Titan Through Time

Unlocking Titan's
Past, Present and Future

NASA Goddard Space Flight Center

April 3th - 5th, 2012

Order of Scientific Presentations

Tuesday, April 3th

08:00-09:00 Badging and Registration

Session 1.1: Titan's Interior

Chair: Ralph Lorenz

09:00-09:15 *Workshop Welcome* - Conor Nixon;

Goddard Welcome - Anne L. Kinney

09:15-09:30 - Local arrangements

09:30-10:00- **Review** - *Titan's internal structure and evolution* – Francis Nimmo

10:00-10:15 *Thermal and compositional evolution of a three-layer Titan* – Michael Bland et al.

10:15-10:30 *The dynamic tidal response of a subsurface ocean on Titan and the associated dissipative heat generated* – Robert Tyler

10:30-11:00 **Coffee Break**

Session 1.2: History and Evolution

Chair: Francis Nimmo

11:00-11: 30 **Review** - *Origin of Titan's Atmosphere* – Yasuhito Sekine

11:30-11:45 *The influence of photochemical fractionation on the evolution of the nitrogen isotope ratios – detailed analysis of current photochemical loss rates* – Kathleen Mandt

11:45-12:00 *Crater topography on Titan: Implications for landscape evolution* – Catherine Neish

12:00-12:15 *Titan's Impact Cratering Record: Erosion of Ganymedean (and other) Craters on a Wet Icy Landscape* – Paul Schenk

12:15-12:30 *Titan's Timescales: Constraints on the Age of the Methane-Supported Atmosphere* – Conor Nixon

12:30-14:00 **Lunch**

Session 1.3: Surface Topology and Processes

Chair: Jason Barnes

14:00-14:30 **Review** - *Titan's Surface Diversity and Ongoing Processes-A Review* – Laurence Soderblom

14:30-14:45 *Progressive Poleward Migration of Fluvial Processes on Titan* – Jeffrey Moore et al.

14:45-15:00 *Do Titan's river channels carve into ice bedrock or loose regolith?* – Geoffrey Collins et al.

15:00-15:15 *Temperate Lakes Discovered on Titan* – Graham Vixie

15:15-15:30 *Is Titan's shape caused by its meteorology and carbon cycle?* – M. Mathieu Choukroun et al.

15:30-16:30 **Posters and Refreshments**

Session 1.4: Titan Posters I

A Near-Infrared and Thermal Imager for Mapping Titan's Surface Features – Shahid Aslam et al.

Global Patterns of Tectonism on Titan from Mountain Chains and Virgae – Casey Cook et al.

Celebrating one year of atmospheric evolution on Titan since Voyager with Cassini/CIRS – Athena Coustenis et al.

Models of a partially hydrated Titan interior with a clathrate crust – Jonathan Lunine et al.

Short period librations in a three-layer Titan – Nicolas Rambaux et al.

Cassini Titan Flybys: The Next Year (April 2012 through April 2013) – Trina Ray

Seasonal variations in Titan's stratosphere observed with Cassini/CIRS: temperature, trace molecular gas and aerosol mixing ratio profiles – Sandrine Vinatier

Session 1.5: Atmosphere / Surface Interactions

Chair: Jonathan Mitchell

16:30-16:45 *Insolation Distribution in Titan's Lower Atmosphere* – Juan Lora et al.

16:45-17:00 *Evolution of Titan's equinoctial weather patterns and accompanying surface changes and implications thereof* – Elizabeth Turtle et al.

17:00-17:15 VIMS *Near-Infrared Imaging and Spectra of Precipitation-Associated Surface Changes* – Jason Barnes et al.

17:15-17:30 *Spectral changes associated with rain on Titan: observations by VIMS* – Bonnie Buratti

Public Event: Goddard Visitor Center

19:00 Titan in History and Popular Culture - Ralph Lorenz

Wednesday, April 4th

Session 2.1: Lower / Middle Atmosphere - Physical

Chair: Darrel Strobel

09:00-09:15 Local arrangements

09:15-09:45 **Review** - *Titan Meteorology* - Jonathan Mitchell

09:45-10:00 *Titan's methane cycle in the Titan WRF general circulation model* – Claire Newman et al.

10:00-10:15 *A new look at Titan's zonal winds from Cassini radio occultations* – Mike Flasar et al.

10:15-10:30 *Temporal Variations of Titan's Stratospheric Structure from Cassini CIRS Observations* – Richard Achterberg

10:30-11:00 Coffee Break

Session 2.2: Middle Atmosphere - Composition

Chair: Elizabeth Turtle

11:00-11:15 *Titan's post-equinox circulation revealed using chemical tracers* – Nicholas Teanby et al.

11:15-11:30 *Titan's stratospheric condensibles at high northern latitudes during northern winter* – Carrie Anderson et al.

11:30-11:45 *Ice layers in Titan's stratosphere* – Erika Barth

11:45-12:00 *Water vapor on Titan: the stratospheric vertical profile from Cassini/CIRS infrared spectra* – Valeria Cottini et al.

12:00-12:15 *Observations of H_2O in Titan's atmosphere with Herschel* – Raphael Moreno et al.

12:15-12:30 *Photochemical modeling of H_2O in Titan's atmosphere constrained by Herschel Observations* – Luisa Lara et al.

12:30-14:00 **Lunch**

Session 2.3: Middle / Upper Atmosphere - Composition

Chair: Claire Newman

14:00-14:30 **Review** – *Titan's chemical complexity* – Veronique Vuitton

14:30-14:45 *On the absence of significant aerosol chemistry below Titan's stratopause at 300 km* – Robert Samuelson et al.

14:45-15:00 *Forward Modeling of the 2003 November 14 Titan Occultation: New Retrievals of Temperature, Density and Opacity Profiles from about 350 to 500 km* – Eliot Young et al.

15:00-15:15 *Non-LTE diagnostics of CIRS observations of Titan's mesosphere* – Alexander Kutepov

15:15-15:30 *Compositional Variations from UVIS Observations of Titan's Dayglow and Comparisons with in situ INMS Observations* – Michael Stevens et al.

15:30-16:30 **Posters and Refreshments**

Session 2.4: Titan Posters II

Experiments on Titan's lakes and surface interactions at JPL and preparation for future in-situ missions – Mathieu Choukroun et al.

Analysis of High-Resolution Mid-Infrared Laboratory Allene Spectra and the Interpretation of Titan's Infrared Spectra – Tilak Hewagama et al.

The solubility of ^{40}Ar in liquid hydrocarbons: implications for Titan's geological evolution – Robert Hodyss et al.

Nitrogen Chemistry in Titan's Upper Atmosphere – Joshua Kammer et al.

Update from the Analysis of High Resolution Propane Spectra and the Interpretation of Titan's Infrared Spectra – Valerie Klavans et al.

Tholin sensitivity to atmospheric methane abundance and the implications for multiple stable states of Titan's climate system – Erik Larson et al.

Radiolysis of frozen methane by heavy ions at different temperatures – Christian Fernando Mejía Guaman et al.

Influence of Benzene on the Optical Properties of Titan Haze Laboratory Analogs in the Mid-Visible – Yeonjoo Heidi Yoon et al.

Session 2.5: Upper Atmosphere

Chair: Michael Flasar

16:30-17:00 **Review** – *Titan's Upper Atmosphere: The Great Escape?* – Darrell Strobel

17:00-17:15 *Energetic particle energy deposition in Titan's upper atmosphere* – Joseph Westlake et al.

17:15-17:30 *Ionization processes in the atmosphere of Titan: from electron precipitation along magnetic field lines to high-Z cosmic rays ionization* – Guillaume Gronoff et al.

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19:00 - Workshop Dinner

The Chart House, Annapolis

Thursday, April 5th

Session 3.1: Laboratory Simulations

Chair: Veronique Vuitton

09:00-09:15 Local Arrangements

09:15-09:30 *Titan Influence of methane concentration on the optical indices of Titan's aerosols analogues* – Ahmed Mahjoub et al.

09:30-09:45 *Comparison of Nitrogen Incorporation in Tholins Produced by FUV Irradiation and Spark Discharge* – Sarah Hörst et al.

09:45-10:00 *The Titan Haze Simulation experiment: laboratory simulation of Titan's atmospheric chemistry at low temperature* – Ella Sciamma-O'Brien

10:00-10:15 *Chemical and Optical Properties of Titan Aerosol Analogs Produced from Aromatic Precursors* – Melissa Trainer et al.

10:15-10:30 **Review** - *Mission Paradigms and Planetary Exploration: Titan's place in the NASA Mission Portfolio* – Curt Niebur

10:30-11:00 **Coffee Break**

Session 3.2: Future Exploration

Chair: Conor Nixon

11:00-11:15 *Descent and Surface Wind Expectations for Titan North Polar Summer Exploration* – Ralph Lorenz et al.

11:15-11:30 *Formation and Growth of Wind-Driven Waves on Titan's Hydrocarbon Seas* – Ralph Lorenz et al.

11:30 11:45 *Composition of a Cryogenic Sea Studied by the Titan Mare Explorer* – Paul Mahaffy et al.

11:45-12:15 **Review** - *Future Titan Missions* – Hunter Waite et al.

12:15-12:30 **Closing Remarks** - Conor Nixon

Abstracts of Scientific Presentations

Session 1.1: Titan's Interior

Titan's internal structure and evolution

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Gravity measurements indicate that Titan's normalized moment of inertia is 0.33-0.34, larger than expected for a fully differentiated body. There is circumstantial evidence for a subsurface ocean, from Huygens electromagnetic observations, Titan's spin state, and Titan's non-hydrostatic shape. Detection of gravity variations due to tides may confirm the presence of an ocean. If Titan's shape is due to shell thickness variations, this indicates the shell is not convecting, probably because of a cold, ammonia-rich ocean beneath. Long-term shell convection is also inconsistent with Titan's surprisingly high eccentricity. Titan's moment of inertia suggests either hydrated silicates or an ice-rock mixture in its deep interior, both of which imply relatively cold temperatures. On the other hand, the (approximately) hydrostatic gravity means that temperatures must have been warm enough to permit long-term relaxation of the interior. Low internal temperatures require accretion primarily from relatively small objects, and depletion of radiogenic elements (e.g. by leaching). Moderate (5-10%) outgassing of the silicate interior is indicated by the presence of ^{40}Ar in the atmosphere. The required reservoir of CH_4 probably resides in the near-surface, perhaps in clathrates. Communication between the atmosphere, ocean and interior likely resulted in feedbacks and a complex history.

Thermal and compositional evolution of a three-layer Titan

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Cassini gravity data indicate that Titan is only partially differentiated. Two-layer models of Titan's internal structure have been proposed consisting of an ice layer (ice I and high-pressure phases) and a "core" (mixed rock and ice, or low-density, hydrated rock); however, such two-layer models face fundamental difficulties (see McKinnon and Bland, AGU abs. P33F-04, 2011). An alternative to these models are three-layer models that assume a pure ice layer (including high-pressure phases and a sandwiched ocean), a mixed ice+rock layer, and a silicate core. Here we model the thermal and compositional evolution of hypothetical Titans to examine whether three-layer internal structures are thermally stable over Solar System history (i.e., can a three-layer Titan avoid further differentiation?)

Our thermal model assumes an initial three-layer internal structure and calculates the temperature of each layer, following the numerical approach in Bland et al. (2008, Icarus 198, 384-399) and Bland et al. (2009, Icarus 200, 207-221). Both conduction and convection are permitted in each layer. Heating by decay of long-lived radiogenic species is included in both the mixed ice-rock and silicate layer. If the temperature of the ice or mixed ice-rock layer exceeds the minimum melting point of pure ice, melting and ocean formation occurs (if not present post-accretion). Melting of the mixed layer liberates silicate material, which is assumed to sink to the top of the silicate layer over time scale short relative to simulation time scales.

We find that melting of Titan's pure ice shell is common early in Solar System history and that melting can extend into Titan's nominal mixed ice-rock layer. Such melting leads to irreversible unmixing of some of the mixed ice-rock layer. Long-lived radiogenic species are generally incapable of completely melting and separating Titan's mixed layer, however. Titan's current moment of inertia can therefore be achieved using a thermally stable, three-layer structural model if Titan's interior is assumed to begin in a less differentiated state that evolves to its present-day internal structure. Three-layer structural models are therefore a viable alternative to two-layer models. Parameter variations, rock dehydration, and the effects of ammonia will also be discussed.

The dynamic tidal response of a subsurface ocean on Titan and the associated dissipative heat generated

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The tidal flow response and associated dissipative heat generated in a satellite ocean depends strongly on the ocean configuration parameters as these parameters control the form and frequencies of the ocean's natural modes of oscillation; if there is a near match between the form and frequency of one of these natural modes and that of one of the available tidal forcing constituents, the ocean can be resonantly excited, producing strong tidal flow and appreciable dissipative heat.

Of primary interest in this study are the ocean parameters that can be expected to evolve (notably, the ocean depth in an ocean attempting to freeze, and the stratification in an ocean attempting to cool) because this evolution can cause an ocean to be pushed into a resonant configuration where the increased dissipative heat of the resonant response halts further evolution and a liquid ocean can be maintained by ocean tidal heat. In this case the resonant ocean tidal response is not only allowed but may be inevitable.

Previous work on this topic is extended to describe the resonant configurations in both unstratified and stratified cases for an assumed global ocean on Titan subject to both obliquity and eccentricity tidal forces. Results indicate first that the assumption of an equilibrium tidal response is not justified and the correct dynamical response must be considered. Second, the ocean tidal dissipation will be appreciable if the ocean configuration is near that producing a resonant state. The parameters values required for this resonance are provided in this study, and examples/movies of calculated ocean tidal flow are also presented.

Session 1.2: History and Evolution

Origin of Titan's Atmosphere

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Titan has remarkable features – a dense N_2 atmosphere and hydrological cycles of CH_4 – that resemble those of Earth. How did the atmosphere develop on Titan? Was its origin similar to that of Earth's atmosphere? Although these questions remain unsolved, the Cassini-Huygens mission has provided important clues to understand the origin of Titan's atmosphere. 1) The low abundance of primordial Ar indicates that Titan's N_2 would have been delivered in less volatile form, probably as NH_3. 2) Titan's interior may have been only partially differentiated or may consist of low-density rock materials, suggesting that the interior would have been cooler than previously thought. 3) Observations of Enceladus' plume suggest that the chemical composition of building materials of the Saturnian satellites would have been similar to that of comets; i.e., CO_2 would have been more abundant than CH_4 in the satellitesimals. 4) Relatively young surface age, high levels of radiogenic Ar, and the absence of global CH_4 oceans suggest recent degassing of CH_4 from the interior.

The observations 1) and 2) imply the importance of conversion process of NH_3 to N_2 on Titan while maintaining the interior cool. However, because all of proposed mechanisms converting NH_3 to N_2 (e.g., photolysis, shock heating, and impact) also dissociate primordial CO_2 to CO, the lack of abundant CO in the present atmosphere is a big issue. Furthermore, if Titan's interior is undifferentiated, this is apparently inconsistent with a view of young surface and recent degassing. So far, there is no model which explains the above observations consistently. In this paper, we review the proposed mechanisms to create a N_2-CH_4 atmosphere on Titan and discuss new problems raised by Cassini. Then, we will discuss a plausible history of Titan's atmosphere on the basis of the new observations.

The influence of photochemical fractionation on the evolution of the nitrogen isotope ratios – detailed analysis of current photochemical loss rates

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Tracking the evolution of molecular nitrogen over geologic time scales requires an understanding of the loss rates of both isotopologues ($^{14}N_2$ and $^{14}N^{15}N$) as a function of time (e.g. Mandt et al., 2009). The relative loss rates, if different, "fractionate" the isotopes so that the ratios change as a function of time, and rate at which the ratio changes due to a loss process is determined by the "fractionation factor." Photochemistry is known to fractionate the nitrogen isotopes in Titan's atmosphere by preferentially removing the heavy isotope from the molecular nitrogen inventory and increasing the ratio (heavy/light) in one of the primary photochemical products, HCN. This fractionation occurs due to a selective shielding during photodissociation where the photons that dissociate $^{14}N^{15}N$ penetrate deeper into the atmosphere (Liang et al., 2007) than the photons that dissociate $^{14}N^{14}N$. Two methods can be used to determine the photochemical fractionation factor, f. The first approach for calculating f is based on the isotopic ratios of the photochemical source and product, as measured by the Huygens Gas Chromatograph Mass Spectrometer (GCMS) (Niemann et al., 2010) and the Cassini Infrared Spectrometer (CIRS) (Vinatier et al., 2007), respectively. The second method uses the loss rates and the ratio of the source and requires detailed photochemical modeling to ensure that the loss rates are calculated accurately.

We compare these two methods for calculating the photochemical fractionation factor for N_2 by using measurements of the isotopic ratios of N_2 and HCN combined with an updated coupled ion-neutral-thermal model (De la Haye et al., 2008). We find that accurate magnetospheric electron fluxes and a rotating model that accounts for diurnal variations are essential for accurate calculations of the HCN densities and for determination of the fractionation factor through photochemical modeling.

References:

De La Haye, V., J. H. Waite, Jr., T. E. Cravens, I. P. Robertson, and S. Lebonnois: " Coupled ion and neutral rotating model of Titan's upper atmosphere". Icarus, Vol. 197, pp. 236-262, 2008.

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Vinatier, S., et al.: "Vertical abundance profiles of hydrocarbons in Titan's atmosphere at 15° S and 80° N retrieved from Cassini/CIRS spectra". Icarus, Vol. 188, pp. 120–138, 2007.

Crater topography on Titan: Implications for landscape evolution

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Unique among the icy satellites, Titan's surface shows evidence for extensive modification by fluvial and aeolian erosion, which act to change the topography of its surface over time. Quantifying the extent of this landscape evolution is difficult, since the original, 'non-eroded' surface topography is generally unknown. However, fresh craters on icy satellites have a well-known shape and morphology, which has been determined from extensive studies on the airless worlds of the outer solar system (Schenk *et al.*, 2004). By comparing the topography of craters on Titan to similarly sized, pristine analogues on airless bodies, we can obtain one of the few direct measures of the amount of erosion that has occurred on Titan.

Cassini RADAR has imaged >30% of the surface of Titan, and more than 60 potential craters have been identified in this data set (Wood *et al.*, 2010; Neish and Lorenz, 2012). Topographic information for these craters can be obtained from a technique known as 'SARTopo', which estimates surface heights by comparing the calibration of overlapping synthetic aperture radar (SAR) beams (Stiles *et al.,* 2009). We present topography data for several craters on Titan, and compare the data to similarly sized craters on Ganymede, for which topography has been extracted from stereo-derived digital elevation models (Bray *et al.,* 2012). We find that the depths of craters on Titan are generally within the range of depths observed on Ganymede, but several hundreds of meters shallower than the average (Fig. 1). A statistical comparison between the two data sets suggests that it is extremely unlikely that Titan's craters were selected from the depth distribution of fresh craters on Ganymede, and that is it much more probable that the relative depths of Titan are uniformly distributed between 'fresh' and 'completely infilled'. This is consistent with an infilling process that varies linearly with time, such as aeolian infilling.

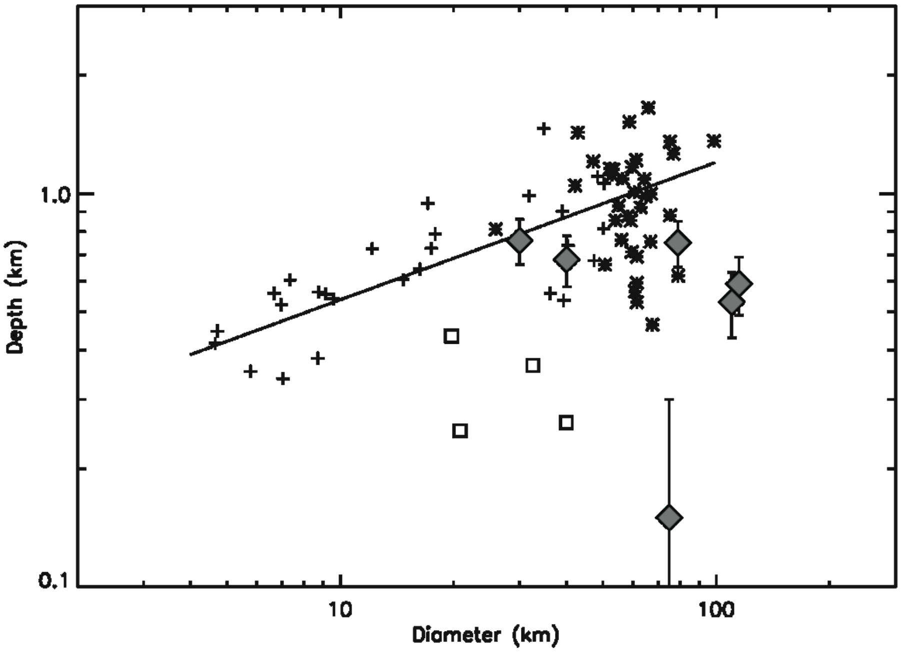

Figure 1: Depth of craters on Titan (gray diamonds) compared to similarly sized, fresh craters on Ganymede (central peaks, +; central pits, *) and a handful of relaxed craters (black squares) from Bray *et al.* (2012).

References:

Bray, V., et al.: "Ganymede crater dimensions – implications for central peak and central pit formation and development". Icarus, Vol. 217, pp. 115-129, 2012.

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Schenk, P.M., et al.: "Ages and interiors: the cratering record of the Galilean satellites". In: Bagenal, F., McKinnon, W.B. (Eds.), Jupiter: The Planet, Satellites, and Magnetosphere, Cambridge University Press, Cambridge, UK, pp. 427-456, 2004.

Stiles, B.W., et al.: "Determining Titan surface topography from Cassini SAR data". Icarus, Vol. 202, pp. 584-598, 2009.

Wood, C.A., et al.: "Impact craters on Titan". Icarus, Vol. 206, pp. 334-344, 2010.

Titan's Impact Cratering Record: Erosion of Ganymedean (and other) Craters on a Wet Icy Landscape.

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We examine the cratering record of Titan from the perspective of icy satellites undergoing persistent landscape erosion. First we evaluate whether Ganymede (and Callisto) or the smaller low-gravity neighboring icy satellites of Saturn are the proper reference standard for evaluating Titan's impact crater morphologies, using topographic and morphometric measurements (Schenk, 2002; Schenk et al. (2004) and unpublished data). The special case of Titan's largest crater, Minrva, is addressed through analysis of large impact basins such as Gilgamesh, Lofn, Odysseus and Turgis. Second, we employ a sophisticated landscape evolution and modification model developed for study of martian and other planetary landforms (e.g., Howard, 2007).

This technique applies mass redistribution principles due to erosion by impact, fluvial and hydrological processes to a planetary landscape. The primary advantage of our technique is the possession of a limited but crucial body of areal digital elevation models (DEMs) of Ganymede (and Callisto) impact craters as well as global DEM mapping of Saturn's midsize icy satellites, in combination with the ability to simulate rainfall and redeposition of granular material to determine whether Ganymede craters can be eroded to resemble Titan craters and the degree of erosion required.

References:

Howard, A. D., "Simulating the development of martian highland landscapes through the interaction of impact cratering, fluvial erosion, and variable hydrologic forcing", Geomorphology, 91, 332-363, 2007.

Schenk, P. "Thickness constraints on the icy shells of the galilean satellites from impact crater shapes". Nature, 417, 419-421, 2002.

Schenk, P.M., et al. "Ages and interiors: the cratering record of the Galilean satellites". In: Jupiter: The Planet, Satellites, and Magnetosphere, Cambridge University Press, Cambridge, UK, pp. 427-456, 2004.

Titan's Timescales: Constraints On The Age of The Methane-Supported Atmosphere

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Titan's atmosphere, unique amongst moons in the solar system presents a persistent riddle: how can it survive over geologic time if its methane is being rapidly destroyed by solar radiation and will last only another ~20 Myr? (Yung et al. 1984; Krasnopolsky 2010) Methane, the second most abundant (CH_4, 2-6%) atmospheric gas after nitrogen (N_2, 98-94%) supports the entire atmosphere via its greenhouse effect (McKay 1991) and total loss of methane could theoretically lead to atmospheric collapse (Lorenz et al. 1997).

In this talk we will review the available evidence constraining methane's prior lifetime in the atmosphere, including (i) isotopic constraints, especially D/H and $^{12}C/^{13}C$ in CH_4 (Nixon et al. 2012; Mandt et al. 2012), ^{40}Ar and ^{36}Ar abundances, and $^{14}N/^{15}N$ in N_2 (Niemann et al. 2010); (ii) the surface hydrocarbon inventory (Lorenz et al. 2008); (iii) the time to chemically produce Titan's CO (Hörst et al. 2008); (iv) the crater retention age of the surface (Neish and Lorenz 2012); and (v) interior models (Tobie et al. 2006). Each of these independent lines of evidence yields a time estimate that, although individually ambiguous, combine to provide context for a cohesive understanding of the history of Titan's methane.

We will conclude by summarizing the current constraints on the age of Titan's atmosphere in its present form, and highlight the key remaining challenges and critical measurements and modeling work needed to further refinement our understanding of Titan's perplexing atmospheric history.

References:

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Lorenz, R. D., C. P. McKay and J. I. Lunine, *Science*, **275,** 642-644, 1997.

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Niemann, H. B. et al., *J. Geophys. Res.*, **115**, E12006, 2010.

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Tobie, G., J. I. Lunine and C. Sotin, *Nature*, **440**, 61-64, 2006.

Yung, Y. L., M. Allen and J. P. Pinto, *Astrophys. J. Supp.*, **55**, 465-506, 1984.

Session 1.3: Surface Topology and Processes

Titan's Surface Diversity and Ongoing Processes-A Review

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Titan's landscapes exhibit a wealth of surface diversity that rivals the glossary for a textbook on Earth's geomorphological styles and geological processes. Long before Cassini-Huygens' arrival, evidence suggested that Titan's surface might harbor liquid hydrocarbons, methane and ethane, in the form of lakes, seas, or even oceans. And, as the surface gradually became visible to the Huygens Probe on its slow descent, it became clear that liquids had been quite active in sculpting and dissecting the terrains: a network of dendritic channels densely drapes the highlands located a few kilometers north of the landing site. This led Tomasko and colleagues to lead off the title of their Huygens report with "Rain, winds and haze …" And not only were winds responsible for the Probe's erratic change in direction as it neared the surface but soon we discovered that they also drive vast seas of longitudinal dunes eastward, wrapping the equatorial zone. Current thinking is that the dunes consist of coarse grains of solid hydrocarbons, perhaps mixed with water ice, that saltate in the slow-moving dense atmosphere. And, although we did not find vast methane-ethane oceans, we did find polar lakes and seas, vast in the north and sparse in the south. Elsewhere impact, tectonic, and, more arguably, volcanic features appear to be ubiquitous. The subjects of Titan's geology continue to cascade into a host of new details of the subjects of process and geomorphology; the collection terms, familiar to terrestrial science, continues to grow.

References:

Tomasko, M. G., et al. (2005) "Rain, winds and haze during the Huygens probe's descent to Titan's surface". Nature, Vol. 438, pp.775-778.

Progressive Poleward Migration of Fluvial Processes on Titan

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Titan may have acquired its massive atmosphere relatively recently in solar system history. The warming sun may have been key to generating Titan's atmosphere over time, starting from a thin atmosphere with condensed surface volatiles like Triton, with increased luminosity releasing methane, and then large amounts of nitrogen (perhaps suddenly), into the atmosphere. This thick atmosphere, initially with much more methane than at present, resulted in global fluvial erosion that has over time retreated towards the poles with the removal of methane from the atmosphere. Basement rock, as manifested by bright, rough, ridges, scarps, crenulated blocks, or aligned massifs, mostly appears within 30° of the equator. This landscape was intensely eroded by fluvial processes as evidenced by numerous valley systems, fan-like depositional features and regularly-spaced ridges (crenulated terrain). Much of this bedrock landscape, however, is mantled by dunes, suggesting that fluvial erosion no longer dominates in equatorial regions. High mid-latitude regions on Titan exhibit dissected sedimentary plains at a number of localities, suggesting deposition (perhaps by sediment eroded from equatorial regions) followed by erosion. These dissected plains may be evidence for the poleward retreat of rain erosion. The polar regions are mainly dominated by deposits of fluvial and lacustrine sediment. Fluvial processes are active in polar areas as evidenced by alkane lakes and occasional cloud cover.

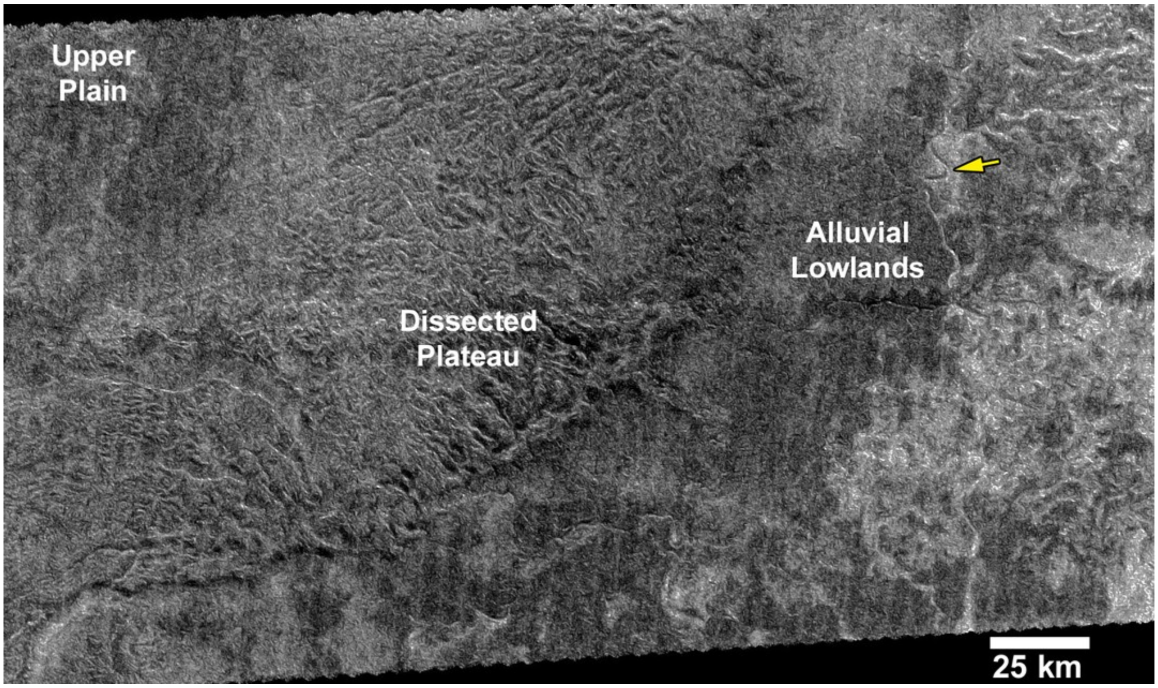

Figure 1. High mid-latitude region exhibiting a partially-dissected surface (“Dissected Plateau”). The dissection is interpreted to be fluvial due to dendritic valleys draining southward. The undissected surface to the left “Upper Plain” may be alluvial lowlands or an undissected part of the plateau bordering it to the right. The smooth radar-dark surface in center right is suggested to be “Alluvial Lowlands” because it is crossed by several broad, sinuous valleys or channels (arrow). Portion of swath T39, ~50°S, 210°W.

Do Titan's river channels carve into ice bedrock or loose regolith?

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Final results from our experiments investigating the abrasion resistance and strength of polycrystalline ice and ice/contaminant mixtures at Titan temperatures allow us to update the calculations of *Collins* (2005), which examined the ease of fluvial incision into ice bedrock on Titan. If Titan's stream channels run over exposed bedrock, the rate of channel downcutting is limited by the supply of sediment particles to abrade the bedrock surface, or by the production of pluckable blocks from joints in the bedrock. By adapting the equations of *Sklar and Dietrich* (2004) to Titan, we estimate the relative rate of bedrock incision caused by abrasion of sediment particles, and find that bedrock on Titan responds like a welded tuff or a quartzite on Earth, rather than the weak sandstone-like response found initially by *Collins* (2005).

Using the range of values for the HLS drainage basins used by *Perron et al.* (2006) and the sediment sizes observed by *Keller et al.* (2008), we adjust the unknown sediment supply rate into the channels to find the upper limit of the bedrock incision rate during rainstorm-runoff events. Maximum incision rates are about 1 micron per hour. If typical peak runoff events only last for a few hours, it would take on the order of 10^5 to 10^6 rainstorms for a channel to incise one meter into the solid bedrock. However, the mass flux of sediment from farther upstream required to erode this much bedrock implies that transportation of loose sediment would lower the entire catchment area 100 times faster than the bedrock in the channel is lowered. This is logically unsustainable, and leaves us with two options for erosion of the stream channels. One option is that the stream channels are even more supply limited than they are in our maximization calculation, and channel incision on Titan is an even slower process than outlined above. A more likely explanation is that Titan's streams are instead primarily cutting into bedrock that is pre-fractured into transportable blocks, and/or that most of the channels are transport-limited and are primarily acting to redistribute an existing loose regolith layer across Titan's surface.

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Temperate Lakes Discovered on Titan

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We have discovered two temperate lakes on Titan using *Cassini*'s Visual and Infrared Mapping Spectrometer (VIMS). Three key features help to identify these surface features as lakes: morphology, albedo, and specular reflection. The presence of lakes at the mid-latitudes mean liquid can accumulate and remain stable outside of the poles. We first identify a lake surface by looking for possible shorelines with a lacustrine morphology. Then, we apply a simple atmospheric correction that produces an approximate surface albedo. Next, we prepare cylindrical projection maps of the brightness of the sky as seen from any points on the surface to identify specular reflections. Our techniques can then be applied to other areas, such as Arrakis Planitia, to test for liquid.

Currently, all the known lakes on Titan are concentrated at the poles. Lakes have been suggested in the tropic zone by Griffith et al. Our discovery of non-transient, temperate lakes has important implications for Titan's hydrologic cycle. Clouds have been recorded accumulating in the mid-latitudes and areas have been darkened by rainfall but later brightened after evaporation (Turtle et al. 2011). Stable temperate lakes would affect total rainfall, liquid accumulation, evaporation rates, and infiltration. Polaznik Macula (Figure 1) is a great candidate for lake filling, evaporation rates, and stability.

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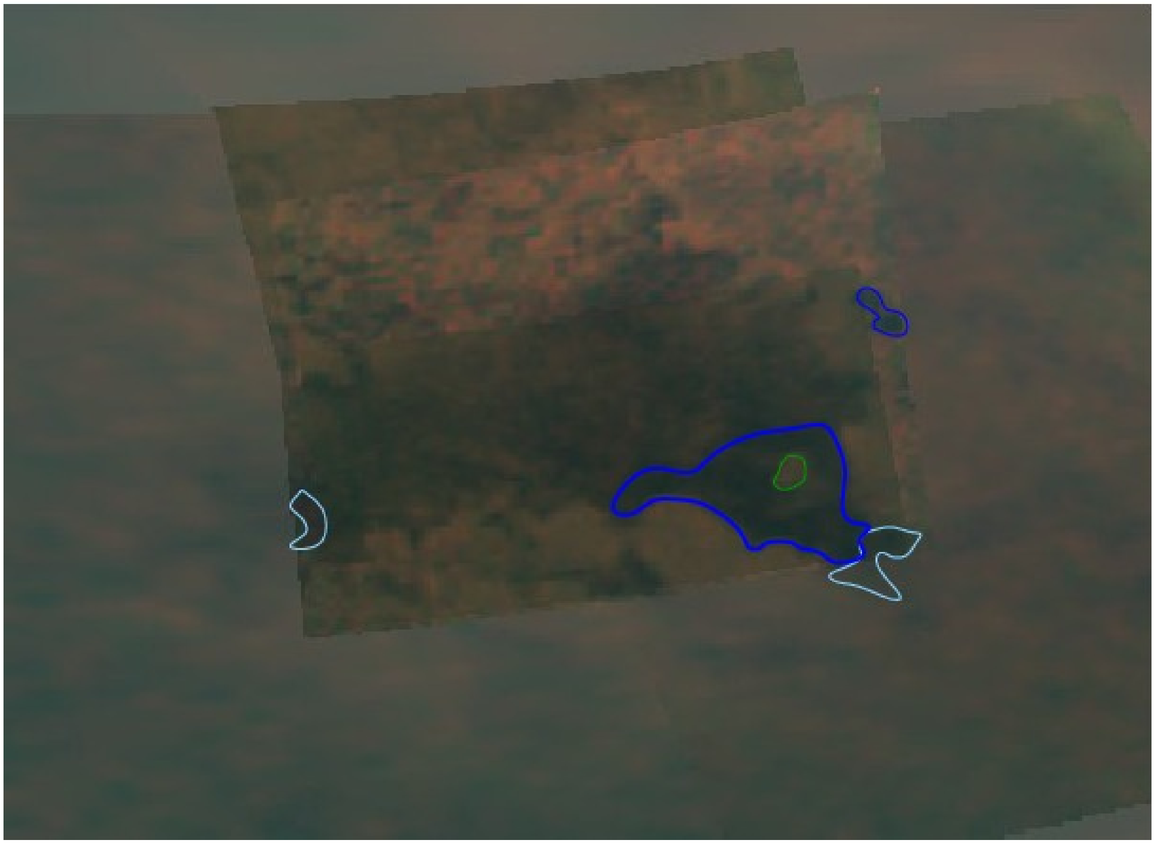

Figure 1: Polaznik Macula is the large, dark area central to the figure. The encircled dark blue areas represent positively identified lake regions in the T66 flyby. The light blue areas represent lake candidates still under analysis. The green circle marks a non-lake surface feature enclosed by a lake.

Is Titan's shape caused by its meteorology and carbon cycle?

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Titan's shape is characterized by a difference between the long equatorial radius and the polar radius that is several hundred meters larger than that predicted by the flattening due to its spin rate. The North Polar Region is covered by large mare filled with hydrocarbons, including ethane. Moreover global circulation models predict ethane precipitation on the polar areas. This study shows that the shape of Titan can be explained by the subsidence associated with the substitution of methane with ethane-rich liquids percolating into the crust which, as suggested by evolution models, may be composed of methane clathrate hydrates. Such substitutions have been observed in laboratory experiments. This process would provide an additional methane source as required for sustaining the presence of this constituent in Titan's atmosphere through its history. A 270 m subsidence of the polar caps is explained by the circulation of 1.5 to 6×10^{18} kg of ethane in the top three kilometers of an initially methane-clathrate crust. This process would have operated during the last 300-1200 Myr at the present ethane production rate. This age coincides with: 1) the isotopic age of methane in the atmosphere, ~ 500 Myr; 2) the age of Titan's surface from a recent evaluation of its cratering record, 300-1000 Myr; 3) and thermal evolution models, which predict a major methane outgassing event that occurred (or started) ~ 500 Myr ago.

This work has been conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA. Support from the NASA Astrobiology Institute and government sponsorship acknowledged.

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Session 1.4: Titan Posters I

A Near-Infrared and Thermal Imager for Mapping Titan's Surface Features

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Approximately 10% of the solar insolation reaches the surface of Titan through atmospheric spectral windows. We will discuss a filter based imaging system for a future Titan orbiter that will exploit these windows mapping surface features, cloud regions, polar storms. In the near–infrared (NIR), two filters (1.28µm and 1.6 µm), strategically positioned between CH_4 absorption bands, and InSb linear array pixels will explore the solar reflected radiation. We propose to map the mid-infrared (MIR) region with two filters: 9.76 µm and 5.88-to-6.06 µm with MCT linear arrays. The first will map MIR thermal emission variations due to surface albedo differences in the atmospheric window between gas phase CH_3D and C_2H_4 opacity sources. The latter spans the crossover spectral region where observed radiation transitions from being dominated by thermal emission to solar reflected light component.

The passively cooled linear arrays will be incorporated into the focal plane of a light–weight thin film stretched membrane 10 cm telescope. A rad-hard ASIC together with an FPGA will be used for detector pixel readout and detector linear array selection depending on if the field-of-view (FOV) is looking at the day– or night–side of Titan. The instantaneous FOV corresponds to 3.1, 15.6, and 31.2 mrad for the 1, 5, and 10 µm channels, respectively. For a 1500 km orbit, a 5µm channel pixel represents a spatial resolution of 91 m, with a FOV that spans 23 km, and Titan is mapped in a push-broom manner as determined by the orbital path. The system mass and power requirements are estimated to be 6 kg and 5 W, respectively. The package is proposed for a polar orbiter with a lifetime matching two Saturn seasons.

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Global Patterns of Tectonism on Titan from Mountain Chains and Virgae

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This research is based on the exploration of tectonic patterns on Titan from a global perspective. Several moons in the outer solar system display patterns of surface tectonic features that imply global stress fields driven or modified by global forces. Patterns such as these are seen in Europa's tidally induced fracture patterns, Enceladus's tiger stripes, and Ganymede's global expansion induced normal fault bands. Given its proximity to Saturn, as well as its eccentric orbit, tectonic features and global stresses may be present on Titan as well. Titan displays possible tectonic structures, such as mountain chains along its equator (Radebaugh et al. 2007), as well as the unexplored dark linear streaks termed virgae by the IAU.

Imaged by Cassini with the RADAR instrument, mountain chains near the equator are observed with a predominante east-west orientation (Liu et al. 2012, Mitri et al. 2010). Orientations such as these can be explained by modifications in the global tidal stress field induced by global contraction followed by rotational spin-up. Also, due to Titan's eccentric orbit, its current rotation rate may be in equilibrium between tidal spin-up near periapsis and spin-down near apoapsis (Barnes and Fortney 2003). Additional stress from rotational spin-up provides an asymmetry to the stress field. This, combined with an isotropic stress from radial contraction, favors the formation of equatorial mountain chains in an east-west direction.

The virgae, which have been imaged by Cassini with both the Visual and Infrared Mapping Spectrometer (VIMS) and Imaging Science Subsystem (ISS) instruments, are located predominately near 30 degrees latitude in either hemisphere. Oriented with a pronounced elongation in the east-west direction, all observed virgae display similar characteristics: similar relative albedos as the surrounding terrain however darkened with an apparent neutral absorber, broken-linear or rounded sharp edges, and connected, angular elements with

distinct, linear edges. Virgae imaged during northern latitude passes are oriented with their long dimensions toward Titan's anti-Saturn point.
If the virgae are of tectonic origin, for instance if the turn out to be i.e. grabens, they could serve as markers to Titan's global stress field. Using them in this way allows for a mapping of global tectonic patterns. These patterns will be tested for consistency against the various sources of global stress and orientations of mountain chains. By determining what drives Titan's tectonics globally, we will be able to place Titan within the context of the other outer planet icy satellites.

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Celebrating one year of atmospheric evolution on Titan since Voyager with Cassini/CIRS

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Seven years after Cassini's Saturn orbit insertion, we have in hand almost a complete picture of the stratospheric evolution within a Titanian year by combining Voyager 1 Infrared Radiometer Spectrometer (IRIS) measurements from 1980, Cassini Composite Infrared Spectrometer (CIRS) continuous recordings from 2004 to 2010 and the intervening ground-based and space-borne observations with ISO (Coustenis et al. 2003).
We have re-analyzed the Voyager 1/IRIS data acquired during the 1980 encounter, 30 years (one Titan revolution) before 2010, with the most recent spectroscopic data releases and haze descriptions (Vinatier et al. 2010, 2012) by using our radiative transfer code (ART). The re-analysis confirms the V1/IRIS retrievals by Coustenis & Bezard (1995) and updates the abundances for all molecules and latitudes based on new temperature, haze and spectroscopic parameters.

ART was also applied to all available CIRS spectral averages corresponding to more than 70 flybys binned over 10° in latitude for both medium (2.5 cm^{-1}) and higher (0.5 cm^{-1}) resolutions and from nadir and limb data both. In these spectra, we search for variations in temperature (following the method in Achterberg et al. 2011) and composition at northern (around 50°N), equatorial and southern (around 50°S) latitudes as the season on Titan progresses and compare them to the new V1/IRIS, ISO and other ground-based reported composition values (Coustenis et al., 2012, in prep). Other latitudes were examined in previous papers (e.g. Coustenis et al. 2010).

With this study we search for interannual stratospheric thermal and chemical variations at a time when the season is exactly the same as the one of the Voyager flyby and until it moves towards northern summer solstice which will be observed by the Cassini extended Solstice mission. We find significant temperature variations, essentially a decrease with time during the Cassini mission. Little departure from the original V1/IRIS abundances at the lower latitudes, but some variations in the northern latitudes, with C_2H_2, HCN and CO_2 presently above and the complex hydrocarbons C_3H_4 and C_4H_2 below the initial values. This allows us to set constraints on seasonal, photochemical and circulation models of Titan.

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Models of a partially hydrated Titan interior with a clathrate crust

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We present a model of the interior evolution of Titan over time, assuming the silicate core was hydrated early in Titan's history and is dehydrating over time. The original model presented in Castillo-Rogez and Lunine (2010) was motivated by a *Cassini*-derived moment of inertia (Iess et al., 2010) for Titan too large to be accommodated by classical fully differentiated models in which an anhydrous silicate core was overlain by a water ice (with possible perched ocean) mantle. Our model consists of a silicate core still in the process of dehydrating today, a situation made possible by the leaching of radiogenic potassium from the silicates into the perched liquid water ocean. The most recent version of our model accounts for the likely presence of large amounts of methane in the upper crust invoked to explain methane's persistence at present and through geologic time (Tobie et al. 2006).

The methane-rich crust turns out to have essentially no bearing on the temperature of the silicate core and hence the timing of dehydration, but it profoundly affects the thickness of the high-pressure ice layer beneath the ocean. Indeed, the insulating effect of the methane clathrate crust could have delayed the formation of the high-pressure layer, resulting in the interaction of liquid water with the silicate core for extended periods of time. Although a high-pressure ice layer is likely in place today, it is thin enough that plumes of hot water from the dehydrating core probably breach that layer. The implications of such a deep hydrothermal system for the later stages of the evolution of Titan's interior and surface will be discussed.

Part of this work has been performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA. Government sponsorship acknowledged.

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Short period librations in a three-layer Titan

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The knowledge of the rotational motion is an important piece of information about the interior process of bodies and to understand the tidal response. Recently, trough the observations acquired by the space mission Cassini, the rotational motion of Titan has been determined. The variations around the uniform rotational motion are the librations and they present a wide spectrum of frequencies due to the orbital variations of the satellite. Here we investigate the librational signature of Titan in longitude and latitude by taking into account the gravitational coupling of Saturn with a non-keplerian orbit and internal couplings. Two different timescales dominate the spectrum, long periods related to the motion of the nodes of the orbit and short periods related to the orbital period of the satellite. These long period librations have amplitudes almost independent of the distribution of mass and bring no information on the geophysical interior. On contrary, the short period librations are sensitive to the interior as for example the presence of the putative ocean increases strongly the amplitude of short period librations. Nevertheless, it is necessary to take into account all librations (long and short) in order to interpret the spacecraft observations.

Cassini Titan Flybys: The Next Year (April 2012 through April 2013)

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Our knowledge and understanding of Titan, Saturn's largest moon, has increased significantly as a result of data obtained from the 83 targeted Titan flybys by the Cassini spacecraft during its successful Prime and Equinox and ongoing Solstice missions.

Cassini science instruments are body-fixed with limited ability to articulate; thus, the spacecraft pointing during the flybys must be allocated among the instruments to accomplish the mission's science goals. The science that is planned on each flyby at closest approach affects the attitude of the spacecraft, which in turn affects the altitude at which the project decides to fly by Titan. Therefore, the decision about what Titan science is being done on each flyby was required well in advance [1]. Because of this early work, we can present a summary of the science opportunities during the coming year's Titan flyby, including T83 through T90.

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Seasonal variations in Titan’s stratosphere observed with Cassini/CIRS: temperature, trace molecular gas and aerosol mixing ratio profiles

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Titan's northern spring equinox occurred in August 2009. General Circulation Models (e.g. Lebonnois et al., 2012) predict strong modifications of the global circulation in this period, with formation of two circulation cells instead of the pole-to-pole cell that occurred during northern winter. This winter single cell, which had its descending branch at the north pole, was at the origin of the enrichment of molecular abundances and high stratopause temperatures observed by Cassini/CIRS at high northern latitudes (e.g. Achterberg et al., 2011, Coustenis et al., 2010, Teanby et al., 2008, Vinatier et al., 2010). The predicted dynamical seasonal variations after the equinox have strong impact on the spatial distributions of trace gas, temperature and aerosol abundances.

We will present here an analysis of CIRS limb-geometry datasets acquired in 2010 and 2011 that we used to monitor the seasonal evolution of the vertical profiles of temperature, molecular (C_2H_2, C_2H_6, HCN, …) and aerosol abundances.

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Session 1.5: Atmosphere / Surface Interactions

Insolation Distribution in Titan's Lower Atmosphere

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Variable solar heating drives the seasonal variability of Titan's lower atmospheric dynamics, and therefore its hydrological cycle. Circulation models that have been developed to examine this methane cycle tend to produce a globally oscillating Hadley circulation, the upwelling arm of which follows a diurnal-mean insolation maximum that reaches the pole in summertime (e.g. Mitchell et al., 2006; Schneider et al., 2012). These models use highly simplified parameterizations of radiative transfer, designed to fit Huygens measurements from the equatorial regions; they do not account for the increased attenuation of sunlight at higher latitudes due to Titan's curvature.

Haze scattering in Titan's atmosphere complicates the calculation of the radiation field that reaches the troposphere. However, based on Huygens DISR measurements, Tomasko et al. (2008) computed solar heating rates as a function of altitude for different latitudes, and at different seasons, including a scattering model. In their results, the maximum heating, during solstice, below ~50 km (i.e., in the troposphere) occurred at mid-latitudes, not the poles as might be assumed from the insolation distribution at the top of the atmosphere. Based on these results, we calculated an insolation distribution near the surface that differs significantly from that used in previous models (Lora et al., 2011). This has implications for the circulation, which we explored with a very simple box model that accounts only for thermally driven advection: Forced with the calculated insolation distribution, the model produces surface temperatures in agreement with observations (Jennings et al. 2009), and a circulation pattern significantly different than the one produced with the simplified distribution from the top of the atmosphere.

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Evolution of Titan's equinoctial weather patterns and accompanying surface changes and implications thereof

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Post-equinox changes in Titan's atmospheric circulation brought clouds and extensive methane rain to Titan's low latitudes [1,2]. Observations by Cassini ISS over the ~1.5 years since the storm revealed most of the changes to be short-lived; only a few darkened patches persisted through Fall 2011. In an unsaturated permeable medium, infiltration rates are >20 mm/week [3], so persistence of surface liquids over several months suggests either a shallow impermeable layer or that the local methane table lies close to the surface. Evaporation rates >1 mm/week are predicted in equatorial regions [4] and rates of 20 mm/week have been documented at the poles [5], thus areas where darkening persisted must be saturated ground at the level of a methane table or have had liquid ponded to depths of 2.5-50 cm.

Several smaller areas of surface brightening were also observed, a phenomenon that is less well understood. Cassini VIMS spectra of these regions do not match those of clouds or other surface units [6, 7]. Interpretations include cleaning by runoff [2] or deposition of fresh methane ice [6, 7]. In general, brightening has persisted longer than darkening, but these areas are also reverting to their original appearance, which could constrain the rate of re-deposition of darker hydrocarbon materials by aeolian transport or possibly precipitation of aerosols from the atmosphere.

Although we monitor Titan frequently (at least a few times per month), little cloud activity has been observed since Fall 2010. This lack of clouds may indicate that the outbreak removed enough methane from the atmosphere and the lapse rate stabilized sufficiently that activity will not resume until the onset of convection at mid-northern latitudes later in northern spring. A similar lapse followed a large outbreak of south-polar clouds in Fall 2004 [8], which also appeared to produce significant rainfall [9].

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VIMS Near-Infrared Imaging and Spectra of Precipitation-Associated Surface Changes

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Cassini ISS saw large-scale surface darkenings in the wake of a tropical cloudburst event in 2010 September. In concert with the abstract by Turtle et al., in this presentation we show that weeks to months after darkening the surfaces did not revert to their pre-cloudburst brightness, but rather became brighter. VIMS observations of four distinct areas show these brightenings: Yalaing Terra, Hetpet Regio, Concordia Regio, and Adiri. Each study area brightened within each near-infrared atmospheric window, though not equally. In each case the brightened areas fade to their original spectra over a timescale of about a year. This rapid reversion time is inconsistent with chemical alteration of the surface – haze fallout would take hundreds to tens of thousands of years to recover an altered surface. Instead the deposition and removal of a volatile layer is more consistent with the observed evolution. Different scenarios for the production and removal of such a layer are possible. We will discuss these scenarios, which include evaporative cooled frost that later sublimates, and dissolution and reprecipitation of surface organics that may later be eroded by wind.

Spectral changes associated with rain on Titan: observations by VIMS

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Titan has an erosional cycle similar to that on the Earth, with solid, liquid, and gaseous methane taking the place of the Earth's water. Lakes and ponds, drainage and fluvial features, and clouds all suggest that rain is falling on Titan. A darkening event near clouds covering the Huygens landing site, followed by a return to the previous state, strongly suggested rainfall followed by evaporation (Turtle et al., 2011).

The *Cassini* Visual infrared Mapping Spectrometer (VIMS) obtains medium resolution spectra in the 0.35-5.1 µm spectral region, which includes several atmospheric "windows" that offer glimpses of Titan's surface. The albedo of the surface can be measured in these windows, and some compositional information, including changes through time, can be derived. VIMS observed an area near 15° south latitude and 330° longitude at two separate times: in August 2009 during T61 and in May 2011 during T76. A spectral analysis of this region, including compensation for varying atmospheric path lengths, shows substantial spectral changes in the two and five micron atmospheric windows. A comparison of the changes with that expected from the deposition and later evaporation of liquid methane or another hydrocarbon shows them to be consistent with rain on Titan.

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Session 2.1: Lower / Middle Atmosphere - Physical

Titan Meteorology

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Titan's methane clouds have received much attention since they were first discovered spectroscopically (Griffith et al. 1998). Titan's seasons evolve slowly, and there is growing evidence of a seasonal response in the regions of methane cloud formation (e.g. Rodriguez et al. 2009). A complete, three-dimensional view of Titan's clouds is possible through the determination of cloud-top heights from Cassini images (e.g., Ádámkovics et al. 2010). Even though Titan's surface is warmed by very little sunlight, we now know Titan's methane clouds are convective, evolving through tens of kilometers of altitude on timescales of hours to days with dynamics similar to clouds that appear on Earth (Porco et al. 2005). Cassini ISS has also shown evidence of rain storms on Titan that produce surface accumulation of methane (Turtle et al. 2009). Most recently, Cassini has revealed a 1000-km-scale, arrow-shaped cloud at the equator followed by changes that appear to be evidence of surface precipitation (Turtle et al. 2011b). Individual convective towers simulated with high fidelity indicate that surface convergence of methane humidity and dynamic lifting are required to trigger deep, precipitating convection (e.g. Barth & Rafkin 2010). The global expanses of these cloud outbursts, the evidence for surface precipitation, and the requirement of dynamic convergence and lifting at the surface to trigger deep convection motivate an analysis of storm formation in the context of Titan's global circulation.

I will review our current understanding of Titan's methane meteorology using Cassini and ground-based observations and, in particular, global circulation model simulations of Titan's methane cycle. When compared with cloud observations, our simulations indicate an essential role for planetary-scale atmospheric waves in organizing convective storms on large scales (Mitchell et al. 2011). I will end with predictions of Titan's weather during the upcoming northern hemisphere summer.

Titan's methane cycle in the Titan WRF general circulation model

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Observations of methane clouds, surface lakes and precipitation (or evidence of past precipitation) on Titan allow us to assemble information about the seasonal evolution of Titan's methane cycle, as well as Titan's lower atmosphere and near-surface environment in general. Using the TitanWRF general circulation model [Newman et al., 2011] we attempt to reproduce some of these observations by simulating Titan's atmospheric circulation and methane cycle, assuming limited surface methane and using a simple large-scale cloud scheme both with and without latent heating effects included.

We have performed both 'current' and 'reversed perihelion' simulations, i.e. using the current solar forcing (perihelion in southern summer) and its exact opposite (perihelion in northern summer, as occurred at some time in the past), to test the hypothesis that the timing of perihelion explains the asymmetry in surface methane distribution currently observed. We look at the net transport and latitudinal distribution of surface methane as the simulations tend toward steady state after >100 Titan years. Initially, as the equatorial regions lose and the high latitudes gain significant methane each Titan year, our results are highly sensitive to initial conditions. However, as the simulations tend toward steady state and specifically as the tropics dry out, the 'current' and 'reversed perihelion' results increasingly tend toward 'mirror images' of each other. With the decreased significance of tropical moisture sources, the methane balance becomes dominated by pole-to-pole exchange (inter-polar competition for methane) with the simulations tending toward final states with significantly more high latitude surface methane in the hemisphere with the longer, cooler summer (*i.e.*, in the northern hemisphere for current solar forcing, in line with the asymmetry observed).

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A new look at Titan's zonal winds from Cassini radio occultations

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We use the existing thirteen Cassini radio-occultation soundings to construct a meridional cross section of geopotential height vs. pressure and latitude. The assumption of balanced flow permits the construction of a similar cross section of zonal winds, from near the surface to the 0.1-mbar level. In the lower troposphere, the winds are ~10 m s^{-1}, except within 20° of the equator, where they are much smaller. The winds increase higher up in the troposphere to nearly 40 m s^{-1} in the tropopause region, but then decay rapidly in the lower stratosphere to near-zero values at 20 mbar (~80 km), reminiscent of the Huygens Doppler Wind Experiment result. This null zone extends over most latitudes, except for limited bands at mid-latitudes. Higher up in the stratosphere, the winds become larger. They are highest in the northern (winter) hemisphere. We compare the occultation results with the DWE and CIRS retrievals and discuss the similarities and differences among the data sets.

Temporal Variations of Titan's Stratospheric Structure from Cassini CIRS Observations

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Since orbit insertion in July 2004, the Composite Infrared Spectrometer (CIRS) onboard the Cassini Orbiter has been routinely making two sets of observations of Titan designed for measuring the temperature structure of the upper stratosphere and lower mesosphere. During the majority of Titan flybys, CIRS performs a nadir mapping sequence, which allows mapping of temperatures between roughly 0.5 mbar and 5 mbar over one hemisphere of Titan with a spatial resolution of ~2.5° of arc. CIRS also performs limb mapping observations, each of which covers 30° to 90° of latitude at 5° intervals, with a vertical resolution of 30 to 50 km but with limited longitude coverage, and which allows retrieval of temperature between 0.005 mbar and 5 mbar. Results through 2009 (northern spring equinox) were published in Achterberg et al. (2011).

Since equinox, stratospheric temperatures have become progressively more symmetric between hemispheres. In the mid-stratosphere, southern hemisphere temperatures have been decreasing while northern hemisphere temperatures increase, with the zonal mean temperatures becoming nearly symmetric in late 2011. The warm, elevated north polar stratopause has continued to cool; beginning in mid-2010 a warm elevated stratopause began to form at the south pole, increasing in temperature into 2011.

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Session 2.2: Middle Atmosphere - Composition

Titan's post-equinox circulation revealed using chemical tracers

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Titan's atmosphere harbors a vast array of minor chemical compounds produced by its active photochemical cycle – including many hydrocarbon and nitrile species. These species have a wide range of lifetimes and can be used as chemical tracers of atmospheric motion on a variety of time scales (Teanby et al 2008). Therefore, by measuring how the abundances of these species vary during Cassini's mission so far, it is possible to probe changes in Titan's general circulation. Here we use eight years of Cassini Composite InfraRed Spectrometer (CIRS) data to study how the atmospheric circulation behaves during the equinox and post-equinox periods. As northern winter progressed to northern spring, significant changes in the distribution of trace gases were observed. These include an increase in trace gas abundance at the north pole and northward migration of the vortex boundary. The implications of the observed changed will be discussed – including a possible interpretation of the recent changes as a weakening of the north polar vortex accompanied by a reduction in cross-vortex mixing.

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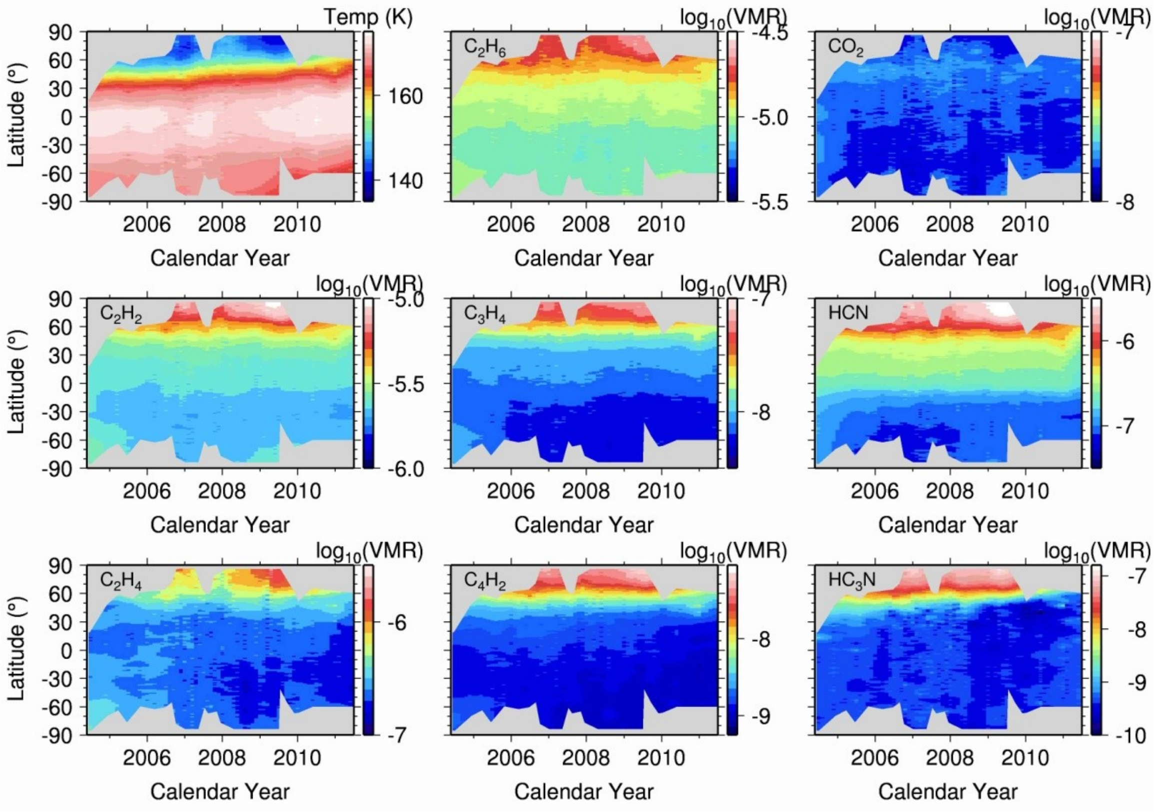

Figure showing the observed variations in temperature and composition from the mission so far.

Titan’s stratospheric condensibles at high northern latitudes during northern winter

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The Infrared Interferometer Spectrometer (IRIS) instrument on board Voyager 1 caught the first glimpse of an unidentified particulate feature in Titan’s stratosphere that spectrally peaks at 221 cm^{-1}. Until recently, this feature that we have termed ‘the haystack,’ has been seen persistently at high northern latitudes with the Composite Infrared Spectrometer (CIRS) instrument onboard Cassini. The strength of the haystack emission feature diminishes rapidly with season, becoming drastically reduced at high northern latitudes, as Titan transitions from northern winter into spring.

In contrast to IRIS whose shortest wavenumber was 200 cm^{-1}, CIRS extends down to 10 cm^{-1}, thus revealing an entirely unexplored spectral region in which nitrile ices have numerous broad lattice vibration features. Unlike the haystack, which is only found at high northern latitudes during northern winter/early northern spring, this geometrically thin nitrile cloud pervades Titan’s lower stratosphere, spectrally peaking at 160 cm^{-1}, and is almost global in extent spanning latitudes 85°N to 60°S. The inference of nitrile ices are consistent with the highly restricted altitude ranges over which these features are observed, and appear to be dominated by a mixture of HCN and HC_3N. The narrow range in altitude over which the nitrile ices extend is unlike the haystack, whose vertical distribution is significantly broader, spanning roughly 70 km in altitude in Titan’s lower stratosphere.

The nitrile clouds that CIRS observes are located in a dynamically stable region of Titan’s atmosphere, whereas CH_4 clouds, which ordinarily form in the troposphere, form in a more dynamically unstable region, where convective cloud systems tend to occur. In the unusual situation where Titan’s tropopause cools significantly from the HASI 70.5K temperature minimum, CH_4 should condense in Titan’s lower stratosphere, just like the aforementioned nitrile clouds, although in significantly larger abundances.

We will present the spectral and vertical distribution of Titan’s stratospheric particulates during northern winter on Titan. The drastically changing abundance of the haystack over a small latitude range will be highlighted, specifically comparing the IRIS and CIRS epochs. Finally, we will discuss the situation in which CH_4 condenses in Titan's lower stratosphere, forming an unexpected quasi steady-state stratospheric ice cloud.

Ice layers in Titan's stratosphere

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Processes in Titan's upper atmosphere, such as photochemical destruction of methane along with the destruction of nitrogen molecules from energetic electrons, result in the production of a number of hydrocarbon and nitrile compounds which are capable of condensing in the colder temperatures of Titan's lower stratosphere. Stratospheric ices can contribute to the opacity of Titan's atmosphere as well as affect the chemistry of the more optically thick clouds seen in the troposphere, should they serve as condensation nuclei. Recently, Anderson & Samuelson (2011, Icarus, v. 212, p. 762) looked at data from the Cassini Composite Infrared Spectrometer (CIRS) and found evidence for emission features centered around 90 km which are consistent with nitrile ices, notably HCN and HC_3N. These compounds along with other possible contributors have been added to the Titan-CARMA column microphysics model (Barth & Toon, 2006, Icarus, v. 182, p. 230) to explore altitudes for condensation as well as expected particle sizes in these stratospheric ice layers.

Water vapor on Titan: the stratospheric vertical profile from Cassini/CIRS infrared spectra

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Water vapor in Titan's middle atmosphere has previously been detected only by disk-average observations from the Infrared Space Observatory (Coustenis et al., 1998). We report here the successful detection of stratospheric water vapor using the Cassini Composite Infrared Spectrometer (CIRS, Flasar et al., 2004) following an earlier null result (de Kok et al., 2007a). CIRS senses water emissions in the far-infrared spectral region near 50 microns, which we have modeled using two independent radiative transfer and inversion codes (NEMESIS, Irwin et al 2008 and ART, Coustenis et al., 2010). From the analysis of nadir spectra we have derived a mixing ratio of (0.14 ± 0.05) ppb at 100 km, corresponding to a column abundance of approximately (3.7 ± 1.3) × 10^{14} mol/cm^2. Using limb observations, we obtained mixing ratios of (0.13 ± 0.04) ppb at 125 km and (0.45 ± 0.15) ppb at 225 km of altitude, confirming that the water abundance has a positive vertical gradient as predicted by photochemical models. In the latitude range (80°S – 30°N) we see no evidence for latitudinal variations in these abundances within the error bars.

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Observations of H_2O in Titan's atmosphere with Herschel

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Disk averaged observations of several H_2O far infrared lines in Titan's atmosphere were performed with the Herschel Space Observatory, as part of the guaranteed time key program "Water and related chemistry in the Solar System" (HssO, see Hartogh et al 2011). Two instruments were used: (i) HIFI, a heterodyne instrument ($R \sim 10^6$) in the sub-millimeter, which measured the $H_2O_{(110-101)}$ rotational transition at 557 GHz on June 10 and Dec. 31, 2010 (ii) PACS, a photoconductor spectrometer ($R \sim 10^3$) which measured three water lines at 108.1, 75.4 and 66.4 microns on June 22, 2010. Additional PACS measurements at 66.4 microns on Dec. 15 and 22, 2010 and on July 09, 2011, do not show any significant line intensity variation with time, nor between the leading/trailing sides (i.e. longitude).

Spectra were analyzed with a line-by-line radiative transfer code accounting for spherical geometry (Moreno *et al.* 2011). This model considers the H_2O molecular opacity from JPL catalog (Pickett *et al.* 1998) and also includes collision-induced opacities N_2-N_2, N_2-CH_4 and CH_4-CH_4 (Borysow and Frommhold 1986, 1987, Borysow and Tang 1993). Far infrared aerosol opacities derived by CIRS were included, following Anderson and Samuelson (2011) for their vertical distribution and spectral dependencies.

Analysis of the 557 GHz narrow line (FWHM ~ 2 MHz) indicates that it originates at altitudes above 300 km, while lines measured with PACS probe mainly deeper levels (80-150 km).

The HIFI and PACS observations are fitted simultaneously, considering a vertical distribution of H_2O mixing ratio which follows a power law dependency $q=q_0(P/P_0)^n$, *where* q_0 *is the mixing ratio at some reference pressure level* P_0*, taken near the expected condensation level.* Model fits will be presented, and compared with previously proposed H_2O vertical distributions. We show in particular that both the steep profile proposed by Lara et al. (1996) (and adopted by Coustenis et al. (1998) to model the first detection of H_2O by ISO) and the shallower profiles from the Hörst et al (2008) photochemical model fail to explain the observations. Additional profiles, described in Lara *et. al.*, (this workshop) are tested against the data.

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Photochemical modeling of H_2O in Titan's atmosphere constrained by Herschel Observations

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As a species subject to photolytic, chemical and condensation losses, H_2O present in Titan's stratosphere must be of external origin. The discovery of CO_2 by Voyager (Samuelson et al. 1981) pointed to an external supply of oxygen to Titan's atmosphere. Indeed, CO_2, which also condenses, was recognized to be formed via CO+OH, where OH was likely produced by H_2O photolysis. This view was supported by the ground-based discovery of CO (Lutz et al. 1983) and subsequent measurements confirming an abundance of ~50 ppm. The source of CO itself remained elusive, but inspired by the Cassini/CAPS discovery of a O^+ influx rate (Hartle et al. 2006), Hörst et al. (2008) showed that an external source of O or O^+ leads to the formation of CO, also pointing to the likely external origin of this compound.

The most up-to-date model of Titan's oxygen chemistry by Hörst et al. (2008) adjusted the OH/H_2O deposition rate as a function of the eddy diffusion coefficient below 200 km to match the observed CO_2 mixing ratio (15 ppb, uniform over 100-200 km), and producing a H_2O profile that was deemed consistent with ISO/SWS measurement of the H_2O abundance at a nominal altitude of 400 km (Coustenis et al. 1998). Therefore, the Hörst et al. (2008) study provided an apparently self-consistent picture of the origin of oxygen compounds in Titan's atmosphere, with the three main species (CO, CO_2 and H_2O) being produced from a permanent external supply of oxygen in two distinct forms.

However, recent measurements of several H_2O lines by the HIFI and PACS instruments (Herschel Space Observatory) have shown that none of the H_2O profiles calculated in Hörst et al. (2008) reproduces the observed lines (Moreno et al., this workshop), and neither does the Lara et al. (1996) H_2O profile. Here we revisit the Lara et al. (1996) photochemical model by including (i) an updated eddy diffusion coefficient profile (K(z)), constrained by the C_2H_6 vertical distribution (ii) an adjustable O^+/OH/H_2O influx. Our main finding is that the OH/H_2O influx required to match the observed H_2O profile is significantly smaller than previously thought (i.e. several times 10^5 $cm^{-2}s^{-1}$, instead of a few times 10^6 cm^{-2}s^{-1}). This flux in itself is insufficient to explain the CO_2 abundance. We are exploring solutions to this problem

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Session 2.3: Middle / Upper Atmosphere - Composition

Titan's chemical complexity

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We review here our current knowledge of Titan's gas phase chemistry. We base our discussion on photochemical models as well as on laboratory experiments. We identify the lower mass positive [1,2] and negative [3] ions detected in the upper atmosphere and we show that their formation is a direct consequence of the presence of heavy neutrals. We demonstrate that the observed densities of CO, CO_2 and H_2O can be explained by a combination of exogenous O, and OH/H_2O input [4]. We argue that benzene [5] and ammonia [6] are created in the upper atmosphere through complex chemical processes involving both neutral and ion chemistry. These species diffuse downward where they are at the origin of heavier aromatics and amines, respectively. Finally, we discuss the impact on hydrocarbon densities of recent theoretical calculations of the rate constants of association reactions [7].

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On the absence of significant aerosol chemistry below Titan's stratopause at 300 km

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Analyses of CIRS data indicate inhomogeneities in the distribution of Titan's aerosol below 300 km (~0.1 mbar). With some exceptions, the aerosol scale height tends to exceed the pressure scale height at most latitudes, indicating that dynamical mixing is not strong enough to erase the abundance gradient initially produced by an aerosol source at high altitudes and a sink near the surface. Additionally, variations in aerosol mole fraction are found in both altitude below 300 km and in latitude from 85°N to 58°S. These spatial inhomogeneities, when coupled with well-known latitudinal abundance variations of several organic gases, suggest that variability of aerosol chemical composition should occur below 300 km provided aerosol chemistry is still taking place at these altitudes. On the other hand, uniformity of aerosol spectra between 80 cm^{-1} and 1460 cm^{-1} throughout the region below the stratopause appears to indicate otherwise. As a result there is a spatial variability in aerosol abundance in the atmosphere below 300 km, but no corresponding spectral variability in the aerosol opacity. This strongly suggests that below the stratopause the formation and chemical evolution of the aerosol proceeds at a much slower rate than the rate of dynamical overturning of Titan's atmosphere, even though the latter rate is not large enough to eliminate inhomogeneities in the spatial distributions of the aerosol. This in turn implies that almost all of Titan's aerosol chemistry occurs above the stratopause where pressures are lower than 0.1 mbar. On the other hand laboratory analogs to Titan's aerosol (tholins) tend to be produced at pressures considerably greater than 0.1 mbar. These high pressure conditions tend to favor the production of aliphatics instead of aromatics, and with less nitrogen being incorporated into the refractory structure. The significant spectral differences between aerosol and tholin corroborate the apparent environmental differences under which the two products are formed.

Forward Modeling of the 2003 November 14 Titan Occultation: New Retrievals of Temperature, Density and Opacity Profiles from about 350 to 500 km

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On 2003 November 14, Titan occulted a relatively bright star (V = 10.7). This event was observed from La Palma Observatory using ULTRACAM in three simultaneous wavelengths (358, 487 and 758 nm), as reported by Zalucha et al. (2007). The event was near-central, but only the long-wavelength light curves show a central flash. Zalucha et al. (2007) extracted temperature profiles from 350 to 485 km, estimated the altitudes where line-of-sight aerosol optical depths are one in the three ULTRACAM filters and fit the three-peaked central flash feature to atmospheric shape models that are comparable to those used by Hubbard et al. (1993) in the 28 Sgr occultation.

We now use a more flexible forward-modeling approach to re-examine the ULTRACAM light curves. The output of this effort is a thin-screen representation of Titan's upper atmosphere consisting of line-of-sight opacities and phase delays - it is a flexible technique to simultaneously retrieve extinction and refractivity profiles and bulk atmospheric shape. We will present temperature, density and opacity profiles that are consistent with the retrieved thin-screen model and compare model light curves generated from HASI temperature profiles to the occultation observations.

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Non-LTE diagnostics of CIRS observations of Titan's mesosphere

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Titan's low-resolution limb spectra from 600-1500 cm-1 collected by CIRS over 80 flybys provide a significant source of information about the temperature structure and composition of Titan's atmosphere up to an altitude of 700-800 km, allowing the extension of existing temperature and trace gas density retrievals up to altitudes in the lower thermosphere. At these altitudes, however, both for day and night conditions, the breakdown of local thermodynamic equilibrium (non-LTE) has significant impact on the formation of the mid-infrared ro-vibrational band emissions of methane and various trace gases [Yelle, 1991]. Nevertheless, up to now the analysis of CIRS limb spectra was based solely on the assumption of local thermodynamic equilibrium. We discuss the importance of the non-LTE diagnostics of the CIRS limb low-resolution spectra, show the effects of non-LTE on temperature and trace gas density retrievals and demonstrate that accounting for the non-LTE provides better agreement between measured by CIRS [Vinatier et al, 2007, 2010] and modeled [Krasnopolsky, 2009, 2010] trace gas densities in Titan's mesosphere.

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Compositional Variations from UVIS Observations of Titan's Dayglow and Comparisons with in situ INMS Observations

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The Cassini Ultraviolet Imaging Spectrograph (UVIS) observed Titan's dayside limb on multiple occasions between 2007 and 2011. The airglow observations reveal the same variety of EUV (600-1150 Å) and FUV (1150-1900 Å) emissions arising from photoelectron excitation and photofragmentation of molecular nitrogen (N_2) on Earth. Through spectral analysis we extract radiance profiles for each set of UVIS limb emissions in the EUV and FUV, which are attenuated by methane (CH_4). Using a terrestrial airglow model adapted to Titan, we derive the N_2 and CH_4 density profiles using the prescribed solar irradiance for the relevant Cassini orbit and compare the calculated radiance profiles directly with observations. We find that the UVIS airglow observations can be explained by solar driven processes, although fluctuations in the observed airglow between flybys suggest compositional changes in the background atmosphere. We compare the compositional variations inferred from the UVIS airglow to in situ observations by the Cassini Ion and Neutral Mass Spectrometer (INMS) from the same Titan orbit and discuss how the variations may be related to Titan's varying plasma environment.

Session 2.4: Titan Posters II

Experiments on Titan's lakes and surface interactions at JPL and preparation for future in-situ missions

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This paper will present some aspects of the experimental research conducted at the Jet Propulsion Laboratory to better understand the interactions between Titan's lakes and its solid surface, and to prepare for a future in-situ missions to Titan. Three aspects, besides other presentations at this meeting (Choukroun and Sotin; Hodyss et al.), are the subject of ongoing research and experimental developments.

(1) A cryogenic chamber is being used to investigate the wetting of icy substrates by liquid hydrocarbons. Substrates investigated so far are polycrystalline and monocrystalline ice samples, as well as clathrate hydrates, and ice with tholins deposited on the surface. The substrates are cooled to 90 K, and methane and ethane are liquefied and dripped onto the surface. Absorption within the porous substrates and wetting angle estimations will be presented.

(2) A custom-made cryostat is being used to study the fate of materials dissolved in the lakes that precipitate upon evaporation. Dominant solid products of Titan's atmospheric chemistry, such as benzene and acetylene, are dissolved in liquid ethane up to saturation. Then the liquid is evaporated under a slow flow of N_2 and the precipitate's morphology and chemistry are analyzed within a cryostage using optical microscopy and Raman spectroscopy. Preliminary results will be presented.

(3) A cryogenic chamber is being developed to provide a testbed useful to the community for both science applications and instrument testing for future in-situ missions to Titan. This chamber will allow long-duration (up to weeks) testing at Titan's conditions, and is being constructed to hold up to 10 L of liquid hydrocarbon mixtures under a 1.5 bar N_2 pressure. The design considered will

allow optical access for observations at visible and infrared wavelengths, sampling of the gas and liquid for chemical analyses, and other diagnostics. This testbed is designed to support existing and future research and instrumentation projects. We will report on the status of this development and expected capabilities.

This work has been conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA. Support from the JPL TEFIM program and the NASA Astrobiology Institute, and government sponsorship, are acknowledged.

Analysis of High-Resolution Mid-Infrared Laboratory Allene Spectra and the Interpretation of Titan's Infrared Spectra

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We report initial results on the mid-infrared spectroscopic parameters of gas phase allene ($H_2C{=}C{=}CH_2$). Voyager's Infrared Spectrometer and Cassini's Composite Infrared Spectrometer (CIRS) observations revealed a plethora of trace gas species including hydrocarbons and nitriles in the atmosphere of Titan. The interpretation of Titan's top-of-the-atmosphere spectra observed by CIRS requires the use of molecular line atlases with complete and accurate spectroscopic parameters. Furthermore, after removing calculated signatures characteristic of known atmospheric compounds, residuals in observed CIRS spectra can potentially unveil hidden species.

Mid-infrared molecular spectroscopy parameters of gas phase allene are not readily available in a spectral resolution commensurate with the analysis of CIRS observations. To rectify this lack of line atlas information, we are using previously unpublished 0.0025 cm^{-1} resolution data, obtained by Jennings et al. using the Kitt Peak National Observatories McMath-Pierce Fourier Transform Spectrometer, to extract optical constants that characterize the ν_9 (999 cm^{-1}) and ν_{10} (841 cm^{-1}) ro-vibrational bands of room temperature gas phase allene. Line atlas products will be distributed to the community in HITRAN/GEISA formats for use in the interpretation of CIRS spectra. Initial results of absolute line intensities and transition frequencies will be presented herein. We will also discuss the use of the spectroscopic parameters in searching for other hidden trace chemical species in Titan's atmospheric spectra.

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The solubility of ^{40}Ar in liquid hydrocarbons: implications for Titan's geological evolution

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The solubility of argon in methane and ethane has been experimentally determined at 94 K. It is found to be very large (47% in methane and 15% in ethane) making liquid alkane reservoirs on Titan an important potential reservoir of ^{40}Ar. The amount of argon in the Titan lakes can be several times the atmospheric amount. Large subsurface reservoirs of liquid ethane and methane could be sufficient to trap much of the argon outgassing from Titan's interior. This can help explain the discrepancy between the potential amount of ^{40}Ar produced inside Titan's interior, and the amount observed in the atmosphere by Cassini-Huygens. Consequently, on Titan, liquid hydrocarbons may function as a buffer in the outgassing of volatiles from the interior, and they may strongly influence the evolution of the atmosphere's composition through release of soluble gases upon evaporation and intake upon condensation.

This work has been conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA. Support from the NASA Astrobiology Institute and government sponsorship acknowledged.

Nitrogen Chemistry in Titan's Upper Atmosphere

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Titan's atmosphere has evolved over time into its current state through complex photochemical processes (Yung et al. 1984), involving nitrogen (N_2), the dominant molecular species in the atmosphere, as well as methane (CH_4). It has been proposed that this composition may be analogous to the early Earth's, as it certainly provides an abundance of hydrocarbons the like from which early life may have arisen (Coustenis & Taylor 1999; Lunine 2005). Recent results from the Cassini spacecraft have greatly improved our knowledge of the current state of Titan's atmosphere, and measurements made by the Ultraviolet Imaging Spectrograph (UVIS) in particular are able to probe the region of interest from 400 km to 1500 km in altitude where much of the photochemistry on Titan occurs (Shemansky et al. 2005, Koskinen et al. 2011). This photochemistry in part converts nitrogen from stable N_2 molecules and incorporates it into detectable hydrocarbon products such as HCN, HC_3N, and other heavier compounds. Therefore the nitrogen story is of particular interest, and we examine UVIS occultation observations in both the EUV and FUV regions of the spectrum in order to directly retrieve the vertical profiles of N_2 in addition to its related hydrocarbon derivatives. Constraints from UVIS on temperature profiles of the upper atmosphere are also examined and compared to current results from the Ion and Neutral Mass Spectrometer (INMS), which probes a region above 1000 km altitude in Titan's atmosphere (Westlake et al. 2011).

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Update from the Analysis of High Resolution Propane Spectra and the Interpretation of Titan's Infrared Spectra

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Titan has an extremely thick atmosphere dominated by nitrogen, but includes a range of trace species such as hydrocarbons and nitriles. One such hydrocarbon is propane (C_3H_8). Propane has 21 active IR bands covering broad regions of the mid-infrared. Therefore, its ubiquitous signature may potentially mask weaker signatures of other undetected species with important roles in Titan's chemistry. Cassini's Composite Infrared Spectrometer (CIRS) observations of Titan's atmosphere hint at the presence of such molecules. Unfortunately, C_3H_8 line atlases for the vibration bands v_8, v_{21}, v_{20}, and v_7 (869, 922, 1054, and 1157 cm^{-1}, respectively) are not currently available for subtracting the C_3H_8 signal to reveal, or constrain, the signature of underlying chemical species. Using spectra previously obtained by Jennings, D. E., et al. at the McMath-Pierce FTIR at Kitt Peak, AZ, as the source and automated analysis utilities developed for this application, we are compiling an atlas of spectroscopic parameters for propane that characterize the ro-vibrational transitions in the above bands. In this paper, we will discuss our efforts for inspecting and fitting the aforementioned bands, present updated results for spectroscopic parameters including absolute line intensities and transition frequencies in HITRAN and GEISA formats, and show how these optical constants will be used in searching for other trace chemical species in Titan's atmosphere. Our line atlas for the v_{21} band contains a total number of 2971 lines. The band integrated strength calculated for the v_{21} band is 1.003 $cm^{-1}/(cm\text{-}atm)$.

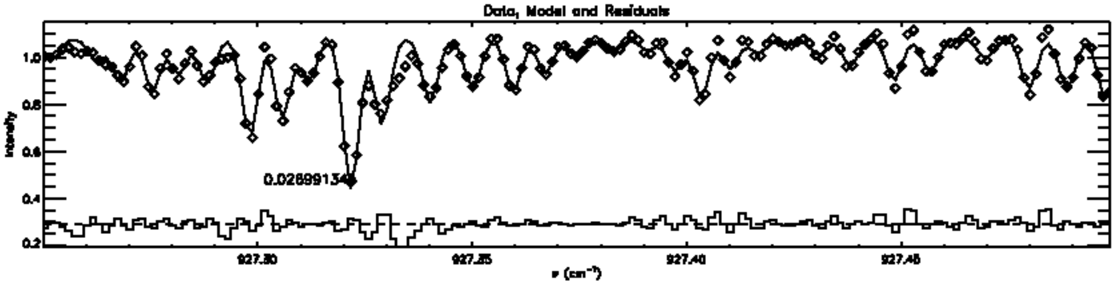

Fig. 1: Demonstration of Gaussian fit for sample spectral region 927.25 to 927.50 cm^{-1} (v_{21}).

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Tholin sensitivity to atmospheric methane abundance and the implications for multiple stable states of Titan's climate system

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We created Titan tholin analogues using cold plasma at five different methane concentrations from 2-10%. Similar to Sciamma-O'Brien et al. (2010, 2011) we measured the tholin production rate and optical constants using ellipsometry. We find that the tholin production peaks at an in situ methane concentration of 2.3%. The tholin imaginary indices of refraction vary by tens of percent and are generally lower than those created by Khare et al. (1983). We use the varying tholin production rates and optical imaginary indices of refraction in a simple model to explore their climatic effects. The radiative equilibrium model we use is similar to that of McKay et al. (1999) and Lorenz et al. (1999), however we have made the tholin production and absorption a function of methane mole fraction. We find that with current volatile inventories our model predicts a warmer Titan atmosphere, than without our corrections. The model also predicts Titan's atmosphere to jump to a runaway greenhouse as the solar constant increases.

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Radiolysis of frozen methane by heavy ions at different temperatures

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Methane ice is found in several bodies of the Solar System, including Titan, interstellar medium and young stellar objects, where it is frequently exposed to cosmic ray and solar wind radiation. The chemical, physical and structural effects induced by fast heavy ion irradiation on methane (CH_4) pure ice at different temperatures are analyzed. Experiments were performed in a high-vacuum chamber ($P \sim 10^{-8}$ mbar) coupled to GANIL accelerator beam lines in France. Ice monitoring during irradiation was done by mid-infrared spectroscopy (FTIR).

Irradiation by 6 MeV $^{16}O^{2+}$ ion beam on the CH_4 pure ice at 15, 25 and 35 K as well as by 220 MeV $^{16}O^{7+}$ [1], 267 MeV $^{56}Fe^{22+}$ and 606 MeV $^{70}Zn^{26+}$ at 15 K were performed. The analysis show that the CH_4 destruction rate at 15 K is higher than at 35 K, and that the production rate of new molecules (C_2H_2, C_2H_4, C_2H_6, C_3H_8, C_4H_8, C_4H_{10} and radicals CH_3 and C_2H_5) increases as the temperature decreases. These findings should be relevant for the understanding of chemical reactions involving CH_4 induced by high energy radiation in the Titan's atmosphere.

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Influence of Benzene on the Optical Properties of Titan Haze Laboratory Analogs in the Mid-Visible

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The Cassini Ion and Neutral Mass Spectrometer (Waite, Jr., *et al.*, 2007) and the Composite Infrared Spectrometer (Coustenis, A., *et al.*, 2007) have detected benzene in the upper atmosphere and stratosphere of Titan. Photochemical reactions involving benzene in Titan's atmosphere may influence polycyclic aromatic hydrocarbon formation, aerosol formation, and the radiative balance of Titan's atmosphere. We measure the effect of benzene on the optical properties of Titan analog particles in the laboratory.

Using cavity ring-down aerosol extinction spectroscopy, we determine the real and imaginary refractive index at 532 nm of particles formed by benzene photolysis and Titan analog particles formed with ppm-levels of benzene. These studies are compared to the previous study by Hasenkopf, *et al.* (2010) of Titan analog particles formed by methane photolysis.

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Session 2.5: Upper Atmosphere

Titan's Upper Atmosphere: The Great Escape?

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The talk will focus on the escape rates of methane and molecular hydrogen from Titan's upper atmosphere. I will argue that the escape rate of molecular hydrogen is governed by Hunten's limiting flux principle and that it is ~ 1×10^{28} H_2 s^{-1}, derived from diffusion modeling of the data (Cui et al., 2011), the Hunten limiting rate, and numerical solutions to the fluid equations, (Strobel, 2011). This actual escape rate is ~ 1.5 (not 2.5) times the Jeans escape rate (~ 6×10^{27} H_2 s^{-1}) in agreement with the Volkov et al. (2011a) results for larger values of the Jeans lambda parameter and confirms that the Jeans escape rate is not accurate for H_2 in Titan's atmosphere.

The inferences of large escape rates are derived from measured INMS density profiles in the thermosphere and diffusive solutions to the fluid equations where the atmosphere behaves as a continuum fluid. While there are a few flybys where the INMS density profiles can be fit with a gravitational, diffusive equilibrium profile with no upward flux, the majority of the INMS density profiles individually and when averaged require upward fluxes with escape rates in the absence of chemistry. The escape problem is thus seemingly intractable, if its escape rate must be constrained to typical non-thermal rates.

Neither vigorous vertical mixing, which is inconsistent with the mole fraction profile and makes it even more difficult to account for the elevated H_2 mole fractions measured by INMS (Strobel 2011), nor the aerosol trapping mechanism which was formulated by Bell et al. (2010) to be most effective below altitudes probed by INMS are solutions. An extremely large chemical loss of due to magnetospheric particle ionization would reduce the escape rate to desired rates, but Cassini magnetospheric measurements rule out the required particle fluxes by at least an order of magnitude. Finally, there has been no reported detection of carbon bearing ions in the outer magnetosphere of Saturn commensurate with the large inferred CH_4 escape rates.

Energetic particle energy deposition in Titan's upper atmosphere

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Titan's upper atmosphere has been observed to be variable on a pass-by-pass basis. During the nominal mission where the Cassini Ion and Neutral Mass Spectrometer (INMS) only sampled the northern hemisphere this variability was initially believed to be tied to solar drivers manifest in latitudinal variations in the thermal structure of the upper atmosphere. However, when Cassini delved into the southern hemisphere the latitudinal dependence was not present in the data. Recently, Westlake et al. (2011) showed that the pass-by-pass variability is correlated with the deviations in the plasma environment as identified by Rymer et al. (2009) and Simon et al. (2010). Furthermore, the studies of Westlake et al. (2011) and Bell et al. (2011) showed that Titan's upper atmosphere responds to changes in the ambient magnetospheric plasma on timescales of roughly one Titan day (16 Earth days). We report on recent studies of energy deposition in Titan's upper atmosphere. Previous studies by Smith et al. (2009), Cravens et al. (2008), Tseng et al. (2008), and Shah et al. (2009) reported on energetic proton and oxygen ion precipitation. Back of the envelope calculations by Sittler et al. (2009) showed that magnetospheric energy inputs are expected to be of the order of or greater than the solar processes. We report on further analysis of the plasma environment around Titan during the flybys that the INMS has good data. We utilize data from the Magnetospheric Imaging Instrument to determine how the magnetospheric particle population varies from pass to pass and how this influences the net magnetospheric energy input prior to the flyby. We also report on enhanced energetic neutral atom emissions during select highly energetic passes.

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Ionization processes in the atmosphere of Titan: from electron precipitation along magnetic field lines to high-Z cosmic rays ionization

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Knowledge of the ionization profile in the atmosphere of Titan is needed to understand its chemistry. The different ionization sources have a different impact in term of altitude of ionization, intensity, and variability. The main sources are the solar EUV-XUV flux, the electrons and protons from the magnetosphere of Saturn, and the cosmic rays.

In this work, we compare the result of the modeling of these ionizations with the observations by the Cassini and Huygens probes. We show that it is possible to observe the effects of the interaction of the Kronian magnetic field with Titan in the precipitating electron flux measured by Cassini. We also show that the aerosols layers, detected in the upper atmosphere, the mesosphere, and the lower atmosphere, are correlated with the ionization layers detected by several instruments. We therefore suggest that these layers are created by ionization: from EUV-XUV and electrons in the upper atmosphere, protons in the mesosphere, and galactic cosmic rays in the main haze layer.

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Session 3.1: Laboratory Simulations

Influence of methane concentration on the optical indices of Titan's aerosol analogues

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Titan's haze is one of the main drivers of the radiative transfer in the atmosphere of Titan and strongly influences its thermal structure (Rannou et al.2010). In Titan's atmosphere, CH_4 concentration may have varied through time during the evolution of this planet (Atreya et al. 2006). So it is of utmost importance to determine the optical constants of tholins synthesized from N_2-CH_4 mixtures with different CH_4 concentration to understand the evolution of Titan atmosphere through time. This work deals with the optical constant characterization of Titan aerosol analogues produced with a radio frequency experimental setup and deposited as thin films onto a silicon substrate (Mahjoub et al. 2012). Tholins were produced in different N_2–CH_4 gaseous mixtures to study the effect of the initial methane concentration on their optical constants. The real and imaginary parts of the complex refractive index were determined using the spectroscopic ellipsometry in the 0.37-1 µm range.

We find that optical indices depend strongly on the methane concentrations of the gas phase: imaginary index (k) decreases by an order of magnitude with initial CH_4 concentration at 1 µm wavelength, while the real index (n) increases from 1.48 up to 1.56 at 1 µm wavelength. The larger absorption in the visible range of tholins produced at lower methane percentage is explained by an increase of amines signatures in tholins, measured by absorption spectroscopy in the mid-IR range.

According to the methane concentration in Titan's atmosphere, the evolution of the visible optical signature of Titan's aerosols may have influenced very differently Titan's climate through time.

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Comparison of Nitrogen Incorporation in Tholins Produced by FUV Irradiation and Spark Discharge

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The discovery of very heavy ions (Coates *et al.,* 2007) in Titan's thermosphere has dramatically altered our understanding of the processes involved in the formation of the complex organic aerosols that comprise Titan's characteristic haze. Before Cassini's arrival, it was believed that aerosol production began in the stratosphere where the chemical processes were predominantly initiated by FUV radiation. This understanding guided the design of Titan atmosphere simulation experiments. However, the energy environment of the thermosphere is significantly different than the stratosphere; in particular there is a greater flux of EUV photons and energetic particles available to initiate chemical reactions, including the destruction of N_2, in the upper atmosphere. Using a High-Resolution Time-of-Flight Aerosol Mass Spectrometer (HR-ToF-AMS), we have obtained *in situ* composition measurements of aerosol particles (so-called "tholins") produced in CH_4/N_2 gas mixtures subjected to either FUV radiation (deuterium lamp, 115-400 nm) (Trainer *et al.*, 2012) or a spark discharge. A comparison of the composition of tholins produced using the two different energy sources will be presented, in particular with regard to the variation in nitrogen content of the two types of tholin. Titan's aerosols are known to contain significant amounts of nitrogen (Israël *et al.,* 2005) and therefore understanding the role of nitrogen in the aerosol chemistry is important to further our knowledge of the formation and evolution of aerosols in Titan's atmosphere.

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The Titan Haze Simulation experiment: laboratory simulation of Titan's atmospheric chemistry at low temperature

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In Titan's atmosphere, a complex organic chemistry between its two main constituents, N_2 and CH_4, leads to the production of heavy molecules and subsequently to solid organic aerosols. Several instruments onboard Cassini have detected neutral, positively and negatively charged particles and heavy molecules in the ionosphere of Titan[1,2]. In particular, the presence of benzene (C_6H_6) and toluene ($C_6H_5CH_3$)[3], which are critical precursors of polycyclic aromatic hydrocarbon (PAH) compounds, suggests that PAHs might play a role in the production of Titan's aerosols. The Titan Haze Simulation (THS) experiment has been developed at NASA Ames' Cosmic Simulation facility (COSmIC) to study the chemical pathways that link the simple precursor molecules resulting from the first steps of the N_2-CH_4 chemistry (C_2H_2, C_2H_4, HCN…) to benzene, and to PAHs and nitrogen-containing PAHs (or PANHs) as precursors to the production of solid aerosols. In the THS experiment, Titan's atmospheric chemistry is simulated by plasma in the stream of a supersonic jet expansion. With this unique design, the gas mixture is cooled to Titan-like temperature (~150K) *before* inducing the chemistry by plasma discharge. Different gas mixtures containing the first products of Titan's N_2-CH_4 chemistry but also much heavier molecules like PAHs or PANHs can be injected to study specific chemical reactions. The products of the chemistry are detected and studied using two complementary techniques: Cavity Ring Down Spectroscopy[4] and Time-Of-Flight Mass Spectrometry[5]. Thin tholin deposits are also produced in the THS experiment and can be analyzed by Gas Chromatography-Mass Spectrometry (GC-MS) and Scanning Electron Microscopy (SEM). We will present the results of ongoing mass spectrometry studies on the THS experiment using different gas mixtures: N_2-CH_4, N_2-C_2H_2, N_2-C_2H_4, N_2-C_2H_6, N_2-C_6H_6, and similar mixtures with an N_2-CH_4 (90:10) mixture instead of pure N_2, to study specific pathways associated with the presence of these trace elements in Titan's atmosphere. We will also present preliminary results of the tholin *ex situ* analysis and discuss the implications of these results in our understanding of Titan's haze formation.

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Chemical and Optical Properties of Titan Aerosol Analogs Produced from Aromatic Precursors

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Since Cassini's arrival at Titan, ppm levels of benzene (C_6H_6) as well as large positive ions, which may be polycyclic aromatic hydrocarbons (PAHs), have been detected in the atmosphere. Aromatic molecules, photolytically active in the ultraviolet, may be important in the formation of the organic aerosol comprising the Titan haze layer even when present at low mixing ratios. Yet there have not been laboratory simulations exploring the impact of these molecules as precursors to Titan's organic aerosol. We will discuss laboratory studies forming aerosol analogs via FUV irradiation of several aromatic precursors – with and without nitrogen heteroatoms – to understand how the unique chemical architecture of the products will influence the observable aerosol characteristics. Optical analyses are focused on the far- and mid-IR spectra of the aromatic aerosol for comparison to the observations of Titan by the Cassini Composite Infrared Spectrometer (CIRS). In particular, observations of Titan by the Cassini Composite Infrared Spectrometer (CIRS) between 560 and 20 cm^{-1} (~18 to 500 μm) have revealed a broad emission feature centered approximately at 140 cm^{-1} (71 μm), which cannot be reproduced using currently available optical constants (Anderson et al., 2011; Khare et al., 1984). Chemical analysis is focused on the isotopic fractionation observed in the aerosol relative to molecular precursors, showing that the aerosol may serve as a sink for the lighter carbon and nitrogen atoms.

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Mission Paradigms and Planetary Exploration: Titan's place in the NASA Mission Portfolio

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Session 3.2: Future Exploration

Descent and Surface Wind Expectations for Titan North Polar Summer Exploration

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Titan's north polar lakes and seas have emerged as an attractive target of future exploration for the early 2020s, notably for the Titan Mare Explorer (TiME) Discovery mission, presently undergoing a Phase A study. In support of that effort, a detailed study has been made of the winds that may be expected at relevant locations and seasons, since the wind profile with altitude is the principal determinant (as with Huygens) of the size of the expected landing ellipse, and winds on the surface may lead to drift of floating capsules and may generate surface waves.

Here we review Cassini data (zonal winds inferred from thermal infrared measurements, as well as a few near-IR cloud-tracking observations) of what should be similar conditions at the 'mirror image' place and season - Titan's southern hemisphere in 2005-2009. In addition, we assess results from four different global circulation models. These inputs are used to define a simple analytic engineering wind envelope for Monte-Carlo descent simulations. The high latitudes of the large seas Ligeia (~80°N) and Kraken (~70°N) during the late summer season (northern autumn equinox is in 2025) mean that stratospheric winds will be considerably weaker than those encountered by the Huygens probe near the equator.

We additionally examine the surface windspeed histories. While the various models have broadly similar speeds (in turn consistent with Huygens data) their time histories are somewhat different in character and direction.

Formation and Growth of Wind-Driven Waves on Titan's Hydrocarbon Seas

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Titan's hydrocarbon seas are an exotic and appealing aspect of that world, yet so far no wind-driven waves have been identified: radar backscatter, altimetry data and near-IR glints show liquid surfaces to be as flat as a millpond.

Yet there are shoreline geomorphological indications of wave action. As we move into northern summer, Global Circulation Models predict winds in the north, home to the large seas Kraken and Ligeia, will freshen. Will Cassini observe waves? First, an analysis of onset and growth mechanisms of capillary-gravity waves on Titan (Hayes et al., submitted) reveals liquid viscosity, surface tension, and density to be significant factors. Methane-rich liquids may begin growing with windspeeds U_{10}=0.4m/s. On the other hand, waves may not form at all in more viscous ethane-rich compositions (likely for the large seas) until U_{10}=0.7m/s, a much less frequent occurrence.

Once waves form, the dense Titan atmosphere causes them to grow. A model of gravity wave growth (Lorenz and Hayes, submitted) shows that Titan's dense atmosphere causes growth rather faster than previously predicted by Ghafoor et al. (2000) but that the limiting ('fully-developed') significant wave height (SWH) is similar, and is $\sim 0.2U_{10}^2/g$ – thus 1m/s winds lead to 0.2m waves.

SWH is the average of the highest one third of wave heights: individual heights typically follow a Rayleigh distribution. Thus in a 3 month period one wave with a height of 2.7 times the SWH might be expected to appear. Combined with GCM predictions (in which there may be calm days even in the windy season), these statistical models can be used to estimate the wave/tide balance of shoreline processes.

These wind-wave models suggest that even in the windy summer, observable waves might not always be present - even with the most sensitive techniques of glint and altimetry - and thus any interpretation of Cassini observations to refine or validate windspeed models should be done probabilistically.

Composition of a Cryogenic Sea Studied by the Titan Mare Explorer

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The Titan Mare Explorer (TiME) mission that proposes to operate from the surface of Ligeia Mare (Fig. 1) is one of the finalists in the latest Discovery small mission competition. One of the TiME instruments is a Neutral Mass Spectrometer that would sample gas from a volatilized sample of this cryogenic sea. Although this Titan sea may be principally ethane (Cordier et al., 2009), the mixing ratios of methane, ethane, propane, and more complex hydrocarbons and nitriles in Ligeia Mare is unknown and their measurement is one of the motivations for this mission. We will describe the approach to securing these measurements including methods developed and tested to robustly sample the cryogenic fluid.

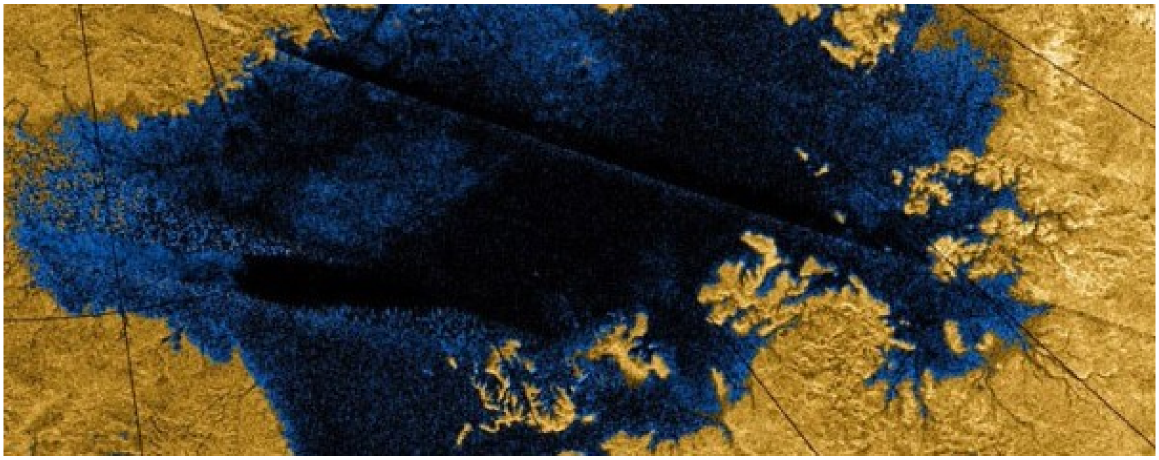

Figure 1. Ligeia Mare (credit NASA/JPL).

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Future Titan Missions

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New discoveries about Titan from the Cassini-Huygens mission have led to a broad range of mission class studies for future missions, ranging from NASA Discovery class to International Flagship class. Three consistent science themes emerge and serve as a framework for discussing the various mission concepts:

Goal A: Explore Titan, an Earth-Like System – How does Titan function as a system? How are the similarities and differences with Earth, and other solar system bodies, a result of the interplay of the geology, hydrology, meteorology, and aeronomy present in the Titan system?;

Goal B: Examine Titan's Organic Inventory—A Path to Prebiological Molecules – What is the complexity of Titan's organic chemistry in the atmosphere, within its lakes, on its surface, and in its putative subsurface water ocean and how does this inventory differ from known abiotic organic material in meteorites and therefore contribute to our understanding of the origin of life in the Solar System?; and Goal C: Explore Enceladus and Saturn's magnetosphere—clues to Titan's origin and evolution – What is the exchange of energy and material with the Saturn magnetosphere and solar wind? What is the source of geysers on Enceladus? Does complex chemistry occur in the geyser source?

Within this scientific framework the presentation will overview the Titan Explorer, Titan AND Enceladus Mission, Titan Saturn System Mission, Titan Mare Explorer, and Titan Submersible. Future timelines and plans will be discussed.

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