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Introduction to special section:
Titan: Pre-Cassini view

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1. Introduction

[1] Titan, Saturn's largest satellite, was discovered in 1655 by Christiaan Huygens using a telescope of his own construction during a period when Saturn's rings were nearly edge-on. About 250 years later, Jose Comas Sola claimed to have seen limb darkening on Titan, and suggested the satellite to possess an atmosphere. In the mid-1940's, *Kuiper* [1944] reported methane absorption bands on Titan, confirming that Titan indeed had an atmosphere. A flurry of activity found place in the 1970's, when Titan was observed with near-infrared spectroscopy, thermal-infrared and radio radiometry, polarimetry and ultraviolet spectroscopy. Models of its atmosphere were developed, in which surface pressures ranged from ~20 mbar for a methane-dominated atmosphere [*Danielson et al.*, 1973; *Caldwell*, 1977] up to ~20 bar for a nitrogen atmosphere [*Hunten*, 1978]. The idea of an atmosphere dominated by nitrogen, rather than the spectroscopically observed methane gas, goes back to *Lewis* [1971], who suggested that Titan's atmosphere might be rich in nitrogen due to photolysis of ammonia. The hypothesis of a nitrogen-dominated atmosphere was confirmed several years later by the Voyager spacecraft, at which time our knowledge of Titan increased exponentially. During an occultation experiment, the Radio Science System successfully probed Titan's atmosphere to the surface, and in the process determined that Titan was second to Ganymede in size, but with an extensive atmosphere that reached pressures of 1.5 bar at the surface. Titan's atmosphere, mainly nitrogen, a few percent methane and other hydrocarbons, seemed to resemble that of the early Earth, before our planet became rich in biogenically produced oxygen.

[2] Despite these profound discoveries, several planetary scientists were quite disappointed not to have 'seen' Titan's surface, and hence the satellite remained a mysterious place. The next Saturn mission was therefore specifically designed to explore Titan with a probe, the Huygens probe, that would explore Titan during its descent down to the surface and shortly after landing. While designs for the probe were being made, *Lunine et al.* [1983] suggested that Titan's surface may be completely covered by a liquid hydrocarbon ocean, since their calculations showed that methane could only persist in Titan's atmosphere for $\sim 10^7$ yrs, i.e., much shorter than the age of our Solar System, unless it would be recycled back into the atmosphere. The probe was therefore designed to float if it would indeed land in an ocean, so it may be able to transmit data back to Earth for a short time after landing.

[3] Approximately half a Titan year after the Voyager encounters, when it became spring in the southern hemisphere, Titan research received a boost with the launch of the Hubble Space Telescope and the development of speckle imaging and adaptive optics (AO) techniques on large, 8–10 m, telescopes. With these new imaging techniques Titan could be resolved (typical resolutions of a few 100 km), and images of its surface, troposphere and stratosphere were obtained. Many results have been published over the past decade, and several more are presented in this special GRL issue.

2. Surface

[4] Just after the Voyager encounters, researchers realized that the photochemical smog on Titan, being opaque at visible wavelengths, was transparent in the infrared, allowing one to actually probe Titan's surface through atmospheric 'windows' in between methane absorption bands [e.g., *Griffith et al.*, 1991; *Lemmon et al.*, 1993]. Surface maps at different wavelengths, as presented by *Gibbard et al.* [2004b] (2.2 μm) and *Roe et al.* [2004] (1.6 μm), as well as by previous workers (e.g., HST data by *Smith et al.* [1996] and HST-NICMOS data by *Meier et al.* [2000]) and still unpublished data (Keck map from Bouchez et al.: http://www2.keck.hawaii.edu/science/titan/index.html, and the VLT: http://www.eso.org/outreach/press-rel/pr-2004/pr-09-04.html) are strikingly similar in appearance, and suggest no obvious color variations across Titan's disk. On the leading side is a bright region, often alluded to as an elevated continent (perhaps washed clean of hydrocarbon residues by runoff [e.g., *Griffith et al.*, 1991; *Lorenz*, 1993], which consists at least in part of exposed water-ice [*Gibbard et al.*, 1999; *Griffith et al.*, 2003]. *Perron and de Pater* [2004] present a model for the axisymmetric spreading of this continent, assuming it is composed primarily of water ice. Based on isostatic equilibrium calculations, they predict the topographic relief of this continent not to exceed 3–7 km. The dark areas on Titan's surface maps have reflectivities close to zero,

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consistent with the presence of hydrocarbon oceans. This, together with recent Arecibo radar observations of Titan's surface [*Campbell et al.*, 2003], which reveal specular reflections consistent with those expected from areas covered by liquid hydrocarbons, makes Titan indeed a very intriguing place to visit.

3. Atmospheric Haze and Dynamics

[5] *Ádámkovics et al.* [2004] present a constructed spectral image data-cube of Titan, obtained in February 2001 with the Keck AO system by stepping a spectrometer slit across the satellite (see also movie at: http://astron.berkeley.edu/~imke/Infrared/Titan/Titanmovie.htm). This work is a prelude to future observations with integral-field spectographs. The authors show images of Titan's surface up through its troposphere and stratospheric levels. Tropopause haze above Titan's south pole at 30–50 km latitude is clearly visible, while at higher altitudes, >100 km, the haze optical depth is higher above the northern than southern hemisphere. This finding agrees with HST and Keck observations at that same epoch, presented by *Lorenz et al.* [2004] and *Gibbard et al.* [2004b]. *Anderson et al.* [2004] present results on essentially the disk-averaged altitude distribution of Titan's haze in the lower 100 km, based upon limb darkening profiles of data at wavelengths between 0.92 and 0.96 μm taken in October and November 1999. Their data suggest a gap in haze below 50 km, with a possible increase in haze abundance near the surface.

[6] We remind the reader that it was northern spring when Voyager flew by in 1980, at which time the northern hemisphere was covered by more stratospheric haze, and the N. polar hood was a prominent feature. During the next half Titan year this excess haze had, somehow, moved to the south when it became winter in the southern hemisphere. This apparent seasonal migration from the spring/summer pole to the winter has been observed at many different wavelengths during the past decade, when it became summer in the south and winter in the north. *Lorenz et al.* [2004] present HST images taken between 1992 and 2002 at wavelengths between 0.34 and 1 μ, and *Gibbard et al.* [2004b] present 2.2 μm Keck data between 1996 and 2004. These different wavelength data probe different altitudes in Titan's atmosphere. In particular the series of data from *Lorenz et al.* [2004] show that the seasonal migration, or reversal of the North-South asymmetry, starts at the highest altitudes, and is happening later at lower levels. Not yet published is our finding that by March 2003 also the haze near Titan's tropopause (30–50 km altitude) had disappeared from the south (I. de Pater et al., manuscript in preparation, 2004, hereinafter referred to as I. de Pater et al., manuscript in preparation, 2004).

[7] The observations above tie in with *Rannou et al.*'s [2002] atmospheric model that couples haze formation to atmospheric transport, a model that explained in particular the Voyager discovery of a detached haze layer, or a gap in the stratospheric haze near 300 km altitude. The circulation in this model is dominated by a summer-to-winter-pole cell, where air flows from the summer pole to the winter pole. Haze particles are photochemically produced at high altitudes (~400–600 km), and 'blown' to the winter pole, where they accumulate to form a polar hood. Here the particles slowly sediment out, while growing in size; a return flow takes place at lower altitudes. Although some of us thought that this return flow might have lead to the tropopause haze seen above Titan's summer (S) pole in 2001, its apparent absence in early 2003 (I. de Pater et al., manuscript in preparation, 2004) calls for a re-examination of this idea. Since the horizontal transport is much faster than the time it takes for aerosols to fall down, an observable gap is created around 300 km altitude above the northern hemisphere. E. Young et al. (Direct imaging of Titan's extended haze layer from HST observations, submitted to *Journal of Geophyscial Research*, 2004) show the recovery of this detached haze layer over Titan's south pole in heavily processed HST images from 1994 and 1996. By 2000 this detached haze layer has moved to the north pole, as expected based upon *Rannou et al.*'s [2002] model. Details on the formation of haze particles are presented by *Trainer et al.* [2004]. They present results of laboratory experiments which simulate Titan haze formation. They show different chemical pathways for haze production depending on the concentration of methane gas. At higher concentrations (~10% CH_4) they show the formation of polycyclic aromatic hydrocarbons (PAHs), while at low methane concentrations (~1%) the haze is produced predominantly from non-aromatic molecules.

4. Clouds

[8] The presence or absence of clouds in Titan's troposphere has been much debated over the years. Some studies indicated a supersaturation of methane gas in Titan's troposphere, indicative of stagnant air [e.g., *Courtin et al.*, 1995; *Samuelson et al.*, 1997], while others advocated a methane cycle analogous to Earth's hydrological cycle [e.g., *Tyler et al.*, 1981]. In the mid-1990's, *Griffith et al.* [1998] presented the first evidence of clouds in Titan's troposphere through an analysis of disk-averaged spectra. Tropospheric clouds were directly imaged with the Keck telescope in December 2001, and were discovered only above Titan's south pole (Figure 1) [*Roe et al.*, 2002; *Brown et al.*, 2002]. The authors suggested that clouds may form only over the south pole because the surface temperature during the summer is high enough for convection to be triggered, and/or fall-out of condensates from Titan's stratosphere, properly coated by ethane, provides condensation nuclei for methane clouds to form. Since *Gibbard et al.* [2004a] saw clouds at Titan's S. pole in 1998 (spring time), cloud formation is not only triggered during the summer when the high surface temperature may drive convection. *Barth and Toon* [2004] present results on the formation of methane clouds based upon microphysical models (no convection). They show that once methane clouds form, only modest supersaturations (~105%) can be maintained. Methane condenses on all ethane cloud particles, but the total number of ethane coated tholins is small (only ~5% of the tholins will be coated by ethane, based upon Barth and Toon's earlier work). This process thus leads to optically thin methane clouds. They suggest that the optically thick methane clouds above Titan's south pole are most likely formed when atmospheric dynamics (consisting of horizontal quasi-barotropic motions) pushes the supersaturation beyond a threshold value.

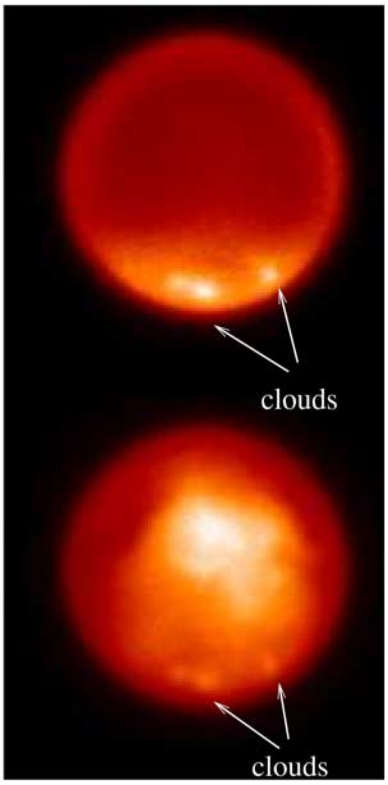

Figure 1. Clouds on Titan observed on 21 December 2001 (UT) with Adaptive Optics on the Keck telescope. Top: Narrow-band filter centered at 2.108 μm, which probes just Titan's troposphere. At least 3 clouds and the tropopause haze near Titan's S. pole are visible. Bottom: Broadband K′ filter, centered near 2.2 μm, which probes both the surface and atmosphere. Adapted from *Roe et al.* [2002] (reproduced by permission of the AAS).

[9] Many more clouds have been imaged since December 2001. Clouds come and go and change on timescales of an hour (or less). Usually there are some small clouds at typical altitudes of 24–30 km [*Griffith et al.*, 2000]; there are days without clouds, and days with giant cloud systems, which occur at altitudes as low as ~14 km. It will be interesting to see if and when clouds will cease to exist above the south pole, and appear above Titan's north pole. This reversal is probably tied in with the disappearance of condensation nuclei above the south pole, and appearance above the north, which should depend on the time it takes the stratospheric haze to fall down to the troposphere.

5. Magnetosphere Interaction

[10] Titan orbits Saturn at ~20 R_S, so that the satellite spends most of its time in Saturn's magnetosphere and every once in a while in the solar wind. When Titan is in the solar wind, the surrounding plasma is faster by ~4× than it is in the magnetosphere. Hence Titan's plasma environment is highly variable over time. *Ledvina et al.* [2004] show results from selfconsistent hybrid simulations (fluid electrons and kinetic ions) of Titan's plasma interaction with Saturn's magnetosphere and the solar wind. While in the magnetosphere or solar wind, the incident convection electric field accelerates ions in Titan's ionosphere away from the satellite, while ions picked up on the other hemisphere are drawn into the wake region and move tailward. So there is a net loss of particles from Titan from both hemispheres. The ion population is dominated by low energy (<300 eV) ions near Titan, both on the dayside (where they are produced by photoionization) and the nightside. In the tail region the ions are spatially segregated by energy while near Titan, but this is no longer true at larger distances. The ion's kinetic energy increases when flowing down the tail, and can reach several tens of keV in the solar wind. Over time, the plasma interaction can remove a significant portion of Titan's atmosphere, producing a torus of material around Saturn along Titan's orbit that has its fate in magnetospheric circulation processes.

6. What's Next

[11] This GRL issue is the product of a Titan workshop held at the University of California in Berkeley on 17 November 2003. We felt the timing opportune to present a coherent pre-Cassini/Huygens view based upon the most recent research results derived from observations and theory. As shown in this issue, we have learned a great deal about Titan over the past decade, but several mysteries still remain, e.g., with regard to surface composition, atmospheric chemistry and dynamics, haze formation and destruction. We believe that the data taken during the descent of the Huygens probe will help solve many of these puzzles – although we would not be surprised if these new data would also present us with many more challenges. The Cassini spacecraft is scheduled to obtain a large variety of Titan data over the next ~4 years, which is about a half Titan season. We encourage groundbased observers to continue to observe Titan during this period, so the Cassini/Huygens data can be tied in with the long-term data base on Titan's seasons. This is essential to develop detailed atmospheric circulation models for the satellite. Finally, let us remind the reader that only through an in-depth remote and in-situ observing program may we be able to relate Titan's atmosphere to our own, before life developed on Earth.

[12] **Acknowledgments.** The Titan workshop in Berkeley was initiated and sponsored by the Center for Integrative Planetary Sciences (CIPS). CIPS, an interdepartmental organization lead by G. Marcy, was approved as an ORU (Organized Research Unit) in 2000 to promote planetary science on the Berkeley campus. IdP acknowledges funding from NSF grant AST-0205893.

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