*R*esearch in
*A*stronomy and
*A*strophysics

INVITED REVIEWS

Cassini-Huygens results on Titan's surface

Athena Coustenis and Mathieu Hirtzig

LESIA, Observatoire de Meudon, 92195 Meudon, France; *Athena.Coustenis@obspm.fr, Mathieu.hirtzig@obspm.fr*

Abstract Our understanding of Titan, Saturn's largest satellite, has recently been considerably enhanced, thanks to the Cassini-Huygens mission. Since the Saturn Orbit Injection in July 2004, the probe has been harvesting new insights of the Kronian system. In particular, this mission orchestrated a climax on January 14, 2005 with the descent of the Huygens probe into Titan's thick atmosphere. The orbiter and the lander have provided us with picturesque views of extraterrestrial landscapes, new in composition but reassuringly Earth-like in shape. Thus, Saturn's largest satellite displays chains of mountains, fields of dark and damp dunes, lakes and possibly geologic activity. As on Earth, landscapes on Titan are eroded and modeled by some alien hydrology: dendritic systems, hydrocarbon lakes, and methane clouds imply periods of heavy rainfalls, even though rain was never observed directly. Titan's surface also proved to be geologically active – today or in the recent past – given the small number of impact craters listed to date, as well as a few possible cryovolcanic features. We attempt hereafter a synthesis of the most significant results of the Cassini-Huygens endeavor, with emphasis on the surface.

Key words: planets and satellites: Titan — space vehicles

1 INTRODUCTION

Titan, Saturn's largest satellite, has been a fascinating world at every stage of its exploration. For three decades after the hazy atmosphere was discovered from ground-based observations in the 1940s, debate followed over whether it was a thin layer of methane or a dense shield of methane and nitrogen. Voyager 1 settled the matter in favor of the latter in 1980, but the details it discovered about the atmosphere raised even more intriguing questions about the nature of its hidden surface and the sources of methane to re-supply the atmosphere. The simplest possibility, that an ocean of methane and its photochemical product ethane might cover the globe, was cast in doubt by Earth-based radar studies, then eliminated by HST observations and adaptive optics imaging in the near-infrared from large Earth-based telescopes in the 1990s. These data, however, did not reveal the complexity of the surface that Cassini-Huygens would uncover. For a review of pre-Cassini knowledge of Titan, see Coustenis & Taylor (1999) and Lorenz & Mitton (2002).

Titan is unique in the Solar System with its extensive atmosphere made mostly of N_2, with a column density 10 times that of Earth's, and possessing a rich organic chemistry thanks to the second most abundant constituent, methane (about 1.4% in the stratosphere). Titan's atmosphere is not in chemical equilibrium. It is a chemical factory initiating the formation of complex positive and negative ions in the high thermosphere as a consequence of magnetospheric-ionospheric-atmospheric interactions involving solar EUV, UV radiation, energetic ions and electrons. As suggested by the Cassini/INMS instrument, the energetic chemistry produces large molecules like benzene, naphthalene, etc, in the

upper atmosphere (ionosphere) which begin to condense out at ~ 950 km, are detectable in solar and stellar UV occultations, and initiate the process of haze formation (Waite et al. 2007). As the haze particles fall through the atmosphere and grow, they become detectable with imaging systems such as the Cassini/ISS at ~ 500 km altitude and are ubiquitous throughout the stratosphere (Porco et al. 2005). They are strong absorbers of solar UV and visible radiation and play a fundamental role in heating Titan's stratosphere and driving wind systems in the middle atmosphere, much as ozone does in the Earth's middle atmosphere. Eventually, these complex organic molecules are deposited on Titan's surface in large quantities, where data from instruments on board Cassini and Huygens hint at their existence. Hence, the upper thermosphere is intimately linked with the surface and the intervening atmosphere.

On Titan, methane can exist as a gas, liquid and solid. Methane, is irreversibly dissociated to produce a host of various gases, such as hydrocarbons (e.g. C_2H_6 and C_2H_2) and nitriles, (e.g. HCN and HC_3N), from the coupled nitrogen chemistry, that are detected in the stratosphere (between 70 and 500 km in altitude) by Cassini/CIRS for instance. Playing a role similar to that of water on the Earth, methane is cycled between the atmosphere, surface and the interior. Cloud systems, the size of terrestrial hurricanes ($\sim$ up to 1000 km across), appear occasionally, while smaller transient systems form on a daily basis. The smaller clouds dissipate quickly, suggesting the presence of precipitation, carving out the fluvial features that cover much of the equatorial landscape and are also common in the vicinity of lakes seen in the northern polar regions. Near-IR observations indicate that clouds exist mainly south of $60\,^\circ$S, and in a band at $40\,^\circ$S latitude. Titan's cloud coverage appears to be less than that of the Earth, but highly variable. Titan's atmospheric methane may be supplemented by high latitude lakes and seas of methane and ethane, which, over time, cycle methane back into the atmosphere where it rains out, creating fluvial erosion over a wide range of latitudes.

With the advent of the Cassini-Huygens mission, our understanding of Titan has significantly improved, while at the same time, the realization of the complexity of this body has brought forward a large number of new questions. For a detailed description of our current status in understanding Titan's complex world after the nominal Cassini mission see Coustenis & Taylor (2008) and Lorenz & Mitton (2008). Hereafter, we review briefly some of the recent discoveries made by the Cassini orbiter and the Huygens probe, working together to unravel, among others, the mysterious surface.

2 THE CASSINI-HUYGENS MISSION

The Cassini-Huygens mission is a fruitful collaboration between ESA and NASA which investigates the Kronian system since 2004, bringing immense new insights about the primary planet, its rings and its satellites. It has thus been instrumental in enhancing our understanding of the environment around Saturn for the past 4 years, and the mission was extended for at least another 2 years, until 2010. One particular target of Cassini-Huygens was Titan, which was visited by the Huygens probe in January 2005.

The Cassini–Huygens NASA/ESA robotic spacecraft consists of two main elements: the NASA Cassini orbiter, named after the Italian-French astronomer Giovanni Domenico Cassini, and the ESA-provided Huygens probe, named after the Dutch astronomer, mathematician and physicist Christiaan Huygens, who discovered Titan in 1625. It was launched on October 15, 1997, and entered into orbit around Saturn on July 1, 2004. On December 25, 2004, the Huygens probe separated from the orbiter at approximately 02:00 UTC; it reached Saturn's moon Titan on January 14, 2005, where it made an atmospheric descent to the surface and relayed scientific information.

The instrumentation of Cassini's orbiter consists of a synthetic aperture RADAR mapper, a charge-coupled device imaging system, a visible/infrared mapping spectrometer, a composite infrared spectrometer, a cosmic dust analyzer, a radio and plasma wave experiment, a plasma spectrometer, an ultra-violet imaging spectrograph, a magnetospheric imaging instrument, a magnetometer and an ion/neutral mass spectrometer. Telemetry from the communications antenna and other special transmitters (an S-band transmitter and a dual-frequency Ka-band system) are also used to make observations of the atmospheres of Titan and Saturn and to measure the gravitational fields of the planet and its satellites.

Fig. 1 Artwork showing the Cassini orbiter observing the Huygens probe landing site with VIMS and UVIS. Credit: NASA/JPL.

The Cassini-Huygens mission is a combined exploration effort (Fig. 1). The orbiter and the probe were designed to be part of a common strategy to uncover the mysteries shrouding the enigmatic satellite of Saturn, Titan. Thus, the organic chemistry detected in the higher atmosphere by the INMS provided feedback and useful information in addition to the stratospheric composition inferred by CIRS, while the tropospheric structure was described by the Huygens instruments. The complete picture of how these chemical processes work on Titan is only better comprehended today, thanks to the synergy among the remote and *in situ* instruments.

The Huygens probe descended through Titan's atmosphere on January 14, 2005, a descent that lasted about 2.5 hrs. It carried six instruments down to the surface, to study the lower atmosphere and to return information on the satellite's surface.

Among these were HASI, GCMS, DISR and SSP, which made significant contributions to our understanding of Titan's surface:

- The Huygens Atmospheric Structure Instrument (HASI) measured the entry deceleration, the density and temperature profile (Fulchignoni et al. 2005).
- The Gas Chromatograph/Mass Spectrometer (GCMS) measured the composition of Titan's atmosphere and at the surface (Niemann et al. 2005)
- The Descent Imager/Spectral Radiometer (DISR) measured the solar radiation and performed surface imaging during the descent and after the landing (Tomasko et al. 2005).
- The Surface Science Package (SSP) investigated the consistency of the material at the probe's landing site (Zarnecki et al. 2005).

At an altitude of about 60 km, the surface-sensing radar was turned on, and at an altitude of $\sim$700 m above the surface, the descent lamp of the imaging instrument was activated. The purpose of this lamp was to enable scientists to accurately determine the reflectivity of the surface. For photography and calibration, the natural lighting by the Sun was sufficient to illuminate the landing site. The light level on the surface of Titan was indeed roughly 1000 times less than we are used to on Earth by day, but 1000 times stronger than the light of the full moon.

Thanks to the parachutes, the surface impact speed was only about 20 km h^{-1} (or 5 m s^{-1}). On the surface, the five batteries onboard the probe lasted much longer than expected, permitting Huygens to collect surface data for 1 h and 12 min. During its descent, the DISR camera returned more than 750

images and numerous spectra, while the probe's other three instruments (HASI, ACP and GCMS) sampled Titan's atmosphere to help determine its composition and structure. The Surface Science Package (SSP) had plenty of time to acquire data after landing. The telemetry data from Huygens was relayed at a rate of 8 kilobits per second and stored in Cassini's solid state memory while the latter was at an altitude of 60 000 km from Titan. Two nearly redundant channels, A and B, were planned, but as a result of a programming error, channel A did not transmit any data. In the end, almost all of the measurements were recovered because the weak signal from Huygens was captured by Earth-based radio telescopes, in effect providing a "Channel C". The signal received via radio telescopes lasted 5 h 42 min, including 3 h 14 min from the surface.

For a full description of the Cassini-Huygens mission, see Coustenis & Taylor (2008, and references therein) and the NASA and ESA dedicated web sites:

http://www.nasa.gov/mission_pages/cassini/main/
http://saturn.jpl.nasa.gov/
http://www.esa.int/SPECIALS/Cassini-Huygens/index.html

3 TITAN'S FASCINATING ATMOSPHERE

One cannot discuss Titan's surface without first making reference to the remarkable atmosphere of the satellite, which, like on our own planet, is highly dynamic and evolves with time. An important feature of this evolution and the fate of the atmosphere is Titan's climate.

It is at first surprising that the most Earthlike body in the solar system is Titan. Indeed, if Titan orbited the Sun rather than Saturn, we would have no hesitation in calling it a planet in its own right. This strange world is larger than the planet Mercury and has a nitrogen atmosphere like that of Earth, yet is denser and laden with an organic smog that hid its surface from view until Cassini-Huygens approached it in early 2004, and later in 2005 when Huygens revealed to us an extraordinary Earth-like landscape.

Venus and Mars both approach end states of volatile loss processes – in Venus' case, the water was lost because greenhouse temperatures near the Sun failed to keep it below an adequate cold trap, while on Mars, the weak gravitational and magnetic fields may have allowed substantial losses to occur. The few known isotopic ratios in Titan's atmosphere attest to re-supply and loss processes, with different results for the nitrogen and carbon reservoirs. The latter, in the form of methane greenhouse gas and surface liquid deposits, makes an appropriate analog for the Earth's water.

Far from the Sun, methane plays the active role on Titan that water plays on Earth, acting as a condensable greenhouse gas, forming clouds and rain, and pooling on the surface as lakes. Titan's icy surface is shaped not only by impact craters and tectonics, but also possibly by volcanism in which the lava is liquid water ("cryovolcanism"), by rivers of liquid methane, and by tidally-driven winds that sculpt drifts of aromatic organics into long linear dunes. Channels likely carved by liquid methane and/or ethane, lakes and seas of these materials, vast equatorial dune fields of complex organics made high in the atmosphere and shaped by wind, intriguing hints of volcanic flows of aqueous materials across an icy crust, and a dearth of impact craters suggest a world with a balance of geologic and atmospheric processes that is the solar system's best analog to Earth. In addition, deep underneath Titan's dense atmosphere and active, diverse surface, data from Cassini's instruments strongly suggest the presence of an interior ocean thought to be largely composed of liquid water.

However, the best atmospheric analogies are between Titan and Earth (Coustenis & Taylor 2008). Most obvious is the existence of a hydrological cycle involving methane clouds, rain and, at least transient, rivers. The possibility of such a cycle had been noted as soon as the proximity of Titan's surface conditions to the methane triple point had been noted in Voyager data, and the first evidence of clouds emerged in spectroscopic data and in Hubble Space Telescope (HST) images, reported since 1995. Another analogy with the Earth relates to the polar stratosphere. Titan was observed by Voyager to have a UV-dark 'polar hood,' a dark haze cap over the winter pole. This cap was seen in high-phase-angle images to stand above the main haze deck and connect with the detached haze layer. Circulation models are able to reproduce this behavior. While connected to the detached haze at high altitudes, the region

is dynamically isolated by the circumpolar vortex. On Earth, the corresponding circumpolar winds isolate the winter stratosphere from the rest of the atmosphere: the catalytic surfaces of polar stratospheric clouds that form on winter nights cause the destruction of ozone whose concentration becomes locally depleted —the ozone hole.

Measurements throughout the atmosphere, both remotely and *in situ*, have indicated the presence of numerous hydrocarbon and nitrile gases, as well as a complex layering of organic aerosols that persists all the way down to the surface of the moon (Coustenis et al. 2007; Tomasko et al. 2005; Israël et al. 2005), although their molecular composition remains to be determined. The structure of the upper atmosphere of Titan was defined by the Cassini Ultraviolet Imaging Spectrometer (UVIS), which observed the extinction of photons from two stars by the atmosphere of Titan during the second Titan flyby. A mesopause was inferred at 615 km with a temperature minimum of 114 K. Six species were identified and measured: methane, acetylene, ethylene, ethane, diacetylene and hydrogen cyanide at altitude ranges from 450 to 1600 km. The higher order hydrocarbons and hydrogen cyanide peak sharply in abundance and are undetectable below altitudes ranging from 750 to 600 km, leaving methane as the only identifiable carbonaceous molecule in this experiment below 600 km. Indirect but solid evidence for high complex organic species in the ionosphere was brought by the Cassini/INMS (see Section 5). These organics are certainly the precursors of the hydrocarbons and nitriles found in the stratosphere, which form aggregates and eventually condense out on the surface.

Radar observations suggest that the ultimate fate of this aerosol precipitation is the generation of expansive organic dunes that lie in an equatorial belt. These sand dunes are remarkable in being exactly the same size and shape as linear (longitudinal) dunes on Earth, such as those found in the Namibian and Saharan deserts. This type of dune forms in a fluctuating wind regime, which on Titan may be provided by the tides in the atmosphere due to Saturn's gravitation acting over Titan's eccentric orbit.

Information on the origin and evolution of Titan's atmosphere is also becoming available through the scarce accurate measurements of the different volatile compounds present in today's atmosphere and on the surface, starting by measuring the noble gas concentrations and their isotopic abundances, as well as the nitrogen and carbon stable isotope ratios. Cassini-Huygens has provided some important information in this regard. The abundance of the radioactively derived ^{40}Ar has indicated that only a few percent of the total volatile inventory has been outgassed from the interior (Niemann et al. 2005). Whereas the relatively low abundance of the primordial ^{36}Ar isotope suggests that nitrogen was not delivered during Titan's initial formation as molecular nitrogen, but more likely as ammonia that underwent subsequent chemical conversion into N_2—the predominant constituent of Titan's present day atmosphere. Furthermore, the enrichment of ^{15}N in N_2 to that of ^{14}N relative to a terrestrial reference suggests that as on Mars, Titan has lost most of its nitrogen over the course of its evolution (Waite et al. 2007). This is substantiated by the measurement of isotopic separation in the upper atmosphere measured by the Cassini/INMS and the escape of methane and hydrogen inferred from the altitude structure of these species in Titan's upper atmosphere (see Section 5). Moreover, the non-detection of neon, krypton and xenon by Huygens raises important questions about Titan's origin and evolution: have these compounds never been incorporated in Titan's building blocks, or have they been lost or recycled and are hidden at the surface and in the interior since Titan's formation? The accurate measurements of the abundances of these noble gases and of their isotopic ratios will provide important clues about the origin and evolution of Titan, and about the overall role of escape, chemical conversion, outgassing and recycling in the evolution of Titan's atmosphere. In particular, the detection of radiogenically-derived isotopes of neon, xenon and krypton will constrain the evolution of the rocky core and the outgassing history of Titan. All these must await new surface analysis techniques, such as noble gas enrichment cells, which were not present on the Huygens GCMS. More information on the atmospheric content of Titan is given in Section 5.

4 A NEW PICTURE OF TITAN'S SURFACE

Glimpses of Titan's surface, hidden at visible wavelengths by layers of optically thick haze, had been acquired since the 1990s from the ground (applying imaging and spectroscopy with the largest telescopes)

and from the Hubble Space Telescope (HST) orbiting the Earth. However, not until Cassini-Huygens arrived in the Saturnian system was it possible to acquire a clear picture of what turns out to be Titan's complex and exciting terrain. While the Cassini orbiter provided detailed views of Titan's surface with its camera, mapping spectrometer and radar, the Huygens probe, descending through the atmosphere on January 14, 2005, returned extraordinarily detailed images with resolutions ranging from 10 m at 10 km down to centimeters at the surface. The features it saw on Titan's surface were more complex than anyone expected, with landforms that seem to resemble the landscapes on Earth, including hills, dunes and a deflated lakebed. The ambient conditions and direct measurement of methane evaporating from under the landed probe (Niemann et al. 2005), imply that the working erosive agent is liquid methane, not liquid water.

4.1 Huygens: Revealing a Fascinating Landscape

After several close Cassini flybys, in January 2005, the Huygens Probe became the first human artifact to descend through Titan's atmosphere, reach the surface and return several hours of data from an exotic landscape cut by channels and apparently soaked, near the surface, with methane, ethane and other hydrocarbons. The probe survived the landing and transmitted from the surface for a much longer time than expected because it touched down on a relatively soft solid surface, so the period of operation on the surface was in the end limited only by the uplink to the Cassini orbiter. Once that went over the horizon as seen from Huygens, the probe's useful life was over even though we know, from the continued reception of the signal by ground-based radio telescopes, that it continued to function for a further few hours. Data on the wind field of Titan were recovered by measuring the probe signal on Earth by radio telescopes and hence the Doppler Wind Experiment (DWE) got its results, although its data from Huygens transmitted through Channel A were lost (Bird et al. 2005).

During its descent through Titan's atmosphere, the Huygens probe flew over an icy surface, floated down and drifted eastwards for about 160 km; its suite of six instruments gathering information about Titan's atmosphere and winds. After a two-and-a-half-hour descent, the ESA spacecraft landed at 10.3 °S and 192.3°W (Lebreton et al. 2008) among Titanian rocks and mud. Amazingly, it continued for an hour to take measurements and relay them to the orbiter (which set over the horizon; the probe apparently operated for another two hours based on tracking from Earth), providing the "ground truth" for the orbital measurements in terms of composition, structure and geomorphology.

The HASI instrument measured the surface temperature and pressure at the landing site: 93.65 ± 0.25 K and 1.467 ± 1 atmospheres (Fulchignoni et al. 2005).

The acoustic sounder in the Surface Science package first detected the ground from 88 meters in altitude, its signal revealing a relatively smooth, but not flat surface below (Zarnecki et al. 2005). The first part of the probe to touch the surface was the penetrometer, also part of the SSP (Fig. 2). With a landing speed of about 5 m s^{-1} the front of the probe followed and hit the surface, then slid slightly before settling. The DISR imager and spectrometer gathered data starting from the first haze-shrouded image of the surface from 49 km above, down to the unprecedented overview recorded from 16 down to a few km over the Huygens landing site, and through the spectral data recorded below 700 m in altitude (enabled by an onboard lamp as a source of illumination) to the final pictures on the surface. Panoramic mosaics constructed from a set of images taken at different altitudes (Fig. 3) show brighter regions separated by lanes or lineaments of darker material, interpreted as channels, which range from short stubby features to more complex ones with many branches (Tomasko et al. 2005). This dendritic network almost certainly was formed through the action of heavy rain — liquid methane —, implying a liquid does flow at some times and places on Titan's surface, although heavy rain was not present at the time of the landing. The stubby channels are wider and rectilinear, often starting or ending in dark circular areas suggesting dried lakes or pits. The dark channels visible in the panoramas may not contain liquid methane today, irrigating the bright elevated terrains before being carried through the channels to the lower regions, but they may have done so in the recent past. Liquid methane flow might clean the water ice surfaces of deposited organics, allowing them to be exposed along the upstream faces of the ridges and leading to the dark-bright contrast within the channels. The slopes are generally on the order
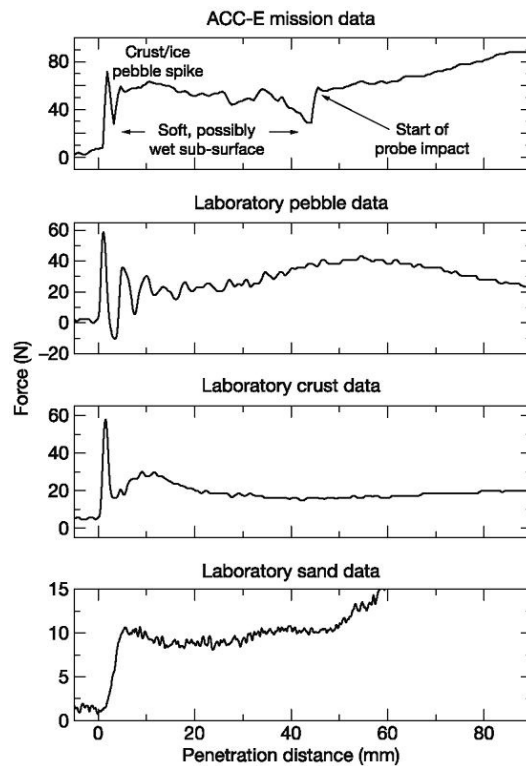
Fig. 2 Ground signature from the penetrator of Huygens/SSP (Zarnecki et al., 2005). The four panels describe the force endured by the penetrometer as a function of penetrated distance, as measured by Huygens (upper panel) or during laboratory tests (for pebbles, crust, or sand textures). The interpretation of the Huygens measurement predicts that the ground at the probe location is made of soft (wet) sand covered by a thin crust of solidified material.

of 30° or more (Soderblom et al. 2007a). Some of the bright linear streaks seen on the images could be due to icy flows from the interior of Titan emerging through fissures. No obvious crater features were observed in the landing site area.

The DISR camera took hundreds of pictures of its surroundings: a landscape suggestive of a drainage outflow strewn with brighter rounded pebbles (Tomasko et al. 2005), that best resembles a pediment or alluvial fan at the foot of a desert mountain range (Fig. 3). A dark area near the landing site closely resembles a dry lake, possibly like those shown in recent Cassini/ISS images near Titan's north pole, some of which may still contain hydrocarbon liquid (Tomasko et al. 2005). The largest pebbles at the landing site are about 15 cm in diameter, and most likely they consist primarily of water ice, with dissolved impurities and a coating of tholin-type material drizzled onto them from the ubiquitous haze (Fig. 4). The underlying material, for which the best current Earthly analogue would be gravel, wet sand, wet clay, or lightly packed snow according to the impact data, is probably also mostly composed of dirty water ice, weathered from the rocks and cliffs by the Titanian analogue of such processes on Earth. The penetrometer data show an initial spike, that suggested at first the soil had a hard crust on top of softer material (Fig. 2), but the spike was later interpreted as more likely to indicate that the probe hit one of the icy pebbles littering the landing area before sinking into the softer, darker ground material.

While there were no open bodies of liquid where Huygens landed on Titan's surface, the ground did show evidence of methane liquid in the surface since a 40% stepwise increase in methane abundance was measured by the GCMS right after landing; thermal conductivity measurements also support the
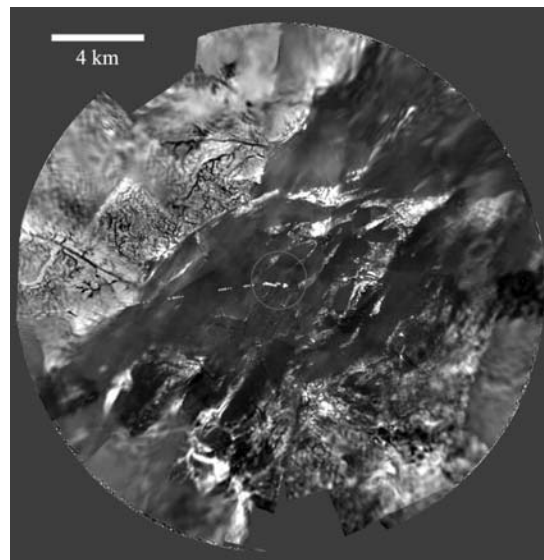
Fig. 3 Panorama mosaic of the Huygens landing site seen by DISR at medium altitude (Tomasko et al. 2005). At 8–17 km of altitude, the dark channels scarring the bright elevated terrain are easily visible. These are fluvial channels flowing into the lower, darker terrain.
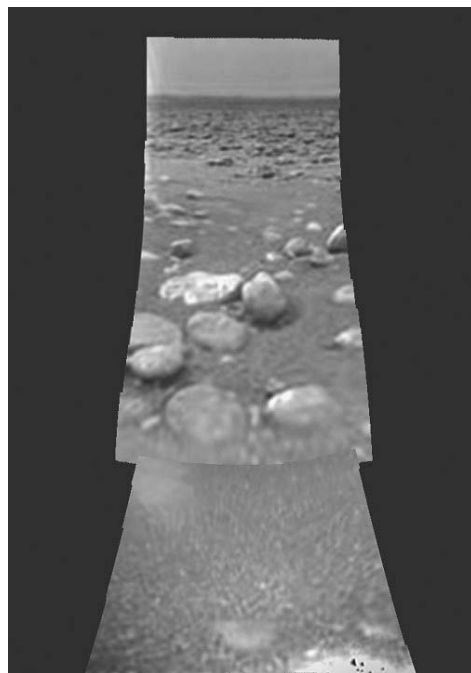

Fig. 4 Titan's surface as imaged by Huygens/DISR (Tomasko et al. 2005) after the probe's landing. Pebbles of water ice lie above a finer-grained dark riverbed. The pebbles measure 10–15 cm in diameter and the soil is probably a mixture of water ice and tholins, in a substrate of liquid methane.
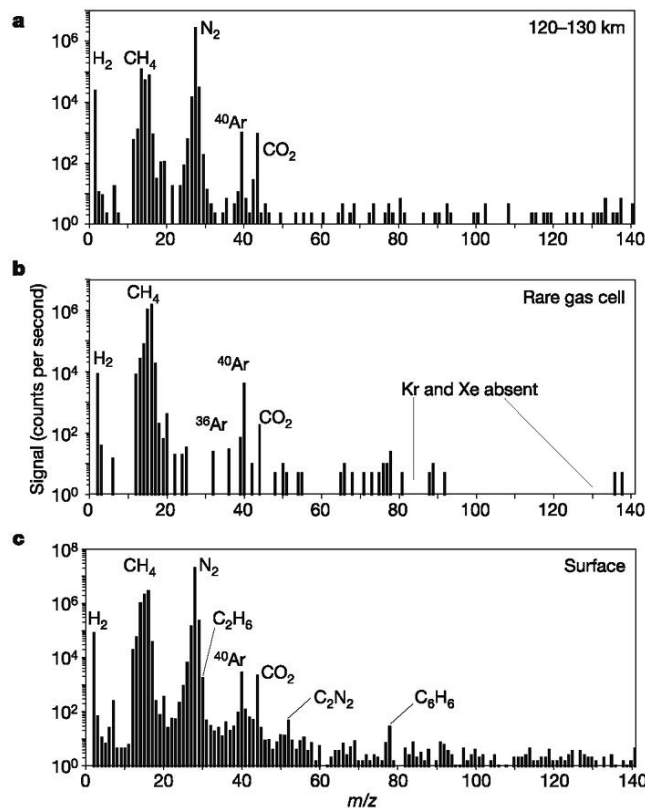
Fig. 5 Mass spectra from Huygens/GCMS at various altitudes (Niemann et al. 2005). These sample-averaged spectra show the ion count rates per second as a function of unit charge ($m\,z^{-1}$), either at 120–130 km (upper panel), or at 75–77 km in the rare gas cell (middle panel), or at the surface (bottom panel). In the latter case, about 432 spectra were acquired and averaged during the 70 min when the probe lived before loss of the signal. It is by this means that a surge of methane and ethane was detected shortly after the probe impact, indicating an evaporation of volatiles from the surface that was being heated by the probe itself. Furthermore, the very presence of Argon may indicate some geological activity on Titan that would transport Ar from the interior through liquid then to solid layers, another clue toward the explanation of the methane replenishment in the atmosphere.

hypothesis of evaporation of subsurface liquid (Lorenz 2006). The surface composition, as determined by the GCMS (Niemann et al. 2005) contains organic species such as cyanogens and ethane (Fig. 5). The nature and extent of the exchange of condensable species between the atmosphere and the surface and the dynamic equilibrium that exists between the two is linked to the mystery of the reservoir that supplies methane to the upper atmosphere where it is rapidly destroyed.

The spectra acquired during the descent gave information on the surface, as well as the atmospheric properties. Indeed, it was shown from spectral reflectance data of the region seen from the probe that the differences in albedo were related to differences in topography which in turn can be connected to the spectral behavior of the ground constituents (Fig. 6). The higher brighter regions were found to be redder than the lowland lakebeds, as are the regions near the mouths of the rivers. The water ice absorption band at $1.5\,\mu$m was observed in spectra taken by DISR, consistent with the earlier findings from ground-based observations. A good match with the DISR spectra also requires, in addition to water ice, the presence of an absorber resembling laboratory tholin, and an unknown blue material on Titan's surface (unknown because its spectral behavior does not match any of the laboratory data we
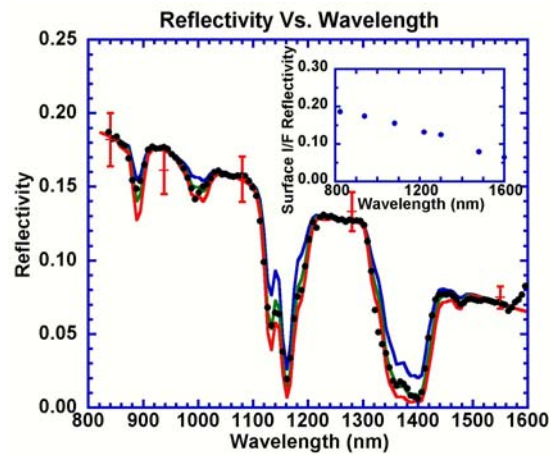
Fig. 6 Titan's reflectivity spectrum shows that the surface amount of methane is close to 5%. Also shown in the insert is the blue slope of the surface reflectivity at the Huygens site, as recorded by DISR (Tomasko et al. 2005).

have currently). No combination of any known ice and organic material has been found that reproduces the characteristics of the blue material, but attempts are being made to identify or synthesize it in the laboratory.

Although many questions still remain about the sequence of flooding and the formation of all the complex structures observed by Huygens, the new data clarify the picture we have of Titan today and at the same time enhance the impression that by studying Saturn's satellite, we are looking at an environment with many facets that resemble the Earth. The astrobiological aspects were also investigated. The GCMS provided the $^{13}C/^{14}C$ isotopic ratio which showed that no active biota exist on Titan and that the methane source is likely abiotic, though a biological source strictly speaking cannot be ruled out.

4.2 Synergistic Orbiter-probe Observations of the Surface

The detection of Argon 40 (Fig. 5) and observations of what appear to be flows from cryovolcanoes suggest that the interior of Titan is geologically active; theoretical calculations suggest a heat flow at present about 8% that of the Earth, sufficient to mobilize water as liquid in the interior as the working fluid for cryovolcanism (Tobie et al. 2006).

One of the most efficient applications of the synergy between the orbiter and the probe is the mapping of Titan's surface. The diversity of the terrains on Titan depicted by the Cassini-Huygens instruments makes for challenging geological interpretations.

As concerns Titan's surface, Cassini and Huygens together have established a diversity of geologic features comparable to that on the Earth:

– erosional features such as channels and dendritic networks, possible lakes and seas, fluvial erosional deltas and other erosional and depositional constructs such as dunes (Radebaugh et al. 2008), possible glacial-flow constructs, etc (Fig. 7);
– impacts: the very low crater frequency (Lorenz et al. 2007) is indicative of active geological surface processes (Fig. 8);
– volcano-tectonic features: domes, possible cryovolcanic flows, and bright spots as well as mountain chains; many of these features may be active regions on Titan's surface (Nelson et al. 2006; Fig. 9)
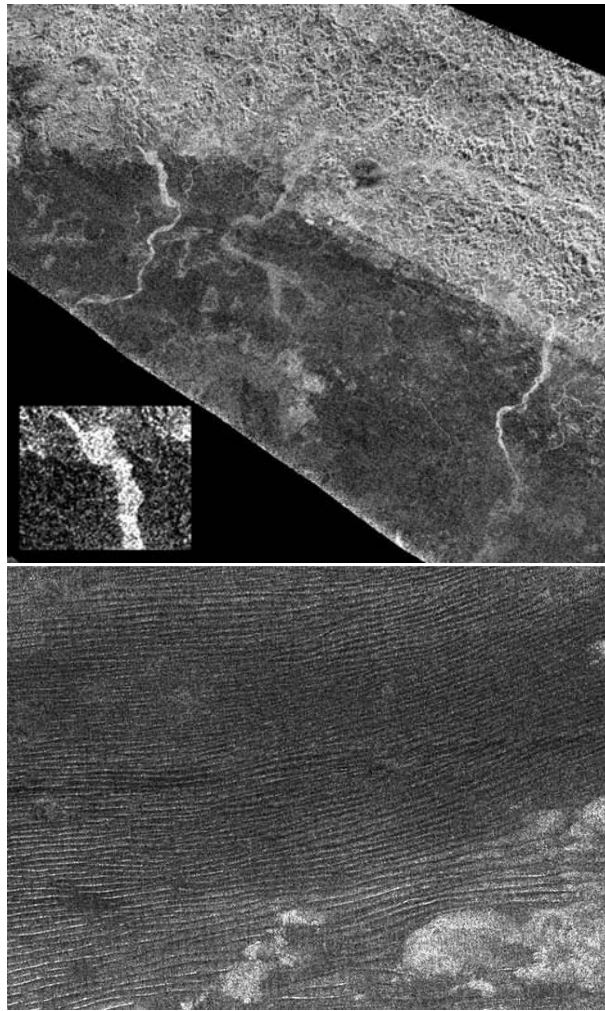
Fig. 7 a) Upper image: unusual channels observed by Cassini RADAR at the edge of Xanadu on May 28, 2008. The border of Xanadu, seen as a crisp bright-dark boundary, shows an unusual set of channels at 15°S, 121°W. While these are brighter (more roughly textured) than the surrounding terrain, some are only slightly so, while some are as wide as 5 km. They appear to flow out of the rough region of Xanadu. Careful inspection reveals smaller tributaries that wind through the brighter and apparently rougher terrain to the north. A close-up of one of the widest channels is shown at the lower left. b) lower image: Cassini/RADAR observations of Titan's fine-grained dunes. These dunes seem to flow around elevated terrain, like the bright blocks in the lower right corner. They are formed by a specific wind regime, with a west-to-east main component, and a north-south component alternating periodically to the north and to the south. Credit: NASA/JPL.

However, detailed knowledge of the global distribution of these features, their possible associations and causal relationships, their ages and the geophysical processes that are responsible for their origin and evolution remain poorly understood, even where Huygens landed (Soderblom et al. 2007b).

With impact craters, dark plains with some brighter flows, mysterious linear black features possibly related to winds, sand dunes, snow dunes and a host of possible agents: solids, liquids, ices, precipitation,
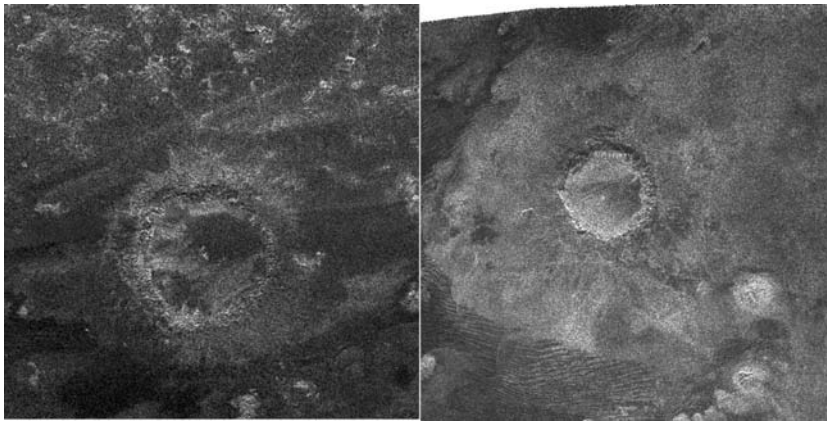
Fig. 8 This side-by-side view shows two impact craters with a total of four such features definitely identified so far on Titan – fewer than 100 features are regarded as possible impacts. Compared with Saturn's other moons, which have many thousands of craters, Titan's surface is therefore very sparsely cratered. This could be due to Titan's dense atmosphere, which burns up the smaller impacting bodies before they can hit the surface, or to geological processes, such as wind and icy volcanism. Both images are about 350 km in width. Sinlap, on the right, is 80 km in diameter, and about 1,300 m deep. The feature pictured on the left is bigger than Sinlap with a diameter of about 112 km. It is located at about 26°N, 200°W, about 1000 km north of the Huygens landing site. In its image, it appears slightly irregular, suggesting that it was modified after it was formed. The crater floor appears flat, and two small bright spots indicate a likely central peak complex. There are ejecta blankets (surrounding material) visible around the craters. Credit: NASA/JPL.
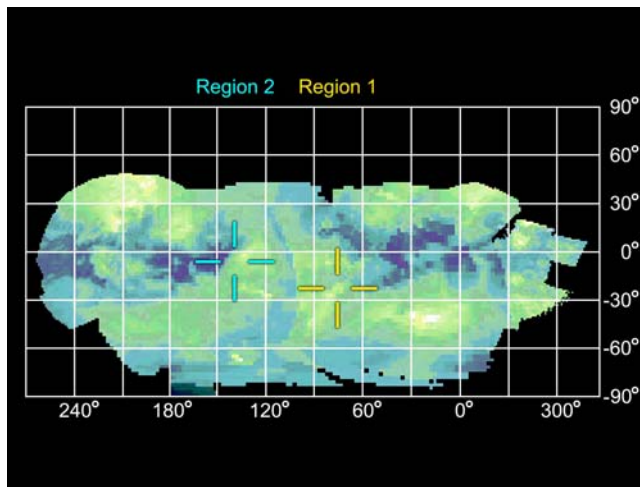

Fig. 9 2.1-μm map of Titan from all Cassini/VIMS (visual and infrared mapping spectrometer) images up through February 2007, at a 25 km per pixel scale. The locations of two regions that changed in brightness are labeled. These regions are hypothesized to be areas of cryovolcanic activity on Titan. Rather than erupting molten rock, it is theorized that the cryovolcanoes of Titan would erupt volatiles such as water, ammonia and methane. Scientists have suspected that cryovolcanoes might exist on Titan, a plausible source to explain the seemingly continuous supply of fresh methane. Credit: NASA/JPL/Univ. of Arizona.
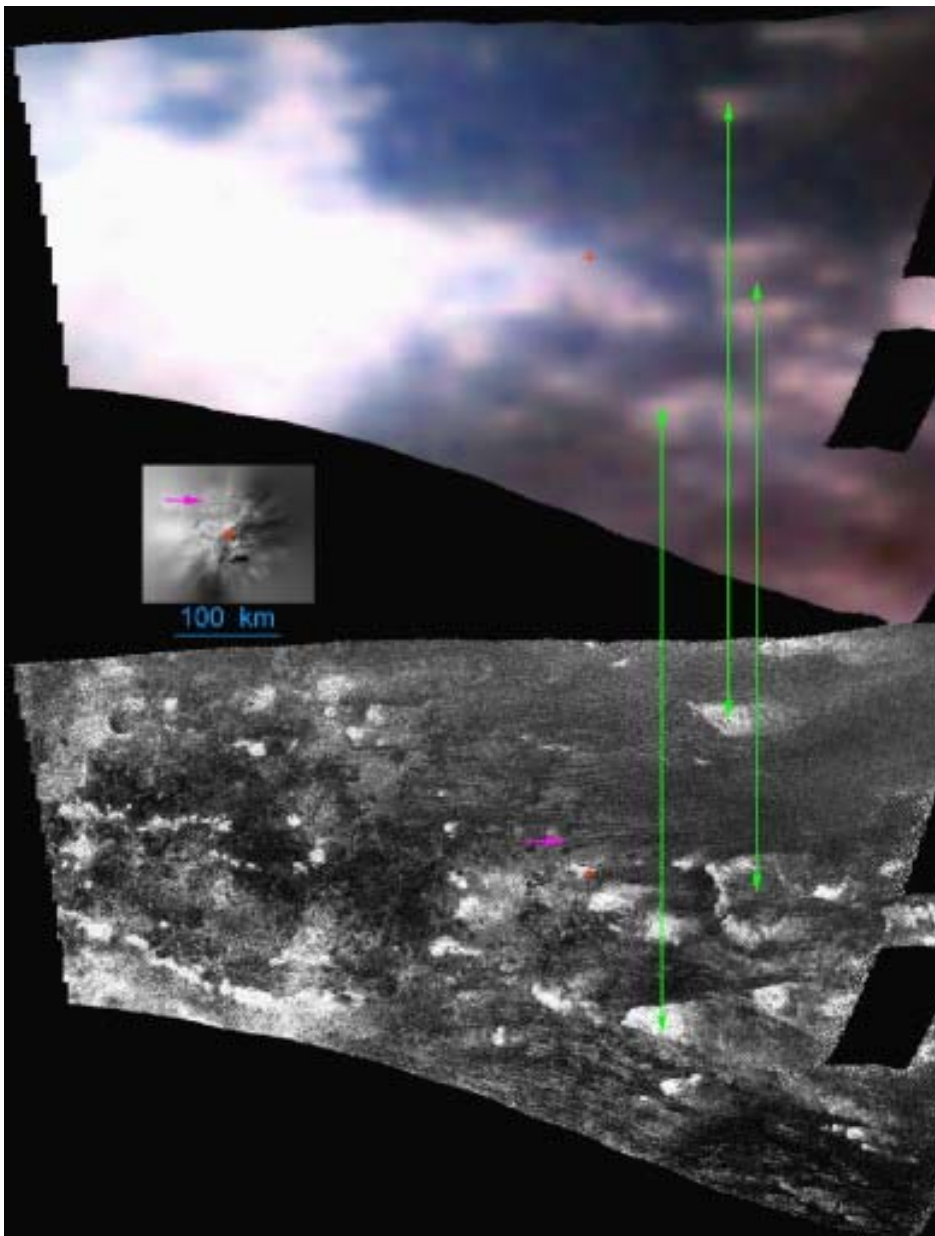
Fig. 10 Comparison of RADAR/SAR and VIMS data. The VIMS false-image picture is a combination of three channels ($R = 5\,\mu$m, $V = 2\,\mu$m, $B = 1.3\,\mu$m), in which dark regions do not appear as dark: "dark blue" regions are supposed to be enriched with water ice. On the RADAR image, rough terrains appear bright, while finer-grained or smoother terrains are darker: black stripes all over the picture correspond to individual dunes, gathered around the elevated, rougher terrains. For comparison, several features have been associated with both views: the Huygens landing site (red cross), an impact crater and two bright and rough features (green arrows). It is worth noting that the bright elevated continent on the west is not uniformly smooth on the RADAR image, which indicates different natures yet to be determined. From Soderblom et al. (2007b).
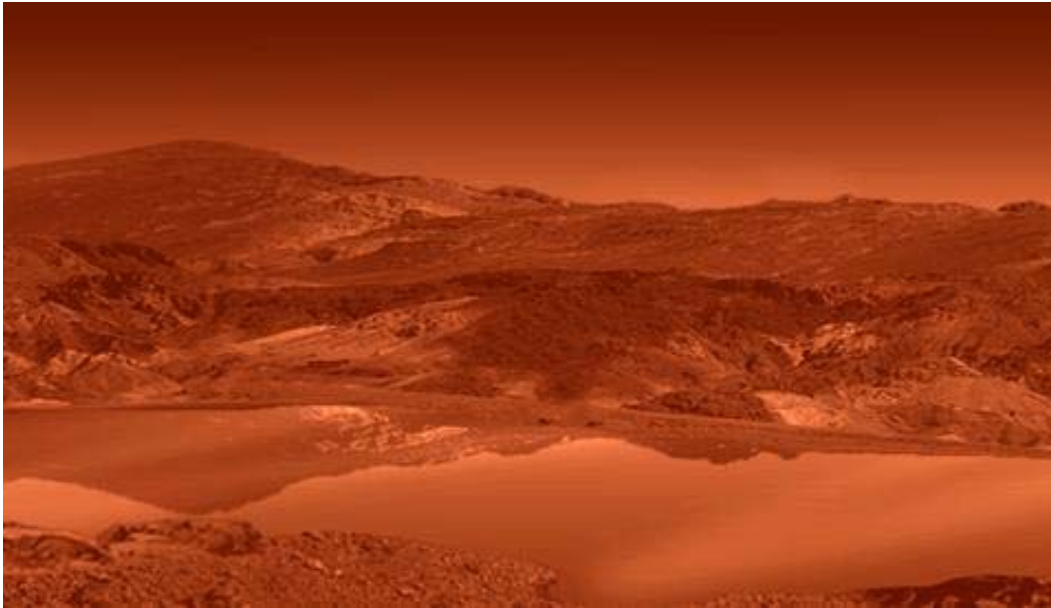
Fig. 11 Artistic concept of a very smooth-surfaced lake, similar to what could perhaps be observed on the Ontario Lacus, in which ethane was recently identified (Brown et al. 2008). Credit: NASA/JPL.

evaporation, flows, winds, volcanism, etc. to be included, Titan has proven to be a much more complex world than originally thought and much tougher to interpret.

There is a strong correlation between the dark brown units observed by VIMS and the dune fields discovered in the RADAR SAR images. On the contrary, the bright and dark blue units observed by VIMS show no obvious correlation with SAR images, at least in these areas. The Huygens landing site was imaged jointly by VIMS, DISR and RADAR (Fig. 10). Studies by Soderblom et al. (2007a,b) have led to the inference of the spectral properties of the bright and dark, dune and non-dune, liquid and solid areas, and to constraints on the surface composition based on differences in appearance. The identification of water ice absorption at 1.54 μm in the DISR near-infrared spectrum of the surface acquired after landing is consistent with the results from the orbiter instruments.

Radar-bright channels (probably cobbled streambeds like that at the Huygens landing site) have been observed at low and mid-latitudes (Lorenz et al. 2008a), while channels incised to depths of several hundred meters are seen elsewhere, and at high latitudes, radar-dark, meandering channels are seen that suggest a lower-energy environment where deposition of fine-grained sediment occurs. Fluvial modification of the surface was very evident at the Huygens landing site. Not only were steeply incised channels a few kilometers long and $\sim$30 m across observed in the bright highlands (Fig. 3), but the close-up vista from the probe after landing showed rounded cobbles (Fig. 4) characteristic of tumbling in a low-viscosity fluid. Radar and near-infrared imagery has revealed channels on much larger scales than those seen by Huygens. Furthermore, beginning in July 2006, there were a series of flybys of the high northern latitudes of Titan during which the RADAR imaged a variety of very dark features that have been interpreted to be liquid-filled basins—"lakes". The features range in size from less than 10 km^2 to at least 100 000 km^2. They are confined to the region poleward of 55 $^\circ$N. To date, some 655 such features have been identified and mapped (Fig. 11) and it has been hypothesized that the dark lakes are filled with liquid, most probably ethane (Stofan et al. 2007; Mitri et al. 2007; Raulin 2008; Hayes et al. 2008).

All of the above provide circumstantial support for the hypothesis that the dark lakes are filled with liquid, but a definitive demonstration must await identification of liquid methane or ethane, or both,

in the lakes, from the Cassini VIMS instrument. Liquid methane is difficult to detect given the large abundance of gaseous methane that dominates much of the near-infrared, but the detection of liquid ethane was announced recently based on VIMS spectra of the Ontario Lacus (Brown et al. 2008; Raulin et al. 2008).

The combination of geomorphologic information from high-resolution RADAR coverage (few hundred meters/pixel) with spectroscopic information from VIMS at more moderate resolution (few hundred meters/pixel to a few km/pixel) have addressed the first order geological and chemical processes in a limited geographical area on Titan's surface. RADAR and VIMS together with Huygens high-resolution imaging and *in situ* studies have completed a preliminary survey of the chemical and physical processes in an area of order $100\,km^2$. Combined ISS, VIMS and RADAR data (Soderblom et al. 2007b) have provided near-global surface coverage at a variety of wavelengths and resolutions (Fig. 10).

5 TITAN'S ORGANIC INVENTORY

A key characteristic of Titan is its massive inventory of organic chemicals. As noted previously, the Voyager 1 Titan flyby in the early 1980s verified the presence of methane in a thick background atmosphere of nitrogen. Even more interesting was the detection of a host of complex hydrocarbons and nitriles that resulted from the photolysis and energetic particle bombardment of the atmosphere and the thick organic haze that both scattered and absorbed visible and infrared photons, thereby playing an important role in determining the satellite's thermal structure. Titan is an organic paradise that is certain to tell us much about the chemical evolution that may lead to life. Water ice and carbon dioxide ice have been reported to exist currently on the surface. Transient episodes of melting of the water ice by either geologic activity or impacts would expose organics to aqueous alteration, as well as contact with carbon dioxide, leading potentially to reaction pathways that mimic those that occurred on the pre-biotic Earth. No other place in the solar system has this type of ongoing chemistry. The Cassini-Huygens era of investigation has furthered our understanding of Titan as the largest abiotic organic factory in the solar system.

The abundance of methane and its organic products in the atmosphere, seas and dunes exceed by more than an order of magnitude the carbon inventory in the Earth's ocean, biosphere and fossil fuel reservoirs (Lorenz et al. 2008a). Indeed, the measured value of the irreversible conversion of the methane in the atmosphere into higher-order organic/nitrile compounds that eventually end up deposited on the surface of Titan is near that of our terrestrial reference, indicating that methane is re-supplied and converted at a rate that prevents the buildup of the heavier isotope over time as is the case of nitrogen (Atreya et al. 2006). The source of the resupply is a mystery that a future mission beyond Cassini-Huygens must address.

Since the advent of Cassini-Huygens, we know a little more about the processes involved in Titan's organic chemistry. The direct analysis of the ionosphere by the Ion Neutral Mass Spectrometer (INMS) during the closest Cassini flybys of Titan shows the presence of many complex organic species, in spite of the very high altitudes (1100–1300 km) (Waite et al. 2007). Extrapolation of the INMS measurements (limited to mass up to 100 Daltons) and of CAPS data strongly suggests that high-molecular-weight species (up to several 1000 Daltons) may be present in the ionosphere (Fig. 12). This new data – if confirmed – would revolutionize the understanding of the organic processes occurring in Titan's atmosphere, with a strong implication that ionospheric chemistry plays a role in the formation of complex organic compounds in Titan's environment, which was not envisaged before (Waite et al. 2007). Thus, it appears that Titan is a chemical factory in which the formation of complex positive and negative ions is initiated in the high thermosphere as a consequence of magnetospheric-ionospheric-atmospheric interaction involving solar EUV, UV radiation, energetic ions and electrons.

With the current picture of Titan's organic chemistry, the chemical evolution of the main atmospheric constituents – dinitrogen and methane – produces complex refractory organics which accumulate on the surface, together with condensed volatile organic compounds such as HCN and benzene. The second most abundant constituent, methane, is irreversibly dissociated to produce hydrocarbons (e.g. C_2H_2, C_2H_4, C_2H_6 and C_3H_8) and nitriles (e.g. HCN, HC_3N), from the coupled nitrogen chemistry.
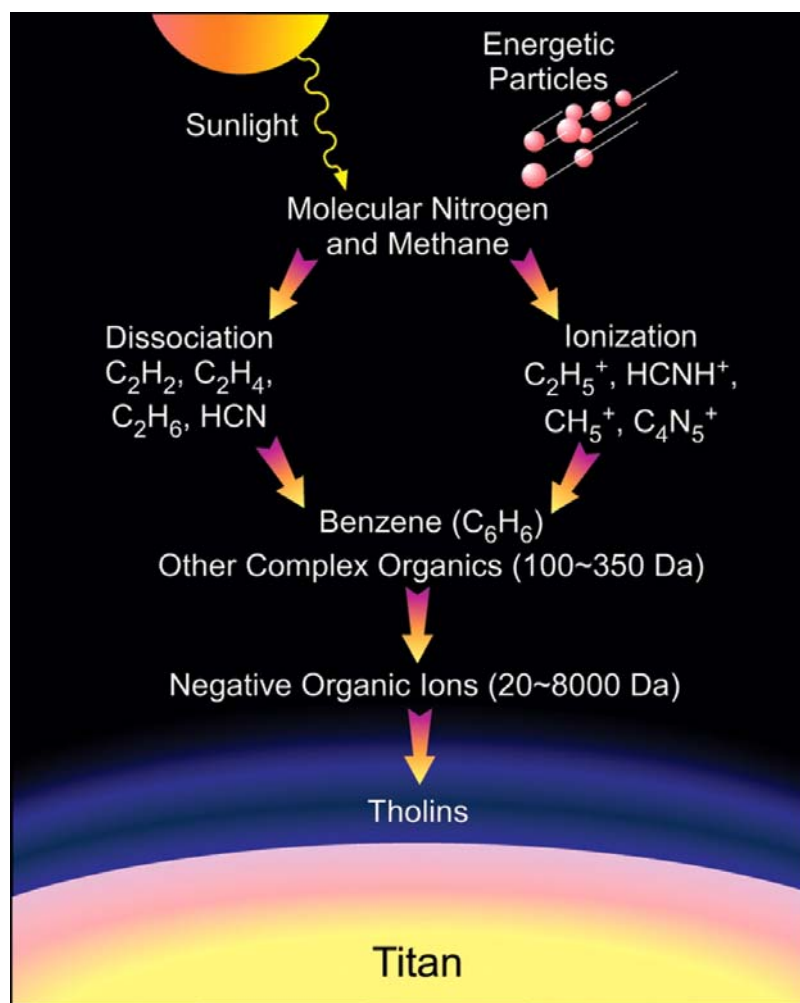
Fig. 12 Organic chemistry cascade observed in Titan's upper atmosphere (Waite et al. 2007).

CIRS, on board of Cassini, has detected these organics in Titan's stratosphere (Fig. 13) and determined their spatial and vertical distributions (Coustenis et al. 2007). Comparisons with previous Voyager and ISO results (Coustenis et al. 2003) have not yet pointed to any significant temporal variations of these species, but the seasons of these measurements were very similar. On the other hand, many of the neutral constituents predicted by models and laboratory measurements and listed on the CIRS "shopping list" have failed to turn up (Flasar et al. 2004). The reason could be the geometry or the rareness of the observations, or the detectability limit of the instrument.

The N_2-CH_4 byproducts in Titan's atmosphere eventually end up as sediments on the surface, where they accumulate presently at a rate of roughly 0.5 km in 4.5 Gyr. Since no large source was detected by Cassini to re-supply methane, cryovolcanic outgassing has been hypothesized (Sotin et al. 2005), yet over what timescales and through which internal processes are unknown. Cassini-Huygens also found that the balance of geologic processes—impacts, tectonics, fluvial, aeolian—is somewhat similar to the Earth's, more so than for Venus or Mars. Titan may well be the best analog to an active terrestrial planet in the sense of our home planet, albeit with different working materials.
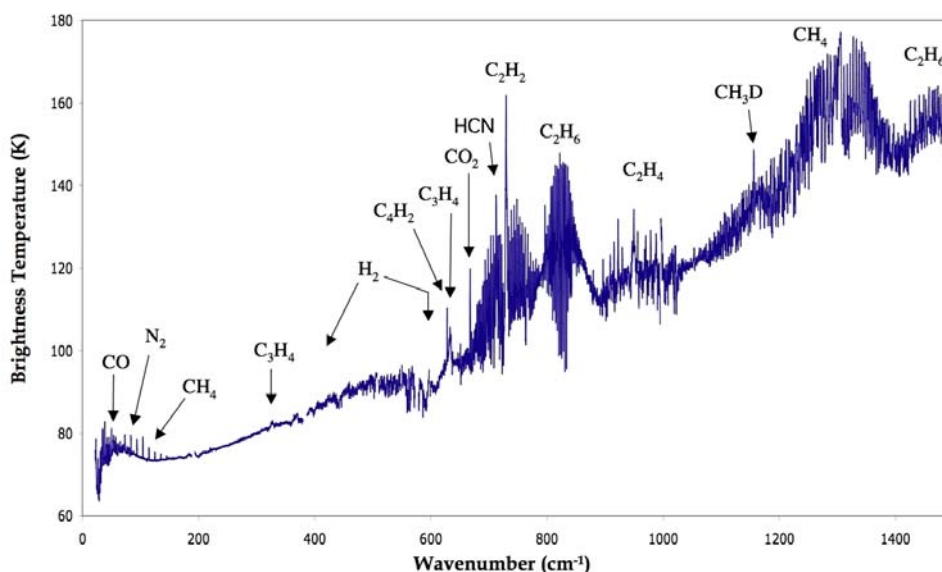
Fig. 13 Titan spectrum in the thermal infrared acquired by Cassini/CIRS showing the various neutral organic molecules observed in Titan's stratosphere (Coustenis et al. 2007).

The surface of Titan, as revealed by the Cassini orbiter and the Huygens probe, offers us an opportunity to stretch our current models in an effort to explain the presence of dunes, rivers, lakes, cryovolcanoes and mountains in a world where the rocks are composed of water ice rather than silicates and the liquid is methane or ethane rather than liquid water, but the limited spatial coverage of high resolution imaging (corresponding to 25%–30% with RADAR and much less with VIMS) limits our view of the range of coupled geologic, geochemical or energetic processes still going on Titan's surface and in the interior. The exciting results from the Huygens post-landing measurements are limited to a fixed site, short timescales, and do not allow for direct sub-surface access and sampling.

Titan's tectonism is not well understood. A number of very-large-scale linear features are seen optically (Porco et al. 2005), notably the dark dune-filled basins. Smaller-scale "virgae" are also seen but are not understood. Radar imagery of some of these features has not helped in their interpretation and is not yet sufficiently widespread to evaluate tectonic patterns, although some linear mountain ranges have been detected, with several forming a chevron pattern near the equator. Near-IR imagery by Cassini VIMS has also shown long ridges (Fig. 14). An outstanding mystery is the nature of the large bright terrain Xanadu and its adjoining counterpart the Tsegihi region. These areas are distinct optically, and they have unusual radar properties. SAR imagery shows Xanadu to be extremely rugged, although the mountain-forming process(es) on Titan has (have) not been robustly identified and may differ from place to place.

Cryovolcanism is a process of particular interest on Titan because of the known astrobiological potential of liquid water erupting onto photochemically produced organics. Several likely cryovolcanic structures have been identified in Cassini using near-infrared and radar images. Although evidence for active volcanism has not yet been widely convincing, there are apparent surface changes in the Cassini data that require explanation (Nelson et al. 2009).

Titan's overall density (1.88 g cm^{-3}) requires it to have roughly equal proportions of rock and ice. After its accretion, Titan was probably warm enough to allow differentiation into a rocky core with a water/ice envelope, but whether an iron or iron–sulfur core formed during the subsequent evolution
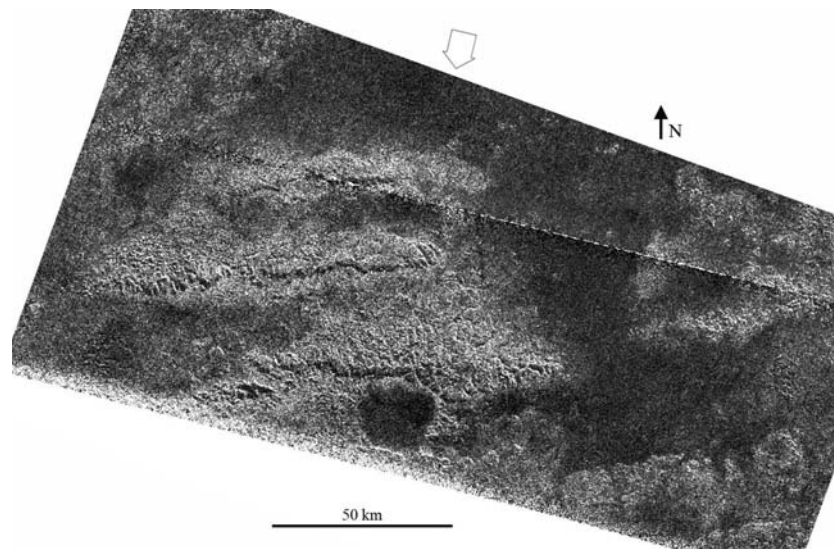
Fig. 14 Titan tectonics. A set of three parallel ridges was seen in the Xanadu mountainous region (2°S, 127°W) by the Cassini spacecraft's radar instrument during the Titan flyby on May 12, 2008. These features are certainly tilted or separated blocks of broken or faulted crust, now exposed as high ridges. Their regular spacing (about 50 km) is typical of regions that have been compressed or extended south-to-north tectonics. Along the south sides of the ridges are prominent cliffs, or scarps, present as thin, radar-dark lines trending west-to-east, and interpreted as faults. These features are dark due to shadowing from the radar illumination (indicated by the open arrow), and have heights up to a few hundred meters. At the bottom center, a probable impact crater, now filled with dark (smooth) material, is about 20 km in diameter. Credit: NASA/JPL.

remains uncertain. Thermal evolution models suggest that Titan may have an icy crust between 50 and 150 km thick, lying atop a liquid water ocean a couple of hundred kilometers deep, with some amount (a few to 30%, most likely ∼10%) of ammonia dissolved in it, acting as an antifreeze. Underneath it lies a layer of high-pressure ice. Cassini's measurement of a small but significant non-synchronous contribution to Titan's rotation is most straightforwardly interpreted as a result of decoupling of the crust from the deeper interior by a liquid layer (Lorenz et al. 2008b).

6 FINAL REMARKS

The two major themes in Titan exploration—the methane cycle as an analog to the terrestrial hydrological cycle and the complex chemical transformations of organic molecules in the atmosphere and the surface—render Titan a very high priority if we are to understand how volatile-rich worlds evolve and how organic chemistry and planetary evolution interact on large spatial and temporal scales. Both are of keen interest to planetology and astrobiology.

The deposition of CH_4-N_2 photochemical materials, including liquid ethane, leads to the creation of lakes and seas of liquid hydrocarbons on Titan's surface in the high latitude regions, making a uniquely evocative landscape. At high spatial resolution, Titan's landscape may be quite exotic, because the working materials differ so much from those on the Earth. Several years of flybys by the Cassini orbiter have led to radar and near-IR maps that, besides the surface liquids poleward of the 70° latitude, also suggest dune fields made of frozen organic fine grains that extend for thousands of kilometers. In the absence

of a massive surface ocean, but with analogs to all other terrestrial hydrological phenomena present, Titan's methane cycle is indeed exotic.

An important Cassini finding needs to be underscored—at all spatial scales, there are structures seen in radar images that correlate with those in the near-IR, however, there are also structures that do not correlate at all. Radar and optical data thus tell us very complementary things about Titan's surface, and consequently, a follow-on mission requires high-resolution global coverage by both techniques. In the near-IR, high-resolution coverage is particularly lacking from Cassini because of the short, rapid flybys. While the surface is spectrally diverse, the identification of surface materials in the spectral windows Cassini is able to observe has proven challenging, making the extension to slightly longer wavelengths (in the region from 5 to 6 microns) highly desirable.

Besides the obvious analogies one can draw between Titan, the Earth and the other terrestrial planets (see Section 3), another and perhaps unexpected analogy could be made between Titan and many extrasolar planets, if moons like Titan orbit the "hot Jupiters" that have been discovered. These moons would be close enough to the star to have the warmth necessary to develop a "habitability zone" or at least enough to be able to host advanced organic chemistry. Indeed, many of the known planets are close enough to their primary star to be tidally locked and thus rotate synchronously. However, non-zero eccentricity (like that of Titan) may mean that there nonetheless are significant tidal effects.

To answer the several remaining vital questions that Cassini has raised for Titan (and for Enceladus, another fascinating object in the Kronian system), a new mission (the Titan Saturn System Mission, TSSM) was proposed and studied during the past year by both ESA and NASA (Coustenis et al. 2009). This new mission would bring the required long-term exploring capabilities combining an orbiter and two in situ elements (a montgolfière and a lander) with state-of-the-art technology with related instrumentation (see *www.lesia.cosmicvision/tssm/tssm-public* and *http://opfm.jpl.nasa.gov/titansaturnsystemmissiontssm/*).

References

Atreya, S. K., Adams, E. Y., Niemann, H. B., Demick-Montelara, J. E., Owen, T. C., Fulchignoni, M., Ferri, F., & Wilson, E. H. 2006, Planet. Space Sci., 54, 1177

Bird, M. K., et al. 2005, Nature, 438, 800

Brown, R. H., et al. 2008, Nature, 454, 607

Coustenis, A., & Taylor, F. 1999, Titan: The Earth-like Moon (Singapore: World Scientific)

Coustenis, A., & Taylor, F. 2008, Titan: Exploring an Earth-like World (Singapore: World Scientific)

Coustenis, A., Salama, A., Schulz, B., Ott, S., Lellouch, E., Encrenaz, Th., Gautier, D., Feuchtgruber, H. 2003, Icarus, 161, 383

Coustenis, A., et al. 2007, Icarus, 189, 35

Coustenis, A., et al. 2009, Exp. Astron. 23, 893.

Flasar, F. M., et al. 2004, Nature, 427, 132

Fulchignoni, M., et al. 2005, Nature, 438, 785

Hayes, A., et al. 2008, Geophys. Res. Lett., 35, L09204

Israël, G., et al. 2005, Nature, 438, 796

Lebreton, J-P., Coustenis, A., Lunine, J., Raulin, F., Owen, T., & Strobel, D. 2008, Astron. & Astrophys. Rev., in press

Lorenz, R. & Mitton, J. 2002, Lifting Titan's Veil: Exploring the Giant Moon of Saturn (Cambridge: Cambridge University Press)

Lorenz, R. D. 2006, Icarus, 182, 559

Lorenz, R., & Mitton, J. 2008, Titan Unveiled: Saturn's Mysterious Moon Explored, by Ralph Lorenz and Jacqueline Mitton. ISBN 978-0-691-12587-9. Published by Princeton University Press, Princeton, NJ USA, 2008

Lorenz, R. D., et al. 2007, Geophys. Res. Lett., 34, 7204

Lorenz, R. D., et al. 2008a, Planet. Space Sci., 56, 1132

Lorenz, R. D., et al. 2008b, Science, 319, 1649

Mitri, G., Showman, A. P., Lunine, J. I., & Lorenz, R. D. 2007, Icarus, 186, 385

Nelson, R. M., et al. 2006, Planet. Space Sci., 54, 1540

Nelson, R. M., et al. 2009, Icarus, 199, 429

Niemann, H. B., et al. 2005, Nature, 438, 779

Porco, C. C., et al. 2005, Nature, 434, 159

Radebaugh, J., et al. 2008, Icarus, 194, 690

Raulin, F. 2008, Nature, 454, 587

Soderblom, L. A., et al. 2007a, Planet. Space Sci., 55, 2015

Soderblom, L. A., et al. 2007b, Planet. Space Sci., 55, 2025

Sotin, C., et al. 2005, Nature, 435, 786

Stofan, E. R., et al. 2007, Nature, 445, 61

Tobie, G., Lunine, J. I., & Sotin, C. 2006, Nature, 440, 61

Tomasko, M. G., et al. 2005, Nature, 438, 765

Waite, J. H., Young, D. T., Cravens, T. E., Coates, A. J., Crary, F. J., Magee, B., & Westlake, J. 2007, Science, 316, 870

Zarnecki, J. C., et al. 2005, Nature, 438, 792