intriguing possibility that these could potentially represent inner solar system material that was ejected into the outer solar system during planet migration, that is now making its way back in. The first object discovered, C/2013 P2 has a spectrum redder than D-type objects, but exhibits low-level activity throughout its perihelion passage. The second one, C/2014 S3, appears to have an S-type asteroid spectrum, and likewise exhibits low-level activity.
Nearly 100 of these objects have now been identified, approximately half of which are still observable, and more are being discovered. We will report on observations made for a selection of these objects with several facilities including Gemini N 8 m, VLT 8 m, Canada-France-Hawaii 3.6 m, PS1 2 m, UH2.2 m, HCT 2 m, and the Lowell 1.8 m telescopes. We will discuss the implications of seeing volatile activity in these objects.

**Author(s): Karen Jean Meech3**, Bin Yang[1], Jan Kleyna3, Olivier R. Hainaut[1], Jacqueline V. Keane3, Marco Micheli[6], Svetlana Berdyugina5, Bhuwan Bhatt[2], Devendra Sahu[2], Henry Hsieh4, Peter Veres3, Richard J. Wainscoat3, Timm-Emanuel Riesen7, Heather Kaluna3
**Institution(s):** *1. European Southern Observatory, 2. Indian Institute of Astrophysics, 3. Institute for Astronomy, 4. Institute of Astronomy & Astrophysics, Academia Sinica, 5. Kiepenheuer-Institut fur Sonnenphysik, 6. SSA NEO Coordination Centre, ESA, 7. University of Bern*

### 507.05 – The effects of the formation of a giant planet on the evolution of the protoplanetary disk: the case of Jupiter in the Solar System

The formation of a giant planet is one of the milestones in the life of a planetary system, as it plays a leading role in shaping its subsequent evolution. Once the core of the forming giant planet reaches the critical mass needed to trigger the hydrodynamical instability in the surrounding nebular gas and start the rapid phase of gas accretion, the planetary system in which the planet is embedded suddenly experience the appearance of a strong gravitational perturber. Even in absence of migration, this event will trigger a 0.5-1 Myr-long phase of violent remixing and enhanced collisional evolution of the planetary bodies in the protoplanetary disk. For what it concerns the giant planet itself, this primordial bombardment will result in the capture of high-Z material from a wide orbital range, including the inner regions of the planetary system. For what it concerns the other bodies of the protoplanetary disk, this phase of remixing and bombardment will result in the collisional erosion of the smallest planetesimals in the dynamically-excited orbital regions and in the delivery of water and volatile elements to the inner regions of the planetary system.
While the mass growth of the giant planet is necessary and sufficient condition to trigger this primordial bombardment, planetary migration plays a major role in determining its intensity.
Using the formation of Jupiter in the Solar System as our case study, we will illustrate how this event affects the Jovian system and the asteroid belt. Concerning the latter, we will also discuss how the composition of asteroid Vesta, whose formation and differentiation predate the formation of Jupiter, supplies information on the primordial dynamical evolution of the giant planet.

**Author(s): Diego Turrini[1]**
**Institution(s):** *1. Institute for Space Astrophysics and Planetology INAF-IAPS*

### 507.06 – In-situ Formation of Mars-like Planets - Results from Hundreds of N-body Simulations That Include Collisional Fragmentaion

Dynamical simulations of the formation of the Solar System have been successful at reproducing the broad characteristics of the terrestrial planets, however they have consistently struggled to reproduce the small mass of Mars within the timescale provided by geochemical constraints. This has prompted the development of new models that invoke various mechanisms, such as giant planet migration, that result in the formation a small Mars. Due primarily to the computationally intensive nature of these models, most previous studies were based on a small (less than a dozen) number of simulations and did not include the effects of collisional fragmentation. However, these systems are highly stochastic and require a large number of simulations in order to infer the results in a statistical manner. Here we show that by performing 150 N-body simulations of terrestrial planet formation around the Sun that include collisional fragmentation, the formation of Mars-analogs is a natural outcome, albeit not a common one. Approximately 13% of the simulations produced a Mars-sized planet near Mars' current orbit that accreted at least 90% of its mass within 3 Myr. The current architecture of the planets in our Solar System can be thought of as one draw from a distribution of planetary systems that can form from essentially the same protoplanetary disk. These results support the idea that Mars may essentially be a stranded embryo that survived the giant impact phase without a significant amount of accretion or erosion, but that it need not be the only outcome from the chaotic process of forming planets.

**Author(s): Thomas Barclay**[1], Elisa V. Quintana[1]
**Institution(s):** *1. NASA Ames Research Center*

## 507.07 – Determining the Location of the Snowline in an Externally-Photoevaporated Solar Nebula

The water snowline in the solar nebula, the point beyond which water exists abundantly as ice, is often taken to lie at 2.7 AU from the Sun, where temperatures are ~170 K, the sublimation point of water [1,2]. While superficially consistent with the spatial distribution of (wet) C-type and (dry) S-type asteroids between 2-3AU [3], most disk models place the snowline closer to ~1AU [4]. Aside from temperature, radial transport and outward diffusion of water vapor, and the inward drift of ices also determine where the snowline is [5,6]. Over many Myr, a steady cycling of water inward and outward across the T=170 K line balance out, with an enhanced ice abundance outside creating the 'snowline'[2]. But external effects like photoevaporation of the nebula by nearby massive stars can potentially shift this balance, lead to net outward water vapor transport from the inner nebula [7,8], pushing the snowline beyond T=170 K, thus giving rise to water-poor planets. To test this hypothesis, we have first built a 1+1D protoplanetary disk evolution model, incorporating viscosity due to the magnetorotational instability with a non-uniform turbulent viscosity α across disk radius r, ionization equilibrium with dust, and external photoevaporation [8]. Our simulation results suggest that the structure of the photoevaporated solar nebula with a non-uniform α(r) was more complex than previously thought, with the following features: (i) very steep Σ profile ($\Sigma(r)=\Sigma_0 r^{-p}$, where slope p = 3–5, > $p_{MMSN}$=1.5) due to the varying α(r), that is further steepened by the effect of dust and photoevaporation, and (ii) transition radius (where net disk mass flow changes from inward flow to outward) that is present very close to the star (~3AU). We apply these new results to study the distribution of water in the solar nebula. **References:** [1] Hayashi, C., (1981) *PThP.Supp.* 70, 35-53 [2] Stevenson,D., & Lunine,J., (1988) *Icarus* 75, 146-155 [3] Gradie, J., & Tedesco, E.,(1982) *Science* 216, 1405-1407 [4] Sasselov, D.D., & Lecar, M., (2000) *ApJ* 528, 995-998 [5] Cuzzi, J .N ., & Zahnle, K .J., (2004) *ApJ* 614, 490-496 [6] Ciesla, F. J., & Cuzzi, J. N. (2006) *Icarus* 181, 178-204 [7] Desch S.J.(2012)LPSC abstract #2770 [8] Kalyaan, A. et al.(in review)

**Author(s): Anusha Kalyaan**[1], Steven Desch[1]
**Institution(s):** *1. Arizona State University*

## 507.08 – Nebular dead zone effects on the D/H ratio in chondrites and comets

Comets and chondrites show non-monotonic behaviour of their Deuterium to Hydrogen (D/H) ratio as a function of their formation location from the Sun. This is difficult to explain with a classical protoplanetary disk model that has a decreasing temperature structure with radius from the Sun.
We want to understand if a protoplanetary disc with a dead zone, a region of zero or low turbulence, can explain the measured D/H values in comets and chondrites. We use time snapshots of a vertically layered disk model with turbulent surface layers and a dead zone at the midplane. The disc has a non-monotonic temperature structure due to increased heating from self-gravity in the outer parts of the dead zone. We couple this to a D/H ratio evolution model in order to quantify the effect of such thermal profiles on D/H enrichment in the nebula.
We find that the local temperature peak in the disk can explain the diversity in the D/H ratios of different chondritic families. This disk temperature profile leads to a non-monotonic D/H enrichment evolution, allowing these families to acquire their different D/H values while forming in close proximity. The formation order we infer for these families is compatible with that inferred from their water abundances. However, we find that even for very young disks, the thermal profile reversal is too close to the Sun to be relevant for comets.
[1] Ali-Dib, M., Martin, R. G., Petit, J.-M., Mousis, O., Vernazza, P., and Lunine, J. I. (2015, in press A&A). arXiv:1508.00263.

**Author(s): Mohamad Ali-Dib3**, R. G. Martin4, J.-M. Petit5, O. Mousis[1], P. Vernazza[1], J. I. Lunine[2]
**Institution(s):** *1. Aix Marseille Université, CNRS, LAM (Laboratoire d'Astrophysique de Marseille) UMR 7326, 2. Center for Radiophysics and Space Research, Space Sciences Building, Cornell University, 3. Department of Physical & Environmental Sciences, University of Toronto at Scarborough, 4. Department of Physics and Astronomy, University of Nevada, 5. Université de Franche-Comté, Institut UTINAM, CNRS/INSU, UMR 6213, Observatoire de Besançon*

## 507.09 – $C^xO$ (x=16,17,18) isotopologue ratios in the solar photosphere

Determination of the oxygen isotope ratios in the solar photosphere is essential to constraining the formation environment of the solar system. The solar CO fundamental and first-overtone bands were previously measured by the shuttle-borne ATMOS Fourier transform spectrometer (FTS), and with the National Solar Observatory FTS on the McMath-Pierce telescope at Kitt Peak. Analyzing the rovibrational bands from these photospheric spectra, a 3D convection model was employed to calculate ratios with improved uncertainties ($^{16}O/^{17}O$=2738±118 and $^{16}O/^{18}O$ =511±10; Ayres et al. 2013), which fall between the terrestrial values and those inferred from solar wind measurements by the *Genesis* spacecraft. However, differences in published CO dipole moment functions yielded a range of isotopic ratios spanning ~ 3 % in $\delta^{18}O$. Here we re-evaluate the CO dipole moment function in order to obtain more accurate isotope ratios for the photosphere. We used a new set of dipole moments from HITEMP which were accurately determined by both semi-empirical and ab initio methods. Preliminary values of isotope ratios using the new dipole moments are in better agreement with the inferred photosphere values from *Genesis*, showing that the solar photosphere is isotopically similar to primitive inclusions in meteorites, but different from the terrestrial planets by ~ 6 %. New spectral observations are needed to reduce uncertainties in photospheric $C^{17}O$ abundances.

**Author(s): James Lyons**[1], Ehsan Gharib-Nezhad[1], Thomas Ayres[2]
**Institution(s):** *1. Arizona State University, 2. University of Colorado*

## 507.10 – Consolidating and Crushing Exoplanets: Did It Happen Here?

Kepler revealed the common existence of tightly-packed super-Earth systems around solar-type stars, existing entirely inside the orbit of our Venus. Those systems must be stable for the ages of their host stars (~10^9 years); their formation mechanism must provide inter-planet spacings that permit long-term stability. If one postulates that most planetary systems form with tightly-packed inner planets, their current absence in some systems could be explained by the collisional destruction of the inner system after a period of meta-stability.
We posit that our Solar System also originally had a system of multiple planets interior to the orbit of Venus. This would resolve a known issue that the energy/angular momentum of our inner-planet system is best explained by accreting the current terrestrial planets from a disk limited to 0.7-1.1 AU; in our picture the disk material closer to the Sun also formed planets, but they have since been destroyed. By studying the orbital stability of systems like the known Kepler systems, we demonstrate that orbital excitation and collisional destruction could be confined to just the inner parts of the system. In this scenario, Mercury is the final remnant of the inner system's destruction via a violent multi-collision (and/or hit-and-run disruption) process. This would provide a natural explanation for Mercury's unusually high eccentricity and orbital inclination; it also fits into the general picture of long-timescale secular orbital instability, with Mercury's current orbit being unstable on 5 Gyr time scales. The common decade spacing of instability time scales raises the intriguing possibility that this destruction occurred roughly 0.6 Gyr after the formation of our

Solar System and that the lunar cataclysm is a preserved record of this apocalyptic event that began when slow secular chaos generated orbital instability in our former super-Earth system.

**Author(s): Brett Gladman[1]**, Kathryn Volk[1]
**Institution(s):** *1. Univ. of British Columbia*

### 507.11 – Exoplanet Population Estimate from Kepler Data

The intrinsic population of exoplanets around Kepler target stars is estimated by comparing the observed numbers of planets at each radius and period against a simulation that accounts for the probability of transit and the estimated instrument sensitivity. By assuming that the population can be modeled as a function of period times a function of radius, and further assuming that these functions are broken power laws, sufficient leverage is gained such that the well-measured short-period planet distribution can effectively be used as a template for the less-well sampled long-period terrestrial planets. The resulting population distribution provides a challenge to models of the origin and evolution of planetary systems.

**Author(s): Wesley A. Traub[1]**
**Institution(s):** *1. Jet Propulsion Laboratory*

## 508 – Icy Satellites

### 508.01 – From One Come Many: A diversity of crater populations from a single impacting population, with application to the Saturnian (and Galilean) Satellites

We present our recent analyses that quantify the spatial and size-frequency distribution (SFD) of crater populations on the mid-sized Saturnian (and Galilean) satellites. The results demonstrate that a single-sized impactor will generate both (i) different-sized primary craters on the icy satellites, and (ii) observably different secondary crater populations (both in terms of SFDs and spatial distributions) between the satellites.
*Relative magnitude of secondaries and their SFDs:* The number of secondary craters generated by a primary impact is a function of the size of the primary crater; v_min, the minimum speed needed to make a secondary ;and v_esc, the escape speed of the target body. The primary crater size controls the amount of ejected material, v_min defines the lower limit of that ejected mass that can make secondaries, and v_esc defines the upper limit of the mass that can make secondaries (i.e. material that escapes the target body cannot make secondaries). Because a single-sized impactor will make different-sized primaries on each of the satellites (resulting in different masses available to make secondaries), and v_esc also varies between the satellites, different amounts of ejecta are available to make secondaries. Because surface gravity is a factor in the size of a crater, a given-sized ejecta fragment will make a different-sized secondary on the satellites even given the same impact speed.
*Spatial distribution of secondaries:* Because of varying surface gravities, g, of planetary bodies, a given ejectum speed will launch a fragment different distances. In conjunction with v_min, the spatial density of adjacent secondaries (or even their existence) will vary depending on surface gravity. At progressively smaller g, v_min results in greater distances, and dense annular clusters surrounding the primary crater won't appear, except for the largest primary craters. On the lower-g objects, v_min corresponds to travel distances that are significant fractions of the object's circumference. Ejecta that make adjacent secondaries on a higher-g object may make a significant population of background secondaries on low-g objects.

**Author(s): Edward B. Bierhaus[1]**, Luke Dones[2], Stuart Robbins[2]
**Institution(s):** *1. Lockheed Martin, 2. Southwest Research Institute*

### 508.02 – Crustal Failure in Large Icy Bodies from a Strong Tidal Encounter

Close tidal encounters among large planetesimals and satellites are more common than grazing or direct impacts. Using a mass spring model simulation, we look at the deformation of the surface of an elastic spherical body caused by a nearly parabolic close tidal encounter with a body that has mass similar to that of the primary body. We delineate a regime for tidal encounters that induce sufficient stress on the surface for brittle failure of an icy crust. Simulated cracks caused by extension of the crust extend a large fraction of the radius of body. Tidal encounters give an alternative mechanism for formation of long graben complexes and chasma on icy satellites such as Dione, Tethys, Ariel and Charon.

**Author(s): Alice C. Quillen[2]**, David Giannella[2], John Shaw[1]
**Institution(s):** *1. Laboratory for Laser Energetics , 2. Univ. of Rochester*

### 508.03 – Discovering sub-micron ice particles across Dione' surface

Water ice is the most abundant component of Saturn's mid-sized moons. However, these moons show an albedo asymmetry – their leading sides are bright while their trailing side exhibits dark terrains. Such differences arise from two surface alteration processes: (i) the bombardment of charged particles from the interplanetary medium and driven by Saturn's magnetosphere on the trailing side, and (ii) the impact of E-ring water ice particles on the satellites' leading side. As a result, the trailing hemisphere appears to be darker than the leading side. This effect is particularly evident on Dione's surface. A consequence of these surface alteration processes is the formation or the implantation of sub-micron sized ice particles.
The presence of such particles influences and modifies the surfaces' spectrum because of Rayleigh scattering by the particles. In the near infrared range of the spectrum, the main sub-micron ice grains spectral indicators are: (i) asymmetry and (ii) long ward minimum shift of the absorption band at 2.02 μm; (iii) a decrease in the ratio between the band depths at 1.50 and 2.02 μm; (iv) a decrease in the height of the spectral peak at 2.6 μm; (v) the suppression of the Fresnel reflection peak at 3.1 μm; and (vi) the decrease of the reflection peak at 5 μm relative to those at 3.6 μm. We present results from our ongoing work mapping the variation of sub-micron ice grains spectral indicators across Dione' surface using Cassini-VIMS cubes acquired in the IR range (0.8–5.1 μm). To characterize the global variations of spectral indicators across Dione' surface, we divided it into a 1°x1° grid and then averaged the band depths and peak values inside each square cell.
We will investigate if there exist a correspondence with water ice abundance variations by producing water ice' absorption band depths at 1.25, 1.52 and 2.02 μm, and with surface morphology by comparing the results with ISS color maps in the ultraviolet, visible and infrared ranges. Finally, we will compare the results with those obtained for Enceladus, Tethys, and Mimas

**Author(s): Francesca Scipioni3**, Pual Schenk3, Federico Tosi[2], Roger Clark4, Cristina Dalle Ore5, Jean-Philippe Combe[1]
**Institution(s):** *1. Bear Fight Institute, 2. INAF/IAPS, 3. Lunar and Planetary Institute, 4. PSI, 5. SETI*

### 508.04 – High energy electron processing of icy regoliths on Saturn's moons

A unique space weathering phenomenon has been identified on several icy Saturnian moons. Cassini revealed anomalous lens shaped regions in both optical and thermal wavelengths, colloquially known as the 'PacMan' feature, which are centered on the leading hemispheres and approximately symmetric about the equators. In particular, the Cassini InfraRed Spectrometer (CIRS) measurements of thermal emission in the mid-IR showed that surface temperature variations during a diurnal cycle were smaller inside the anomalous regions. The locations of the anomalies were shown to closely match the expected deposition profile of high energy (~ MeV) electrons moving counter rotational to the moons, suggesting an energetic source to drive their formation. However, the mechanisms by which thermal conductivity enhancement occur lack quantitative comparison with theoretical and experimental results.

Electron interactions with the grains can excite molecules, which, if near enough to an intergrain contact, can cause atoms or molecules to migrate into the contact region, thus increasing the contact volume or 'sintering' the grains. Sintering improves the thermal contact between grains, leading to increased effective thermal conductivity of the regolith. Equations previously developed to describe material behavior in nuclear reactor were used to estimate the timescale for the energetic electrons to increase the contact volume sufficiently to describe the enhanced thermal conductivity of the anomalous regions. In order to properly constrain the sintering calculations, the unique electron energy distribution measured in the vicinity of each of the moons was used in the calculations, and molecular dynamics simulations of excited electrons in water ice were carried out to determine the length scale for an average electron excitation or ionization event. This length scale determines the distance from the primary reaction at which electrons can still be mobilized to move into the contact region. The sintering timescales were compared to published values for micrometeorite resurfacing rates in order to determine if electron induced sintering can create a stable equilibrium on the surface of the moons.

**Author(s): Micah Schaible[1]**, Robert E Johnson[1]
**Institution(s):** *1. University of Virginia*

### 508.05 – Coherent Backscattering Effect in Saturnian vs. Uranian Satellites: Effects on Band Depths and Shapes

In this work, we examine the changes in depth and shape of individual absorption bands as a function of solar phase angle that are caused by the coherent backscattering effect (CBE) in near-IR spectra of saturnian and uranian satellites. We have quantified band depths and shapes for real-world data (from Cassini Visual & Infrared Mapping Spectrometer (VIMS) and TripleSpec at Apache Point Observatory) and also modeled spectra of densely packed icy particulate surfaces with the MSTM (multisphere T-matrix) version 4.0 code specifically developed to model light scattering in regolith layers. MSTM4 allows us to calculate the brightness for thick fluffy layers on order of 20,000 particles (compared to 1000 with previous code versions). We have now obtained good matches between model and real-world data at specific bands for several higher albedo moons. We are finding that the normalized depth of the absorption band can increase or decrease with solar phase angle depending on the albedo at the wavelength of normalization; this is seen in all the data (VIMS, ground-based, and model spectra). We model the change in the phase-angle-dependent band depth in response to varying the size and packing of the constituent icy particles. Indeed, the coherent backscattering effect can be observed at some wavelengths and entirely disappear at others because CBE requires a specific range of size and packing (cf. Muinonen et al. 2014); we see this effect as well.
This work is supported by NASA’s Outer Planets Research program (NNX12AM76G; PI Pitman), Planetary Astronomy program (NNX09AD06G; PI Verbiscer), and NASA’s Advanced Supercomputing Division. Calibrated Cassini VIMS data cubes appear courtesy of the Cassini VIMS team and the PDS.

**Author(s): Karly M. Pitman[4]**, Ludmilla Kolokolova[5], Anne J. Verbiscer[6], Charles Gulotta[5], Emily C. S. Joseph[3], Daniel W. Mackowski[1], Bonnie J. Buratti[2], Thomas W. Momary[2]
**Institution(s):** *1. Auburn University, 2. Jet Propulsion Laboratory, California Institute of Technology, 3. Planetary Science Institute, 4. Space Science Institute, 5. University of Maryland, 6. University of Virginia*

### 508.06 – Charging and Discharging of Amorphous Solid Water Ice: Effects of Porosity

**Introduction:** Amorphous solid water (ASW) is abundant on Saturn’s icy satellites and rings [1,2], where it is subject to bombardment of energetic ions, electrons, and photons; together with secondary electron and ion emission, this may leave the surfaces charged. Surface potential can affect the flux of incoming charged particles, altering surface evolution. We examined the role of porosity [3] on electrostatic charging and discharging of ASW films at 30–140 K.
**Experiment:** Experiments were performed in ultra-high vacuum [4]. ASW films were deposited at 30 K onto a liquid-He-cooled quartz crystal microbalance (QCM). Film porosity was calculated from the areal mass via the QCM and thickness via a UV-visible interferometry. ASW films were charged at 30 K using 500 eV $He^+$. Surface potentials ($V_S$) of the films were measured with a Kelvin probe, and infrared spectra were collected using a Fourier transform infrared spectrometer.
**Results:** We measured $V_S$ of the ASW film at 30 K as a function of ion fluence (F). The $V_S(F)$ deviates from a straight line at low fluence, attributed to emitted secondary electrons due to the negative polarization voltage [5,6], and increases linearly when the $V_S$ is positive. We also measured $V_S$ as a function of annealing temperature. We prepared ASW films with various porosities by annealing the films to different temperatures ($T_a$) prior to irradiation or varying the vapor-beam incidence angle (θ). Upon heating, we observed sharp decreases of the $V_S$ at temperatures that strongly depend on $T_a$ and θ. Decreases of the infrared absorbance of the dangling OH bands of the charged film share similar trends as that of the $V_S$. We propose a model that includes porosity for electrostatic charging/discharging of ASW films at temperatures below 100 K. Results are applicable to the study of plasma-surface interactions of icy satellites and rings.
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**Author(s): Caixia Bu[1]**, Raul A. Baragiola[1]
**Institution(s):** *1. University Of Virginia*

### 508.07D – Porosity effects on crystallization kinetics of Amorphous Solid Water: Implications for cold icy objects in the Outer Solar System

Crystalline ice has been identified on the cold surfaces of most icy satellites and TNOs [1]. This is surprising since accretion of water vapor at temperatures (T < 100 K) should result in the amorphous phase [2]. There are several possible explanations for the unexpected presence of crystalline ice on cold bodies, including cryovolcanism [3] and pulsed heating by micrometeoritic impacts [4].
A salient feature of ice films condensed at low T is microporosity, known to increase with deposition angle [5]. Here we investigate the dependence of the crystallization rate on the ice porosity, which could contribute to the observed variation in crystallization time $\tau_c$ reported in the literature [2]. Such dependence is noted in other porous materials such as zeolites and titania [6, 7].
Amorphous ice films were deposited on a CsI substrate from a collimated water vapor source at 10 K at incidences varying from 0 to 70°, as well as from an omnidirectional water vapor source. The films were heated to temperatures between 130 and 140 K following deposition. The isothermal transition from amorphous to fully crystalline phase was characterized by analyzing the time-dependent evolution of the OH-stretch absorption band using transmission infrared spectroscopy. Our initial results show that $\tau_c$ decreases with increasing porosity; for instance, a film deposited at 45° was observed to crystallize ~6 times faster than a film deposited at 0°. The preliminary estimate of the porosity of the 45° film is ~50% higher than that of the film deposited at normal incidence. Our findings can explain the reported variation in temperature-dependent $\tau_c$ [2] and contribute to the understanding of crystalline ice on cold bodies in the Outer Solar System.
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**Author(s): Emily H. Mitchell[1]**, Ujjwal Raut[1], Raul A. Baragiola[1]
**Institution(s):** *1. University of Virginia*

### 508.08 – Identifying new surface constituents of icy moons using mid-infrared spectroscopy

Spectroscopic compositional studies of the icy satellites can help us to better understand the formation and evolution of material in the outer solar system. The spectral complexity of the Saturnian satellite system as seen in reflected visible light suggests additional complexity may be present at mid-infrared wavelengths from which unique compositional information can be gleaned [1]. In addition, the mid-infrared is the region of the stronger fundamental diagnostic vibrational modes of many compounds. However, Cassini Composite Infrared Spectrometer (CIRS) surface compositional studies have received little attention to date.
We are exploring the suitability of mid-infrared spectroscopy for discovering non-$H_2O$ compounds on icy moon surfaces. On the dark terrain of Iapetus, we find an emissivity feature at ~855 $cm^{-1}$ and a potential doublet at 660 and 690 $cm^{-1}$ that do not correspond to any known instrument artifacts [2]. We attribute the 855 $cm^{-1}$ feature to fine-grained silicates, similar to those found in dust on Mars and in meteorites, which are nearly featureless at shorter wavelengths [3]. Although silicates on the dark terrains of Saturn's icy moons have been suspected for decades, there have been no definitive prior detections. Serpentines measured at ambient conditions have features near 855 $cm^{-1}$ and 660 $cm^{-1}$ [4]. However, peaks can shift depending on temperature, pressure, and grain size, so measurements at Iapetus-like conditions are necessary for more positive identifications [e.g., 5].
We measured the vacuum, low temperature (125 K) spectra of various fine-grained powdered silicates. We find that some of these materials do have emissivity features near 855 $cm^{-1}$ and match the doublet. Identifying a specific silicate would provide clues into the sources and sinks of the dark material in the Saturnian system. We report on our ongoing exploration of the CIRS icy moon dataset and plans for future measurements in JPL's Icy Worlds Simulation Lab.

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**Author(s): Cindy L Young[2]**, James J. Wray[2], Kevin P. Hand[3], Michael J. Poston[1], Robert W. Carlson[3], Roger N. Clark[5], John R. Spencer[6], Donald E. Jennings[4]
**Institution(s):** *1. California Institute of Technology, 2. Georgia Institute of Technology, 3. Jet Propulsion Laboratory, 4. NASA Goddard Space Flight Center, 5. Planetary Science Institute, 6. Southwest Research Institute*

### 508.09 – Composition and evolution of Triton's icy surface between 2002-2014 from SpeX/IRTF

We observed Triton in the near-infrared (0.7-2.5 μm) over 63 nights using the SpeX instrument at NASA's Infrared Telescope Facility (IRTF) between 2002 and 2014. Triton's spectrum has absorption features due to $N_2$, CO, $CH_4$, $CO_2$, and $H_2O$ in this wavelength range. We calculated the equivalent width (or fractional band depth for $H_2O$) of select absorption bands in each of the 63 night-averaged spectra. Longitudinal distributions for the volatile ices ($N_2$, CO, $CH_4$) show large rotational amplitude, while the non-volatile ices ($CO_2$, $H_2O$) show little amplitude over one Triton rotation. Absorption from $N_2$ and $CH_4$ increased over the period of the observations, whereas absorption from the non-volatile ices remained constant. The sub-solar latitude on Triton is currently at -42 degrees south, so some areas of Triton are visible for a full rotation. Combined with our findings, this suggests that the southern latitudes are dominated by non-volatile ices, with larger concentrations of volatile ices found in the observable region north of the equator. Changing viewing geometry over the period of the observations explains the increase in volatile absorption: As the sub-solar point moves northwards, more of the volatile-rich northern regions are coming directly into view. Geological evidence from Voyager 2 pointed to a southern hemisphere dominated by volatile ices; significant changes have occurred over the intervening quarter century.

**Author(s): Bryan J Holler[1]**, Leslie A Young[3], William M Grundy[2], Cathy B Olkin[3]
**Institution(s):** *1. LASP, 2. Lowell Observatory, 3. Southwest Research Institute*

### 508.10 – The Surprisingly Short Rotation Period of Hi'iaka, Haumea's Largest Satellite

The dwarf planet Haumea stands out from the rest of its Kuiper Belt counterparts with its rapid rotation, two satellites, and associated collisional family of small objects. The larger outer satellite, Hi'iaka, orbits Haumea with a period of 49.462 days, an eccentricity of 0.05, and an inclination of ~2 degrees. If it formed like a regular satellite and tidally evolved to its current location, it would be expected that Hi'iaka would be tidally despun. However, HST and Magellan ground based data show that Hi'iaka shows a 20% peak-to-peak brightness variability, from which we have determined that Hi'iaka's rotation period is ~9.8 hours (double-peaked). The spin period is ~120 times faster than its orbital period and too fast to be caused by standard mechanisms (e.g., spin-orbit resonance or chaos). The unusual spin rate also suggests that Hi'iaka could be the only known "regular" satellite to have a significant free obliquity (as opposed to forced obliquity). This obliquity would result in stable spin axis precession. We have investigated the observability of Hi'iaka's spin precession by determining how the angle between the Earth line of sight and the spin axis direction changes over a precession cycle for various obliquities. If the obliquity is significant, the resulting light curve evolution would be detectable within a ~decade. We will present these results and discuss their implications for the formation of Hi'iaka and Haumea.

**Author(s): Danielle M Hastings[2]**, Darin Ragozzine[2], Daniel C Fabrycky[6], Luke D Burkhart[3], Michael E Brown[1], Cesar Fuentes[5], Matthew J Holman[4]
**Institution(s):** *1. California Institute of Technology, 2. Florida Institute of Technology, 3. Harvard University, 4. Harvard-Smithsonian Center for Astrophysics, 5. Universidad de Chile, 6. University of Chicago*

### 508.11 – Orbital analysis of the inner Uranian satellites from Hubble images

The thirteen inner moons of Uranus form a densely-packed and possibly chaotic system. Numerical simulations show that several groups of moons exhibit complex resonant interactions, and Mab shows as-yet unexplained variations in its orbit. However, the masses of these moons are currently unknown, limiting the insights that can be gained from numerical simulations. Using over 650 long-exposure images taken during 2003-2013 by the Hubble Space Telescope through broadband filters, we have obtained astrometry for eleven of Uranus's inner moons, comprising the Portia group (Bianca to Perdita) plus Puck and Mab; attempts to measure the positions of Cordelia and Ophelia are on-going. Using these measurements, which are frequently accurate to 0.05 pixels or less, we have derived Keplerian orbital elements including the influence of Uranus's oblateness. The elements show year-to-year variations that are statistically significant and indicate the role of mutual perturbations among the moons. We are also using this information to place new constraints on the masses of these moons. We will present our most recent findings.

**Author(s): Robert S. French[2]**, Mark R. Showalter[2], Imke de Pater[3], Jack J. Lissauer[1]
**Institution(s):** *1. NASA ARC, 2. SETI Institute, 3. University of California, Berkeley*

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