ABSTRACTS
Saturn Science Conference

ORAL PRESENTATIONS

Atreya, Sushil: *Origin of Saturn and its Atmosphere, and an Exoplanet Perspective*

Sushil K. Atreya[1], Aurélien Crida[2], Tristan Guillot[2], Jonathan I. Lunine[3], Nikku Madhusudhan[4], and Olivier Mousis[5]
[1]University of Michigan, [2]Observatoire de la Côte d'Azur, [3]Cornell University, [4]University of Cambridge, [5]Observatoire Besançon

The formation of Saturn and the evolution of its atmosphere are reviewed. Observational constraints to the models of Saturn's formation and evolution are presented. In this regard, chemical composition, especially abundances of the heavy elements (> ^{4}He) and the stable isotopes in the atmosphere, is key. However, such data for Saturn is currently severely limited. Nevertheless, important conclusions about Saturn's origin can still be drawn from the data collected by Cassini, ground-based observations, properties of Saturn's moons, comparison to the other gas giant planet, Jupiter − that has been studied in far greater detail − and analogies to the extrasolar giant planets. This talk will cover these areas, and briefly discuss directions for the future exploration of Saturn.

Baines, Kevin: *The Future Exploration of Saturn*

Kevin Baines, Sushil Atreya, Frank Crary, Tom Greathouse, Henrik Melin, Olivier Mousis, Glenn Orton, Tom Spilker, and Anthony Wesley

The fiery demise of the Cassini-Huygens Orbiter in September 2017 presently marks the end of an era of exploration of the planets beyond Jupiter. In particular, no planetary missions are currently planned by any of the World's space agencies to explore the Saturn System. However, several such missions have been proposed or recommended for ESA's Cosmic Visions and NASA's New Frontiers programs, including several that propose in-situ probes to plumb the depths of Saturn. Such probes can uniquely determine the abundances of several light elements and their isotopes, including carbon, nitrogen, sulfur, and, possibly, oxygen, and the abundances of noble gases and their isotopes – particularly helium, argon, and xenon, all key to understanding the origins and evolution of the planet and how its internal heat source is powered today. Beyond missions, the next several decades promise new developments in ground-based and Earth-orbiting observatories and their instrumentation, promising fundamentally new views of the planet. In addition, the amateur astronomical community has made major strides in recent years in observing Saturn, and prospects are that will only continue to progress. This talk will review such prospects, as well as review the unique major science objectives of the 6-month – long "Juno like" phase that is the concluding act of the Cassini Mission in 2017.

Carbary, James: *Saturn's Erratic Clocks - Searching for the Rotation Rate of a Planet*

James Carbary, Matt Hedman, Tom Hill, Xianzhe Jia, William Kurth, Laurent Lamy, and Gabby Provan

The exact rotation period of Saturn is unknown, although the planet displays an abundance of periodicities near 10.7 hours. In the magnetosphere, these "planetary-period oscillations" (or PPOs) appear in charged particles, magnetic fields, energetic

neutral atoms, radio emissions, and motions of the plasma sheet and magnetopause. In Saturn's rings, the spoke phenomenon can exhibit periodicities near 10.7 hours, and ring phenomena themselves may be related to the interior rotation of the planet. In the high-latitude ionosphere, modulations near this period appear in auroral motions and intensities. In the upper atmosphere, some cloud features rotate near this period, although wind speeds are generally faster, and the well-known polar hexagon rotates with a period surprisingly close to 10.7 hours. Some of magnetospheric/ionospheric oscillations differ slightly in the northern and southern hemispheres and do not remain constant, sometimes varying on long time scales of a year or longer and sometimes on much shorter time scales. These variations in the period argue against a cause related to changes interior to Saturn, and because the magnetic and spin axes of Saturn are co-aligned (unlike those of any other known planet), Saturn's periodicities cannot be explained as "wobble" caused by a geometric tilt. Several models have been proposed for the periodicities, including rotating atmospheric vortices, periodic plasma releases, and a flapping magnetodisk, but none can satisfactorily explain all of Saturn's periodicities, and none can determine the exact rotation rate of the planet. This chapter reviews Saturn's "clocks", theories thereof, and how they might be used to determine the elusive rotation rate of the planet.

Christensen, Ulrich: *Saturn's Magnetic Field and Dynamo*

Ulrich Christensen, Michele Dougherty, Krishan Khurana, and Hao Cao

The existence of an intrinsic magnetic field at Saturn was confirmed in 1979 by magnetometer measurements taken during the flyby of Pioneer 11, followed soon afterwards by the two Voyager spacecraft. The properties of the field were surprising. The field strength at the planet's surface is only 1/50 of that of Jupiter's field or 2/3 of the Earth's field. Furthermore, the dipole tilt, which is of order 10 degrees at Jupiter and Earth, was found to be below 1 degree. Cassini measurements have confirmed the unusual magnetic field morphology and placed a tighter upper bound of 0.06 degrees on the dipole tilt. In addition, no non-axisymmetric higher multipole components could be identified unambiguously, although their detection is hampered by the unknown rotation period of Saturn's deep interior. While the early flybys and the Cassini orbital observations allow determination of the field coefficients up to g_{30}, measurements taken during the Cassini orbit insertion, which reached a minimum distance of 1.33 Saturn radii from the planet's center, have been used to infer g_{40} and g_{50}. The magnetic field has an unusual power spectrum, with high power in odd harmonics and low power in even harmonics.

Saturn's dynamo, like Jupiter's, is believed to operate in a region where hydrogen attains metallic electrical conductivity at pressures exceeding approximately 1 Mbar. This pressure is reached at about 0.9 Jupiter radii and about 0.65 Saturn radii. The deeper seated dynamo, together with the lower energy flux that is available to drive it, can only partially explain the relatively weaker field of Saturn. To concur with field strength scaling laws, the top of Saturn's dynamo must be even deeper, at about 0.4 planetary radii. This also coincides with the radius at which the power spectrum in odd harmonics becomes white. Even more challenging to explain is the extreme degree of axisymmetry of Saturn's field, since Cowling's theorem excludes that a homogeneous dynamo can generate a purely axisymmetric field. A plausible explanation is that non-axisymmetric field components inside the dynamo are filtered out and are invisible from the outside. The skin effect in a stably stratified conducting layer above the dynamo region, formed by the phase separation of helium from hydrogen, could have this filtering effect. However, the depth extent of a possible helium rain layer in Saturn remains uncertain. A dynamo with strong differential rotation between its upper and lower layers (Couette dynamo) could explain both the high axisymmetry of the outside field and the prevalence of odd harmonics in the spectrum, but it remains unclear which mechanism could sustain the differential rotation.

Fletcher, Leigh: *Saturn's Seasonally Changing Atmosphere: Thermal Structure, Composition, and Chemistry*

Leigh Fletcher, Julianne Moses,
Thomas Greathouse, Sandrine Guerlet,
and Robert West

Cassini's decade-long exploration of the Saturnian system has provided an unprecedented opportunity to characterise and understand the influence of seasons on giant planet atmospheric phenomena. Saturn's 26.7-degree axial tilt and multi-decade orbit subject the atmosphere to slow seasonal shifts in sunlight, with the poles spending up to fifteen years in the darkness of polar winter. Hemispheric asymmetries in atmospheric temperature, gaseous composition and aerosol properties were identified early in the mission, shortly after the southern summer solstice (2002) and Saturn's orbital perihelion. These asymmetries have evolved with time through the northern spring equinox (2009) as we approach northern summer (e.g., the warming northern hemisphere, variable polar stratospheres, thickening of spring hemisphere aerosol opacity, shifts in stratospheric hydrocarbon distributions), yielding a greater understanding of the processes shaping and perturbing the mean atmospheric state. On more regional scales, processes such as equatorial overturning (Hadley circulations), vertical and horizontal wave activity, and the variable polar circulations modify the smooth asymmetries in these atmospheric properties. This presentation will review Saturn's evolving temperatures, composition and cloud properties and their implications for atmospheric dynamics and chemistry, making predictions for Saturn's atmospheric state at the northern summer solstice and the end of the Cassini mission (2017).

Fortney, Jonathan: *Saturn's Interior Structure*

Jonathan Fortney, Ravit Helled,
Nadine Nettelmann, William Hubbard,
Mark Marley, David Stevenson,
Luciano Iess, and Peter Gierasch

We review the interior structure and thermal evolution history of Saturn after 10 years of the Cassini Mission. Over the past decade there have been dramatic advances in the input physics used in interior models, in particular for the equation of state of hydrogen, and the interaction of hydrogen with helium, ices, and rock. However, uncertainty in Saturn's rotation period has to some degree left us unable to capitalize on this new EOS work to better constrain the state of Saturn’s interior. We have also seen a renewed appreciation for the viability of models that deviate from the simple framework of a distinct core and H/He envelope, and how these models differ in their findings for Saturn’s interior structure and cooling history. The detection of Saturnian oscillations, which sculpt some regions of Saturn's rings, is an important new avenue that is just being explored, which could yield novel information about the planet's core and envelope. We compare our understanding of Saturn's interior to that of Jupiter, as well as giant planets around other stars. We conclude by discussing what we would still like to see from the Cassini, including a determination of Saturn's atmospheric helium abundance, which informs our understanding of the helium phase separation process, and precise measurements of the planet's gravitational and magnetic fields.

Garcia-Melendo, Enrique: *The Great Storm of 2010-2011*

A. Sanchez-Lavega, G. Fisher, L. Fletcher, E. Garcia-Melendo, B. Hesman, S. Perez-Hoyos, K. Sayanagi, and L. Sromovsky

On December 5, 2010 a unique large-scale dynamical phenomenon in Saturn's atmosphere known as a Great White Spot (GWS), began its development. It was the sixth event in the history of Saturn's observations, with previous ones having occurred in 1876, 1903, 1933, 1960 and 1990. These events are huge dynamical phenomena that initiating from a single convective source, evolve into a planetary-scale disturbance that encircles the planet and manifests during months, with decaying times of years. The 2010-11 event has been the best one studied from a battery of ground-based telescopes and their instruments and those onboard the Cassini spacecraft. In this chapter we first review in a comparative way the main characteristics of the six storms and then present in detail the observed aspects: cloud morphology and its vertical structure in the troposphere and stratosphere, motions and wind field, composition anomalies, tropospheric and stratospheric thermal disturbances and related lightning events. Then we discuss models of the nature of the outburst, and present nonlinear simulations of the atmospheric response to the convective source, and the development and evolution of the planetary-scale disturbance in the prevailing zonal wind profile.

Krupp, Norbert: *Global Configuration and Seasonal Variations of Saturn's Magnetosphere*

N. Krupp[1], P. Zarka[2], P.Kollmann[3], M. Thomsen[4], D. Mitchell[3], X. Jia[5], and A. Masters[6]
[1]Max Planck Institute for Solar System Research, Göttingen, Germany, [2]Lesia, Observatoire de Paris, Meudon, France, [3]The Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA, [4]LANL, Los Alamos, NM, USA, [5]University of Michigan, MI, USA, [6]Imperial College London, London UK

The Cassini spacecraft in orbit around Saturn since 2004 explores the Saturnian magnetosphere in great detail. It's trajectory in the Kronian system went through regions at high latitudes as well as very close to the planet never explored before. During the ten years in orbit the spacecraft performed orbits around the ringed planet at different "seasons" before, during and after equinox. We will discuss the new discoveries in the magnetosphere, e.g. seasonal changes, short and long-term variability and periodicities in the plasma, energetic charged and neutral particles based on the Cassini MAPS instruments CAPS, MIMI, MAG, INMS, (DUST, UVIS). These Cassini results heavily modified our knowledge about the global and local configuration of Saturn's plasma environment, the sources and sinks of plasma in the magnetosphere, the most important transport and acceleration processes, and the relationship of phenomena in Saturn's ionosphere/atmosphere/auroral region.

Moore, Luke: *Saturn's Ionosphere: Ring Rain and Other Drivers*

Luke Moore, Marina Galand, Arvydas Kliore, Andy Nagy, and James O'Donoghue

As we have observed it, Saturn`s ionosphere has proven to be highly complex, revealing patterns of ions and electrons that are driven by Saturn`s interactions with its rings. We give a brief overview of Saturn ionospheric science from the Voyager era to the present, with a focus on the wealth of new data and discoveries enabled by Cassini, including the electron density distributions with altitude and latitude. We also discuss recent observations of the effect of "Ring-rain" on the ionosphere by the Keck telescope, published in 2013. Finally, these advances are placed into context with the other Jovian planets, as Saturn is now the most well explored giant planet.

Sayanagi, Kunio: *Saturn's Polar Atmosphere*

Kunio M. Sayanagi, Kevin H. Baines, Ulyana A. Dyudina, Leigh N. Fletcher, Agustin Sanchez-Lavega, Peter L. Read, and Robert A. West

We review the advances made by the Cassini mission in understanding the polar atmosphere of Saturn. Before Cassini, the Voyager flybys in 1980-81 made limited observations of the northern high latitudes, which revealed the hexagonal cloud feature that surrounds the pole at 78 degree N latitude. However, the Voyager images did not resolve the north pole, and the south pole was shrouded in winter darkness. Since its arrival at Saturn in 2004, Cassini has observed the planet over changing seasons using multiple imaging instruments in wavelengths between the mid-infrared and the ultraviolet. Cassini observations have confirmed that the hexagonal feature still persists, and demonstrated that it is not a transient seasonal feature. In 2004, Saturn was in southern summer, and, during high-inclination orbits, the imaging instruments revealed a large hurricane-line cyclonic vortex at the south pole. The north pole was in polar night in 2004; nevertheless, the VIMS instrument captured the motion of clouds silhouetted against the thermal emission of by the planet, and revealed the existence of a similar cyclonic vortex at the north pole as well. The ISS camera has revealed detailed morphology of the cloud fields, and the turbulent motion of the swirling clouds around the poles. The CIRS instrument detected a hot spot at the poles associated with the cyclonic polar vortices. In addition, the decade-long period of Cassini observations has revealed a changing pattern in the high-latitude aerosol distribution in response to seasonal change in insolation.

Showman, Adam: *Saturn's Global Atmospheric Circulation*

Adam Showman, Yohai Kaspi, Richard Achterberg, and Andrew P. Ingersoll

Saturn's global circulation is reviewed. At the cloud level, numerous east-west (zonal) jet streams dominate the circulation, with a broad, fast eastward "superrotating") jet at the equator, and multiple mid-to-high latitude eastward jets separated by regions of weaker eastward or westward flow. In many respects this pattern is analogous to the circulation on Jupiter, although the jets on Saturn are faster and broader. A banded cloud pattern presumably results from a modulation of atmospheric condensation by the tropospheric meridional circulation, but the correlation between the banded pattern and the jet shear is not as straightforward as on Jupiter. Observations of the motions of small cloud features generally suggest that small-scale eddies transport momentum up-gradient into the jet cores, thereby maintaining them against frictional processes; the origin of the eddies has not yet been definitively identified. Overall, the jets and vortices have been suggested to result either from convection in the planet's interior as well as the latitudinal gradient of absorbed sunlight; additional work is needed to tease apart the relative roles of these processes. Still, several recent numerical models have had success in reproducing a banded flow pattern with equatorial superrotation and indicate the probable importance of various eddy-mean flow feedbacks in maintaining the jets. We will discuss available theories and observational constraints on the depth to which the jets penetrate into the interior. In addition to the jets, numerous coherent vortices, waves, and other local features manifest at cloud level; we will summarize available information on their dynamics, vertical structure, and constraints they place on the structure of the jets. The Saturnian stratosphere also contains a number of interesting dynamical phenomena, manifesting in the pattern of temperature perturbations and chemical tracers; we will briefly review this topic and discuss mechanisms by which the stratosphere and troposphere interact. We will summarize with key outstanding questions for the next decade and beyond.

Stallard, Tom: *Saturn's Aurorae*

Tom S. Stallard, Sarah V. Badman, Ulyana A. Dyudina, Laurent Lamy, and Denis Grodent

The aurorae at Saturn represents a direct manifestation of the interaction between the planet's surrounding space environment and its upper atmosphere. Our understanding of this interaction has greatly improved over the past decade, as a result of both in-situ and remote sensing of the aurora by Cassini, as well as through Earth-based observations.

On Earth, the interaction is dominated by the connection between the magnetosphere and the solar wind, with opening and closing of magnetic field lines leading to sporadic aurora that are strongly controlled by changes in the solar wind. On Jupiter, internal plasma sources combine with a rotationally-dominated magnetosphere to produce intense currents associated with the breakdown in co-rotation in the magnetosphere, producing powerful and continuous aurora.

Investigations into Saturn's aurorae have shown that the overall morphology changes dramatically with the arrival of solar wind compression regions, suggesting a strong interaction with the solar wind as at Earth. However, the varying rotation rate of Saturn's magnetosphere, first identified by measurements of Saturn's auroral radio emission, can also be measured in both the intensity and the location of the auroral emission. This in turn suggests a degree of rotational control within the aurorae. As such, the better we understand the relative strength of these influences on the aurorae of Saturn, the more we can understand how the magnetosphere interacts with the planet and how, in turn, the planet drives changes in the magnetosphere.

Here, we will present observations of the auroral emission directly produced by particles precipitating into Saturn's atmosphere (radio emission), the resultant atmospheric auroral excitation this produces in atomic hydrogen (UV and visible emission) and molecular hydrogen (UV emission), as well as thermal emission from both ions produced through auroral ionization and neutral species heated within the auroral region (IR emission). These observations show a wide variety of different auroral features ranging from the rotational pole, though the main auroral emission and down to latitudes where Saturn's atmosphere interacts with magnetic field lines connected to Enceladus.

Observations at these different wavelengths, when compared and contrasted, reveal details about the particle precipitation processes that drive them, as well as the effect these currents have on the surrounding neutral atmosphere. In-situ measurements by Cassini of the particles and magnetic field above the polar region allow us to measure and understand the field-aligned currents that produce the aurora. In comparing these currents with the auroral emission at the foot of these field lines, it is possible to understand the magnetospheric origin for Saturn's auroral emission, as well as the two-way interaction between the atmosphere and magnetosphere that is driven though the currents that produce this aurorae.

Strobel, Darrell: *Saturn's Thermosphere*

Darrell F. Strobel, Tommi Koskinen, and Ingo Mueller-Wodarg

The focus of this chapter is primarily on Saturn's thermosphere, defined as the upper atmosphere above the homopause, the base of the region where the temperature profile has a steep temperature gradient indicative of downward heat transport by molecular heat conditions, and corresponding to a pressure level of approximately 0.1 microbar. The talk will mostly be a review of selected topics from the following list: relevant density data from Voyager UVS and Cassini UVIS occultation data, relevant temperatures from H_3^+ near IR thermal emission and inferred from H_2 density profiles, HI Lyman alpha and He 584 Å airglow data, composition (H_2, He, H, HD, D, CH_4, H_2O). We use CH_4 as a proxy for homopause location. Given the density and temperature data, we discuss the extraction of the global density and temperature structure of Saturn's rapidly rotating, oblate thermosphere. The approximate net heating rate is inferred from radial temperature profiles. Based on an estimated 0.2 ergs $cm^{-2}s^{-1}$, solar EUV/FUV is deemed inadequate, whereas gravity wave heating may be contributory, but not dominant. Other heat sources considered include Joule (Ion-Neutral) heating due to magnetosphere-ionosphere-atmosphere coupling, energetic particle precipitation and heating in polar auroral regions, and equatorial electrojet heating. Radiative cooling of the thermosphere occurs primarily by H_3^+ near-IR emission. Global general circulation models of the thermosphere are reviewed and the problem of the coriolis containment of auroral energy and prevention of global redistribution is discussed.

Wesley, Anthony: *Storm Chasing on Saturn, Amateur Contributions to Saturn Science*

Anthony Wesley, Trevor Barry, Damian Peach, Donald Parker, and Johan Warell

This presentation demonstrates the increasing resolution and quality of images from amateur astronomers using nothing more than their own equipment and freely available software. Planets covered will include Mars, Jupiter, Saturn and Uranus and focuses on modern hardware, software and techniques.

West, Robert: *Clouds and Aerosols in Saturn's Atmosphere*

The visually stunning images of Saturn from the Cassini Visible and Infrared Mapping Spectrometer (VIMS) and the Imaging Science Subsystem (ISS) call out for a deeper understanding of the processes (dynamical, chemical, microphysical) responsible for what we see, and for what they can tell us about Saturn's atmosphere. These observations and processes can be organized according to the following topics: chemical composition of the particles and relation to gas-phase chemistry, dynamical processes including Saturn's giant storm of 2010-2011 and its polar vortices, polar processes including chemistry, energetics and dynamics of the auroral regions, and seasonal and non-seasonal changes. Some of this material circa 2009 was summarized in a book chapter by West et al., "Clouds and Aerosols in Saturn's Atmosphere", in Saturn from Cassini/Huygens, M. Dougherty et al. Eds., Springer, 2009. Since then we have witnessed a giant storm in Saturn's northern hemisphere, details of clouds inside hurricane-like polar vortices, UV-dark and highly polarizing aerosols confined by the northern polar hexagon, ammonia relative humidity maps from the Cassini Radar instrument, and our auroral observational database and seasonal baseline have expended significantly. One of the goals of the final phase of the Cassini mission is to examine cloud morphology and ammonia humidity at even higher spatial resolution. The interpretation of these data is often not straightforward. As for Jupiter we can be led astray by focusing on a narrow range of wavelengths. The goal for future work will be to synthesize data sets over a wide wavelength range and to make sense of changes we see in a very dynamic atmosphere.

This work was performed by the Jet Propulsion Lab, Caltech, under contract with the National Aeronautics and Space Administration.

POSTERS

Achterberg, Richard: *Changes to Saturn's Zonal-mean Tropospheric Thermal Structure After the 2010-2011 Storm*

Richard K. Achterberg, Peter J. Gierasch, Barney J. Conrath, Leigh N. Fletcher, Brigette E. Hesman, Gordon L. Bjoraker, and F. Michael Flasar

We have used far-infrared (20 μm – 200 μm) data from the Cassini Composite Infrared Spectrometer to retrieve the zonal-mean temperature and hydrogen *para*-fraction in Saturn's upper troposphere from observations taken before and after the large northern hemisphere storm in 2010-2011. During the storm, zonal mean temperatures increased by about 3 K in the latitude band between roughly 25°N and 45°N planetographic latitude , while the zonal mean hydrogen *para*-fraction decreased by about 0.04 over the same latitudes, at pressures greater than approximately 300 mbar. These changes occurred over the same latitude range as the disturbed cloud band seen in visible images. The observations are consistent with low *para*-fraction gas being brought up from the level of the water cloud by the strong convective plume associated with the storm, while being heated by condensation of water vapor, and then advected zonally by the winds near the plume tops in the upper troposphere.

Bjoraker, Gordon: *Oxygen Compounds in Saturn's Stratosphere During the 2010 Northern Storm*

G. L. Bjoraker, B. E. Hesman, R. K. Achterberg, D. E. Jennings, P. N. Romani, L. N. Fletcher, and P. G. J. Irwin

The massive storm at 40 degrees North latitude on Saturn that began in December 2010 has produced significant and long-lived changes in temperature and species abundances in the stratosphere throughout the northern hemisphere (Hesman et al. 2012a, Fletcher et al. 2012a). The northern storm region has been observed on many occasions between January 2011 and January 2013 by Cassini's Composite Infrared Spectrometer (CIRS). In this time period, temperatures in regions referred to as "beacons" (warm regions in the stratosphere at certain longitudes in the storm latitude) became significantly warmer than pre-storm values of 140K, peaking at 220K in May 2011 followed by gradual cooling. Hydrocarbon emission greatly increased over pre-storm values and then slowly decayed as the beacon cooled. Radiative transfer modeling has revealed that this increased emission is due to enhanced gas abundances for many of these species, rather than simply due to the temperature changes alone (Hesman et al. 2012b, Bjoraker et al 2012). In order to build a comprehensive picture of the changes to the stratosphere due to the 2010 northern storm we are now investigating the oxygen compounds in Saturn's stratosphere to determine if similar changes in these species occurred. The time evolution of stratospheric CO_2 and H_2O abundances in the beacon regions throughout 2011 and 2012 will be presented and compared with pre-storm measurements made in 2010.

Crary, Frank: *Joule Heating of the Mid-Latitude Thermosphere: Saturn's Other Ring Current*

Saturn's main rings are magnetically connected to Saturn's atmosphere at latitudes between 38 and 48 degrees. The rings do not corotate with the planet and, most likely, neither does the ring ionosphere. This results in a current system which flows across the rings, along field lines and closes in Saturn's mid-latitude ionosphere. The resulting Joule heating depends on the collisional coupling between Saturn's neutral atmosphere and ionosphere, and between the rings and their ionosphere. However, the heating could be as great as 2 mW/m^2.

Flasar, F. Michael: *Saturn's Shape from Cassini Radio Occultations*

F. M. Flasar, P. J. Schinder, R. G. French, E. A. Marouf, and A. J. Kliore

We report on the shape of isobaric surfaces in Saturn's atmosphere, derived from thirty-five Cassini radio-occultation soundings that probe from 0.1 mbar to ~1 bar between 70 S and 60 N latitude. To determine this, we use the gravitational coefficients given by Jacobson et al. [1] and the angular velocities at the cloud-top level from the Voyager winds reported by Sanchez-Lavega et al. [2]. To keep the ray-tracing inversion tractable, we assume that the atmosphere is locally axisymmetric and that its angular velocities are functions of the cylindrical radius from the planetary rotation axis; except for near the equator, this is equivalent to assuming that the winds are barotropic. This permits the use of a geopotential incorporating both gravity and differential rotation and ensures that surfaces of constant geopotential, density, and pressure coincide. Note that the "barotropic" assumption need only apply in the atmospheric shell probed by the occultations. The retrieved isobaric surfaces show evidence of moderate baroclinicity. For example, the deviations of the 1-bar and 100-mbar surfaces from the geopotential surface assumed are of order 10-20 km, less than a pressure scale height.

References

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[2] Sanchez-Lavega, A., et al., Icarus, 147, 405-420, 2000.

Hedman, Matthew: *Kronoseismology with Rings, New Clues to Saturn's Interior*

M.M. Hedman and P.D. Nicholson

Twenty years ago, Marley & Porco [1993, Icarus 106, 508] pointed out that Saturn's normal mode oscillations could potentially produce detectable signatures in the rings, but the data available at that time were insufficient to securely identify whether particular ring features were generated by specific planetary oscillations. Using stellar occultation data obtained by the Visual and Infrared Mapping Spectrometer (VIMS) onboard the Cassini spacecraft, we have been able to determine the symmetry properties and pattern speeds of several of these waves. At least six of these features have pattern speeds that are consistent with those predicted for resonances with low-order acoustic oscillations (f-modes) within the planet. These features therefore provide precise estimates of Saturn's normal-mode oscillation frequencies, and should therefore place strong constraints on Saturn's internal structure. We also identified multiple waves with the same number of arms and very similar pattern speeds, indicating that multiple sectoral modes may exist within the planet, something that was not predicted by many planetary interior models. More recently, we have found waves that appear to be generated by persistent gravitational anomalies rotating around the planet at speeds comparable to Saturn's winds. These features could help clarify how deep these winds extend.

Hesman, Brigette: *The Evolution of Hydrocarbon Compounds in Saturn's Stratosphere During the 2010 Northern Storm*

Brigette E. Hesman[1], G.L. Bjoraker[2], R. K. Achterberg[1], P.V. Sada[3], D. E. Jennings[2], A.W. Lunsford[4], J.A. Sinclair[5], P. N. Romani[2], R.J. Boyle[6], L. N. Fletcher[5], and P. G. J. Irwin[5]
[1]University of Maryland, Maryland, USA, [2]NASA Goddard Space Flight Center, Maryland, USA, [3]Universidad de Monterrey, Mexico, [4]Catholic University of America, Washington D.C., USA, [5]University of Oxford, UK, [6]Dickinson College, Pennsylvania, USA

The massive eruption at 40N (planetographic latitude) in December 2010 has produced significant and long-lived changes in temperature and species abundances in Saturn's northern hemisphere (Hesman et al. 2012a, Fletcher et al. 2012). The northern storm region has been observed on many occasions between January 2011 and June of 2012 by Cassini's Composite Infrared Spectrometer (CIRS). In this time period, temperatures in regions referred to as "beacons" (warm regions in the stratosphere at certain longitudes in the storm latitude) became significantly warmer than pre-storm values of 140K. In this period hydrocarbon emission greatly increased; however, this increased emission could not be attributed due to the temperature changes alone for many of these species (Hesman et al. 2012b, Bjoraker et al. 2012). The unique nature of the stratospheric beacons also resulted in the detection of ethylene (C_2H_4) using CIRS. These beacon regions have also led to the identification of rare hydrocarbon species such as C_4H_2 and C_3H_4 in the stratosphere. These species are all expected from photochemical processes in the stratosphere, however high temperatures, unusual chemistry, or dynamics are enhancing these species. The exact cause of these enhancements is still under investigation.

Ground-based observations were performed using the high-resolution spectrometer Celeste in May 2011 to confirm the CIRS detection of C_2H_4 and to study its spectral signatures at higher spectral resolution. In order to follow the evolution of its emission further observations were performed in July 2011 and March 2012. These observations are being used in conjunction with the CIRS observations to investigate the source of the approximately 100-fold increase of ethylene in the stratospheric beacon.

The time evolution of hydrocarbon emission from C_2H_2, C_2H_4, C_2H_6, C_3H_4, and C_4H_2 in Saturn's Northern Storm beacon regions will be presented.

References:

Bjoraker, G., B.E. Hesman, R.K. Achterberg, P.N. Romani. 2012, "The Evolution of Hydrocarbons in Saturn's Northern Storm Region", AAS DPS Conference, Vol. 44, #403.05.

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Koskinen, Tommi: *Temporal and Meridional Trends in Saturn's Thermosphere from Cassini UVIS occultations*

T. T. Koskinen, B. R. Sandel, R. V. Yelle, I. C. F. Mueller-Wodarg, and D. F. Strobel

We present density and temperature profiles in Saturn's thermosphere retrieved from more than 30 solar and stellar occultations observed by the Cassini UVIS instrument. We find that the exospheric temperature on Saturn increases by 100 - 200 K with latitude from the equator to the poles, ranging from about 370 K to 540 K. This temperature trend implies that the thermosphere is heated at the poles and/or high latitudes, although we find that the meridional temperature gradient is shallower than that predicted by a thermospheric circulation model that self-consistently includes the auroral energy input at the poles (Mueller-Wodarg et al. 2012). We also find evidence indicating that the pressure levels in Saturn's thermosphere expanded at low to mid-latitudes between 2005 and 2010. The observed expansion is likely to arise from enhanced heating of the lower thermosphere during this time period.

Kurth, W. S.: *Saturn Kilometric Radiation Periodicity after Equinox*

G. Fischer, D.A. Gurnett, W.S. Kurth, S.-Y. Ye, and J.B. Groene

The rotation period of Saturn's magnetosphere was found to vary with time, and changing periodicities were identified in magnetic fields, radio emissions, and charged particles. Here we analyze the varying period of Saturn kilometric radiation (SKR) from 2009 to early 2013, i.e. mainly after Saturn equinox of August 2009. A periodicity analysis is first applied to the complete SKR signal, and second to SKR intensities separated by spacecraft latitude and wave polarization, attributed to SKR from the northern and southern hemisphere, respectively. Our analyses are done with the tracking filter approach of Gurnett et al. (2009a) and by simply following the phases of normalized SKR intensity maxima (north and south) with time. It is shown that SKR periods from the northern and southern hemisphere converged during 2009, crossed shortly after equinox, and coalesced in spring 2010. We will show that SKR from both hemispheres not only exhibited similar periods, but also similar phases from March 2010 until February 2011 and from August 2011 until June 2012. The in-between time interval (March to July 2011) shows a slowdown of the southern SKR rotation rate and a slight increase in rotation speed for the northern SKR before rotation rates and phases become equal again in August 2011. We also identify minor SKR components where the modulation phase deviation exceeds one rotation each time Cassini completes one orbit, i.e. this is consistent with the characteristic of a searchlight-like signal. However, the main SKR signal still acts like a clock with a modulation phase independent of the local time of the observer (Cassini spacecraft). A comparison of SKR periodicities after equinox to the planetary period oscillations of the magnetic field shows major differences, and we compare SKR phases to magnetic field phases to explain the deviations.

Mousis, Olivier: *Interpretation of the $^{14}N/^{15}N$ Ratio Measured in Saturn's Ammonia*

O. Mousis, J. I. Lunine, L. N. Fletcher, K. E. Mandt, D. Gautier, and S. Atreya

The recent derivation of a 1-sigma lower limit for the $^{14}N/^{15}N$ ratio in Saturn's ammonia, which is found to be ~500 (Fletcher et al. 2014), prompts us to revise models of Saturn's formation using as constraints the abundances of heavy elements inferred in its atmosphere. This lower limit is found consistent with the $^{14}N/^{15}N$ ratio (~435) measured by the Galileo probe at Jupiter and implies that the two giant planets were essentially formed from the same nitrogen reservoir in the nebula, which is N_2 (Fletcher et al. 2014). However, in contrast with Jupiter whose C and N enrichments are uniform, carbon appears more than twice enriched in Saturn's atmosphere compared to nitrogen. This non-uniform enrichment at Saturn, considered with the recent derivation of a lower limit for the $^{14}N/^{15}N$ ratio, challenges the formation models elaborated so far. Here we propose an alternative formation scenario that may explain all of these properties together.

Mousis, Olivier: *Scientific Rationale and Concepts for an In Situ Saturn Probe*

O. Mousis, D. Atkinson, S. Atreya, A. Coustenis, L. N. Fletcher, D. Gautier, T. Guillot, R. Hueso, J.-P. Lebreton, J. I. Lunine, B. Marty, K. Reh, E. Venkatapathy, J. H. Waite, P. Wurz, and the ESA-M4 Saturn Probe team

Remote sensing observations meet some limitations when investigating the bulk atmospheric composition of the giant planets of our solar system, thus in situ measurements are needed. A remarkable example of the unique value of in situ probe measurements is illustrated by the exploration of Jupiter, where key measurements such as noble gases abundances and the precise measurement of the helium mixing ratio have only been made available through in situ measurements by the Galileo probe. Here we summarize the science case for in situ measurements at Saturn (see also Mousis et al. 2014 for details) and discuss the possible mission concepts that would be consistent with the constraints of ESA M-class missions. This mission would greatly benefit from strong international collaborations. We intend to propose such a mission in response to the upcoming ESA M4 call.

O'Donoghue, James: *On Saturn's 'Ring Rain', Comparison of Results from Years 2011, 2013 and 2014*

James O'Donoghue and Luke Moore

A global-scale interaction between Saturn's ionosphere and ring system was found in April 2011, during Saturn's northern hemisphere spring using the 10-metre Keck telescope. Saturn's ionosphere is produced when the otherwise charge-neutral atmosphere is exposed to a flow of energetic charged particles or solar radiation. At low-latitudes the latter should result in a weak planet-wide glow in the infrared, corresponding to the planet's uniform illumination by the Sun. The observed low-latitude ionospheric electron density is lower and temperature is higher than predicted by models. A planet-ring magnetic connection has been previously suggested in which an influx of water from the rings could explain the lower-than-expected electron densities in Saturn's atmosphere. We reported the detection of a pattern of features in 2011 data, unexpected in the ionosphere, that extend across a latitude band between 25-55 degrees that is superposed on the lower latitude background glow, with peaks in emission that map along the planet's magnetic field lines to features in Saturn's rings. This pattern implies the transfer of charged particles from the ring-plane to the ionosphere. Here we examine new datasets from 2013 and 2014 which have longer integration times than before. We find that either the 'ring rain' water influx is highly variable between different years or that Saturn's low-latitude ionosphere has cooled such that the already weak low-latitude H_3^+ emissions (which are highly temperature dependent) have decreased to below a detectable amount. The latter is supported by evidence that the northern main auroral oval was of the order of 100 Kelvin cooler in 2013 compared with 2011.

Orton, Glenn: *Long-Term Variability of Temperatures and Clouds in Saturn from Ground-Based Observations of Thermal Emission*

G. Orton, L. Fletcher, J. Sinclair, T. Fujiyoshi, T. Greathouse, P. Yanamandra-Fisher, T. Momary, I. Aguilar, A. Spiga, and S. Guerlet

Measurements of Saturn's thermal emission between 5.1 and 24.5 µm have been recorded by ground-based observations from the early 1990's to the present. Our observations included mid-infrared thermal imaging and mapping spectroscopy of the CH_4 7.7-µm ν_4 band to sense stratospheric temperatures and H_2 collision-induced absorption in the 17-25 µm region to sense upper-tropospheric temperatures. Our images at 5.1 µm are sensitive to cloud opacity near the 2-3 bar pressure region.

Observations were made at the Infrared Telescope Facility (IRTF), the Subaru Telescope, the Keck I Telescope, the Gemini South Telescope and the Very Large Telescope. Prominent seasonal variability is easily detected in the observations by comparing emission in opposite hemispheres at wavelengths sensitive to both tropospheric and stratospheric temperatures. The stratospheric temperature differences do not coincide with predictions of a time-dependent radiative model (Guerlet et al. 2014, submitted to Icarus), but they could be reconciled by adding a source of stratospheric heating besides the CH_4 gaseous absorption in the current model.

Warm polar vortices in Saturn are prominent near and after solstice. Orton and Yanamandra-Fisher (2005, Science, 307, 696) differentiated between a broad region of heating due to a combination of radiation and dynamics that covers a region within 30° of the pole and a more compact dynamically driven phenomenon. As of this writing, Saturn's north pole, heading toward solstice in 2017, has not yet displayed the distinct arctic warming that is prominent in 1993, corresponding to Saturn's early spring. Orton et al. (2008, Nature 453, 196) detected a non-seasonal oscillation at low latitudes that appeared to have a period close to 14.7 years, half of Saturn's orbital period, but recent observations indicate a variation from this behavior, which is consistent with independent observations made by the Cassini CIRS investigation (Sinclair et al. 2014, Icarus 233, 281).

Imaging at 5.1 µm has revealed a detailed cloud structure representing variations of cloud opacity around Saturn's 2-3 bar pressure region that we have tracked since 1995 (Yanamandra-Fisher et al. 2001, Icarus 150, 189). 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 not appear to be immediately correlated with seasonal changes. In 2011, the storm latitude became the clearest atmospheric region (i.e. the brightest at 5.1 µm) ever detected. It is gradually returning to its pre-storm state, but at a very slow rate and remains the clearest region on the planet. The stratospheric "beacon" (Fletcher et al. 2011, Science 332, 1413) has subsided into a generally warm axisymmetric band.

Pryor, Wayne: *Cassini Ultraviolet Images of Saturn's Aurorae*

Wayne R. Pryor, A. Jouchoux, L. Esposito, A. Radioti, D. Grodent, J. Gustin, J.-C. Gerard, F. Crary, D. Mitchell, A. Rymer, and the UVIS Team

Cassini has been obtaining auroral images and spectra of Saturn with the Ultraviolet Imaging Spectrograph (UVIS). We will present highlights of the auroral images, showing a variety of morphologies, including multiple arcs, spiral forms, polar cusp activity, and rotating emission features, some of them pulsating with a roughly 1-hour period. A satellite footprint of Enceladus is occasionally visible.

Sromovsky, Larry: *The Composition of Saturn's Storm Clouds: The Great Storm of 2010-2011 and beyond.*

L. A. Sromovsky, K. H. Baines, and P. M. Fry
University of Wisconsin-Madison

Saturn's Great Storm of 2010-2011 lofted deep atmospheric aerosols up to the visible cloud tops, exposing to remote observation normally hidden materials produced at great depths. Sromovsky et al. (2013, Icarus 226, 402-418) used near-infrared spectra of the storm obtained by the Cassini Visual and Infrared Mapping Spectrometer (VIMS) to show that the storm cloud contained a multi-component aerosol population comprised primarily of ammonia ice, with water ice the best-defined secondary component. The most likely third component is ammonium hydrosulfide or some weakly absorbing material similar to what dominates visible clouds outside the storm region. Their best horizontally homogeneous model has an optically thin layer of weakly absorbing particles above an optically thick layer of water ice particles coated by ammonia ice, supporting the hypothesis that these convective storms are powered by condensation of water and originate in the 10-20 bar depths of Saturn. Here we report on recent results of extending the spectral analysis to other storm regions.

This research was supported by NASA's Outer Planets Research Program under grant NNX11AM58G.

Strycker, Paul: *Applying PCA Filtering to Bolide Detection in Video Observations of Saturn and Jupiter*

Impacts with giant planets provide an opportunity to characterize minor bodies in the solar system and to study their effects on planetary atmospheres. Video observations by amateur astronomers are essential for detecting these impacts and constitute the only three temporally resolved observations of short-lived bolide flashes on Jupiter (Hueso et al. 2013, A&A, 560, A55). Objects similar in size to these Jovian impactors (5-19 m) may be challenging to detect with amateur equipment when impacting Saturn, due to (1) its greater distance from Earth and (2) its smaller gravitational potential which results in impactors with a kinetic energy per kilogram that is approximately 36% that of Jovian impactors. The limiting factor in bolide detection is the ability to separate the planet's spatial and temporal signal from that of transient events. Current detection algorithms rely on the difference between individual frames and a reference image, which do not account for the variability in the planet's signal due to atmospheric seeing and imperfections in image registration.

This work addresses these issues with an alternative method of identifying the planet's signal based on principal component analysis (PCA). After confirming that the first several principal components (PCs) of a video do not contain a bolide's signal, a reconstruction of the data without these PCs, known as PCA filtering (Strycker et al. 2013, Nat. Commun., 4, 2620), will remove a large fraction of the planet's spatial and temporal signal. Presented here are preliminary comparisons between the difference-of-images and PCA-filtering methods applied to synthetic Saturnian bolide observations.

This work is based on observations made with the NASA/ESA Hubble Space Telescope, obtained from the Data Archive at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. These observations are associated with program #9354. The author acknowledges partial support from the University of Wisconsin-Platteville and Concordia University Wisconsin.

Sylvestre, Melody: *Seasonal Variations in Saturn's Stratosphere from Cassini/CIRS limb Observations*

Melody Sylvestre, Thierry Fouchet, Sandrine Guerlet, and Aymeric Spiga

Saturn's atmosphere features large seasonal variations of its insolation due to its obliquity (26.7 deg.) and to the rings shadow wrapping up a large fraction of the winter hemisphere. Hence, important seasonal changes are expected in temperature, photochemistry and dynamics, especially in the stratosphere where photochemical and radiative timescales are the shortest.

In order to improve our knowledge of seasonal variations in Saturn's atmosphere, we analyze limb spectra acquired by Cassini/CIRS in 2010 (Ls = 12 deg.) and 2012 (Ls = 31 deg.) during spring in the northern hemisphere to retrieve temperature and hydrocarbons abundances. The latitudinal coverage (from 79N to 70S) and the sensitivity of our observations to a broad range of pressure levels (from 20 hPa to 0.01 hPa) allow us to probe the meridional and vertical structure of Saturn's stratosphere. We compare our results to previous CIRS limb observations performed in 2005, 2006 and 2007 (from Ls = 312 deg. to Ls = 331 deg.) during the previous season (Guerlet et al. 2009). Our results show that in the northern hemisphere, the lower stratosphere (1 hPa) has experienced the strongest warming from winter to spring (+10 K). In contrast the southern hemisphere exhibits weak variations of temperature from summer to autumn. We investigate the radiative contribution in the thermal seasonal evolution comparing these results to our radiative-convective model (Guerlet et al., 2014). We show that radiative heating and cooling by atmospheric minor constituents is not sufficient to reproduce the measured variations of temperature, suggesting dynamical features. The measurements of the abundances of hydrocarbons such as ethane or acetylene and their comparison with the photochemical model of Moses et al. (2005) also give insights on the large scale dynamics. For instance, in winter, Guerlet et al. (2009) measured a local enrichment above the 0.1 hPa pressure level at 25N. Our measurements indicate that this anomaly has disappeared in spring, in contrast with the expected enhancement in photochemical production rates, suggesting a change in the atmospheric circulation.