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TITAN AND THE OTHER SATURNIAN ICY SATELLITES SEEN BY THE CASSINI-HUYGENS MISSION

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Abstract. The Cassini-Huygens mission around Saturn has provided a lot of data that show that Saturn's icy moons are active worlds. We know that Titan's surface is not covered by hydrocarbon oceans and that the origin of methane must be related to internal processes. Titan's surface displays a large variety of geological features including dunes, impact craters, dry rivers, shorelines and cryovolcanoes. The data from both the Huygens probe and the remote sensing instruments provide information about the surface composition that is not yet fully determined. Mid-sized satellites are also active. Enceladus presents a rich atmosphere and geysers that ejects icy particles in Saturn's ring E. We will expose in the present paper the different models that can explain such an activity on such a small satellite. Iapetus' shape is also very intriguing because it suggests that it froze its shape at a rotation rate of 17 hours whereas the present time spin rate is on the order 80 days.

1 Introduction

Following the exploration of the Jovian system by the Galileo spacecraft (1995-2003), the NASA-ESA-ASI Cassini-Huygens spacecraft went into orbit in Saturns system on July 1 2004. This mission is devoted to observations of the giant planet with its stunning rings, its mysterious moon, and its complex magnetic environment. The Cassini spacecraft orbits around Saturn, and regularly flybys its moons, revealing the complexity of the Saturnian system. Here we illustrate the diversity of the Saturn satellite family with three examples: Titan, the largest moon, Enceladus, ten times smaller than Titan, and Iapetus, about three times smaller than Titan, which all exhibit an unique and complex geological history. Titan, the primary target of the mission, is surrounded by a dense and hazy atmosphere, which totally obscurs its surface at visible wavelengths. However, it can be observed in some specific infrared windows where the atmosphere is almost transparent. The VIMS instrument onboard Cassini is able to pierce the veil of the hazy moon and successfully image its surface in the infrared wavelengths, by taking hyperspectral images in the range 0.4 to 5.2 μm (Sotin et al. 2006; Rodriguez et al. 2006; Barnes et al. 2006). The radar, which is not sensitive to the atmospheric absorption and diffusion, also provide high-resolution images of the surface (Elachi et al. 2005; Lorenz et al. 2006). Titan was directly explored on Jan. 14 2005 by the Huygens probe, which reached the surface after a 2 hours and half descent through Titan's dense atmosphere. Images taken before landing revealed outstanding landscapes with fluvial features suggestive of hydrology based on liquid methane. Confrontations between remote sensing by Cassini and direct measurements by Huygens is now used to reconstruct Titan's complex history on a global scale. Another surprise was the direct observation by the different instruments onboard Cassini of jets related to a huge hot spot at Enceladus' South Pole. The origin of this surprising activity remains enigmatic. Cassini also revealed that Iapetus is much more oblate than expected and has a very intriguing ridge more than 10 km high aligned with its equator. The surprising shape and topography probably witness the early evolution of the satellite and provide fundamental constraints on the formation of the Saturnian system. In this paper, we shortly review the main discoveries of Cassini-Huygens after a two years tour, and we discuss the possible internal mechanisms responsible for the past and recent activities on these three satellites.

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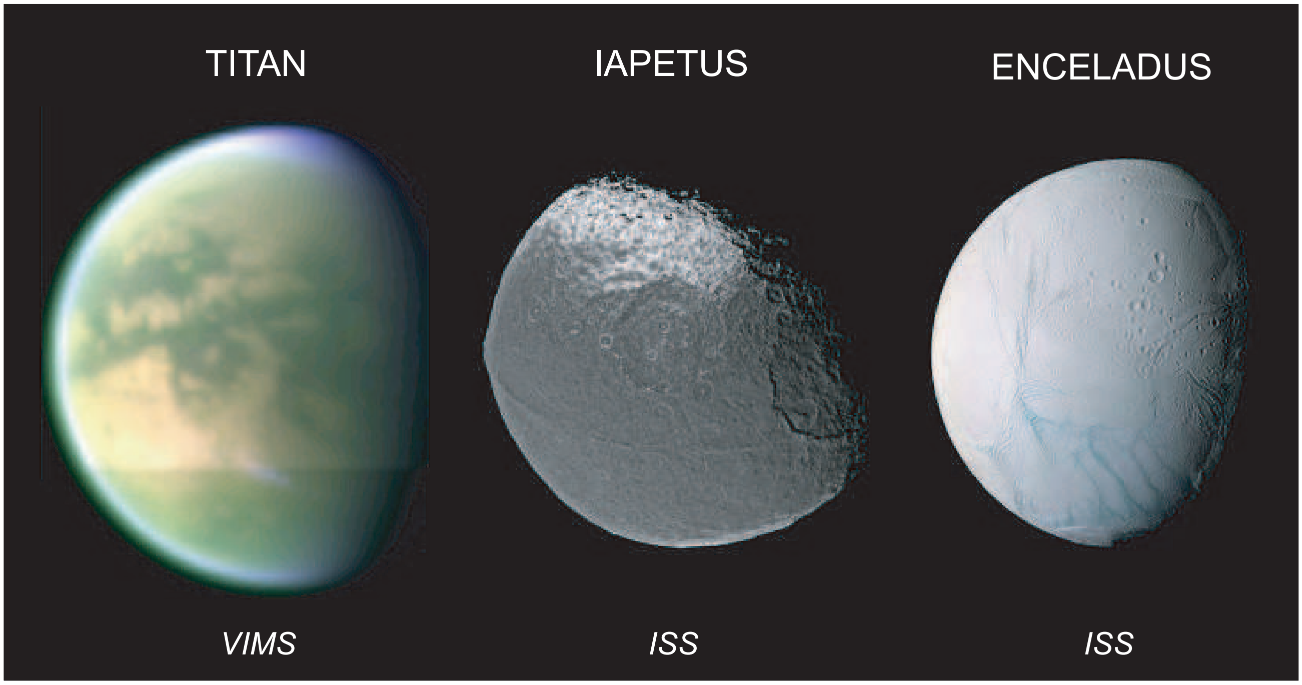

Fig. 1. False-color view of Titan obtained by the VIMS spectro-imager, of Iapetus and of Enceladus obtained by the ISS camera. Owing to the opacity of the dense atmosphere, Titan's surface is only visible in narrow near-IR windows.

2 Titan: a Earth-like world

Remote sensing from the Cassini spacecraft (Sotin et al. 2005; Porco et al. 2005a; Elachi et al. 2005; Lorenz et al. 2006) and in situ measurements by the Huygens probe (Niemann et al. 2005; Tomasko et al. 2005; Zarnecki et al. 2005) revealed that Titan is a complex world, which appears to be influenced by tectonic, cryovolcanic, fluvial and eolian processes, in many way similar to Earth. Only few impact craters has been identified so far, suggesting that an active resurfacing is operating.

Although spectral information in the infrared domain suggests the presence of water ice, different hydrocarbons and possibly carbon dioxide ice on Titan's surface (Tomasko et al. 2005; Rodriguez et al. 2006; Barnes et al. 2006), the real nature of this exotic surface remains enigmatic. Analysis of spectral data is actually in progress to possibly correlate the geological setting of the observed cryovolcanic region with any surface composition variation. This analysis includes the correction of the atmospheric contribution to the observed spectra and the acquisition of laboratory IR spectra of mixtures of potential surface materials (hydrocarbon ices, tholins, water ice, clathrate, hydrate etc.). In addition, correlations between infrared I/F and radar reflectivity variations are used to better understand the chemical and physical nature of Titan's surface.

Direct atmospheric measurements by the Gas Chromatograph Mass Spectrometer (GCMS) indicated that Titan's atmosphere contains up to 5 % of methane near its surface (Niemann et al. 2005). In the observed conditions, methane can condense at some altitudes, preferentially at high latitudes (Griffith et al. 2005; Rannou et al. 2006; Tokano et al. 2006), and precipitations of liquid methane can play an active role in the surface processes in a way similar to water on Earth, as indicated by the numerous observed river and lake features. Nevertheless, contrary to water on Earth, no extensive bodies of liquid hydrocarbons from which methane might be resupplied to the atmosphere in a continuous fashion over geologic time exist on Titan. Solar UV-driven photochemistry in the stratosphere would remove the present-day atmospheric inventory of methane there in a time span of only a few tens of millions of years (e.g. Yung et al. 1984). This means that methane must be derived from another source over Titans history.

Evolution models (Tobie et al. 2006) indicate that the destabilization of a methane clathrate reservoir stored within Titans crust and subsequent methane outgassing would naturally result from the cooling of Titans interior, and may explain the present atmospheric abundance of methane. The first high-resolution IR images taken by the VIMS instrument a few tens of minutes before closest approach on October 26th 2004 revealed the presence of a mesoscale structure interpreted as a cryovolcanic dome (Sotin et al. 2005). This observation supports the idea that methane is released from the interior through eruptive processes. Models of the internal dynamics of Titans icy crust are currently developed to relate the observed geological structure, especially at high-resolution, to the thermal state of Titans interior. The preliminary results suggest that thermal instabilities within the icy crust could induce dissociation of methane clathrate and would be favored by the presence of ammonia.

Experimental and modeling work is now in progress to constrain the effect of ammonia on the dissociation of methane clathrate and on the thermal state of the crust. Ammonia is especially known to reduce the crystallization point of water and should help maintain part of the icy mantle liquid (Grasset & Pargamin 2005, Choukroun et al. 2006). Upwelling of warm ice plumes at shallow depth and subsequent eruptions of methane and ammonia-enriched cryomagma could explain the formation of cryovolcanic edifices such as the one observed by the VIMS instrument (Sotin et al. 2005). Additional remote sensing observations and crater-density statistics should reveal recently modified terrains associated with cryovolcanic edifices. Evolution model and experimental data will provide background supports to interpret the data collected by the Cassini-Huygens mission to reconstruct the evolution of Titans interior, surface and atmosphere and especially the fate of methane from the interior to the atmosphere.

3 Enceladus: a very active miniworld

Enceladus with its 252 km radius is one of the smallest satellite of Saturn. Nevertheless the spectacular images of jets taken by the ISS camera onboard Cassini (Porco et al. 2006) surprisingly reveal that it is one of the most geologically active of the Solar System. Enceladus has long been known to have peculiar surface properties suggesting water frost deposits at a global scale (Squyres et al. 1983). In the early eighties, Voyager had already revealed a wide variety of terrains on Enceladus'surface, going from ancient heavily cratered regions to young smooth regions displaying narrow linear ridges. Different instruments onboard Cassini (in particular ISS, VIMS, CIRS) have recently identified an extremely young and still active province at the south pole from which jets of fine particles are emanated (Brown et al. 2006; Porco et al. 2006; Spencer et al. 2006). This region coincides with a huge thermal anomaly. The hottest temperatures are found along narrow tectonic rifts characterized by crystalline water ice, indicating recent activities in some places (Brown et al. 2006; Spencer et al. 2006). Direct sampling of the south pole jets obtained at closest approach indicates that they are composed of a mixture of fine water ice particles and gas, mainly water vapor (Waite et al. 2006; Spahn et al. 2006), and suggests venting from subsurface reservoirs of liquid water (Porco et al. 2006).

However, the origin of the South Pole activity remains very enigmatic. The CIRS instrument onboard Cassini detected 3 to 7 gigawatts of thermal emission over Enceladus south polar regions (Spencer et al. 2006), which corresponds to more than ten times the radiogenic power currently provided by the rocky interior (assuming chondritic composition). For reasonable values of ice viscosity at the melting point ($10^{1}3$-$10^{1}4$ Pa.s), classical models of thermal convection indicate that the amount of heat that can be released by convection is small compared to that power and cannot explain how a huge thermal anomaly can be generated at the South Pole. However, by incorporating a self-consistent treatment of tidal dissipation in 2D and 3D thermal convection models, we show how small heterogeneities in the radiogenic heat source distribution in the rocky core associated with localized tidal heating in the ice shell could have caused the formation of a large thermal plume. If the plume formed out of the polar region, Enceladus may have globally reoriented, moving the plume region toward the spin axis (Nimmo & Pappalardo 2006). Our models show that a localized pool of liquid water forms at the ice-rock interface below the thermal anomaly due to melting within the tidally heated plume. A deep liquid water zone is expected to enhance the tidal flexing of the above ice shell and to stabilize the active region at the South Pole by creating a negative gravity anomaly. Future geophysical measurements will provide useful constraints on the evolution model of Enceladus and on the origin of the South Pole anomaly.

4 Iapetus: witness of the Saturnian system formation ?

Iapetus is a puzzling body in many respects: orbital characteristics, surface composition variations, shape and geology. This satellite presents unusual topography variations at different scales. It can be described as a triaxial ellipsoid with radii 732x726x722 km and large-scale topography variations of more than 10 km (Porco et al. 2005b). Its shape is consistent with an equilibrium figure for a rotation rate of 17 hours whereas the present spin rate is close to 80 days. This suggests that Iapetus went through a stage of high spin rate early in its history, and rapidly despan without relaxing. Thermal evolution model calculations (Castillo et al. 2005) indicate that shaping in the observed ellipsoidal configuration via hydrostatic equilibrium would require a warm and partially melted interior when the satellite was still in fast rotation. This condition might be met if heating by the radiogenic decay of short-lived isotopes such as ^{26}Al, implying an accretion of the proto-Iapetus not later than 2 millions years after the formation of the CAI inclusions. This provides new timing constraints for the formation of the Saturnian system.

Besides, Iapetus has a curious ridge system, up to 20-km high and 1300 km long, exactly aligned with its equator (Porco et al. 2005b). Different scenarios based on internal or external mechanisms have been proprosed to explain the formation of the ridge. Castillo et al. (2005) proposed that the ridge formation would be a consequence of a preferential diapir activity along the equator and would be subsequent to the fast tidal despinning of the satellite, which created large-scale tectonic stresses. Alternatively, Ip (2006) suggested that the equatorial ridge system would be the result of mass accumulation from the surface impact of an equatorial ring system. Further data analyses and observations by Cassini are required to better understand the geophysical properties of the ridge system and its formation process.

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