


The Exploration of Titan

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The exploration of Saturn's moon Titan is reviewed, noting the dramatic recent improvements in our knowledge of this strange world from the ongoing international Cassini-Huygens mission, results from which are summarized. Among Cassini's discoveries are the remarkable richness and complexity of its organic chemistry, a strikingly Earth-like landscape with hydrocarbon lakes and seas, and vast fields of organic sand dunes interspersed with craters and icy mountains. The breadth of scientific questions posed by Titan's Earth-like landscape and meteorology, and its organic-rich prebiotic chemistry, set the stage for Titan to become a key target for future solar system exploration, possibly by aircraft exploiting its thick atmosphere and low gravity.

INTRODUCTION

The most Earth-like body in the solar system is not another planet but Saturn's largest moon, Titan.¹ Indeed, if Titan orbited the Sun rather than Saturn, we would not hesitate to call it a planet in its own right. This strange new world is larger than the planet Mercury and has a thick nitrogen atmosphere laden with organic smog, which hid its surface from view until only recently (Fig. 1). Since Titan is far from the Sun, methane plays the active role there that water plays on Earth, serving 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 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. Until only 3 years ago, little of this was known.

The dramatic and surprising results obtained from the Cassini-Huygens mission² have shown Titan to be much more diverse and complicated than had been thought, making it much more than just an icy satellite with an atmosphere.

EXPLORATION HISTORY

Titan was discovered in 1655 by the Dutchman Christiaan Huygens, who realized simultaneously that

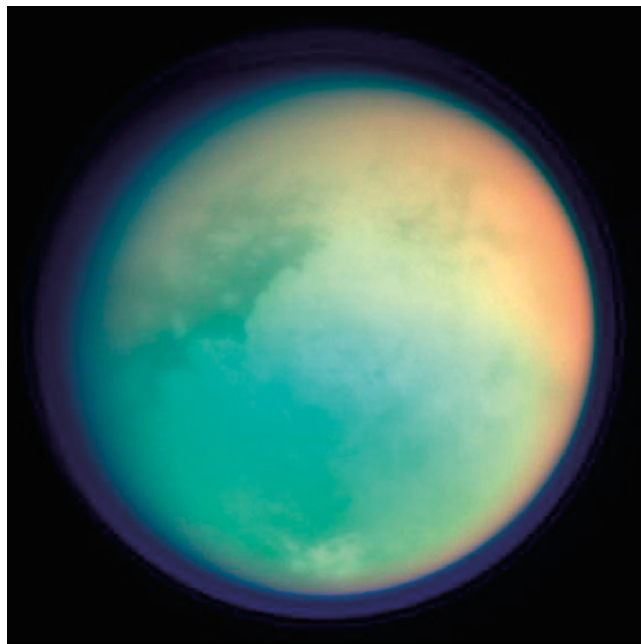


Figure 1. A false-color composite of Cassini International Space Station (ISS) images. The blue is rendered from a UV filter, making it particularly responsive to high-altitude haze, which appears especially abundant over the northern polar region (north is up). The tan is generated from a near-IR filter in a methane absorption band: the northern hemisphere has more haze lying above the bulk of the methane, hence it is more tan. The green channel is from a near-IR “window” that penetrates to the surface, showing the irregular “coastline” at left. The irregular white patch at the bottom is a complex of tropospheric clouds around the south pole, which were observed to move and evolve over periods of a few hours. (Image courtesy of NASA/JPL/Ciclops/University of Arizona.)

Saturn’s rings (seen only as fuzzy blobs before his high-quality telescope was trained on the planet) were just that, rings defining a plane, and that a satellite, later named Titan, orbited in that plane once every 16 Earth days. Huygens was a remarkable thinker and considered that, absent any information to the contrary, other planetary bodies must be Earth-like. He even noted that the outer planets, being so far from the Sun, would be very cold and thus their clouds and rain would have to be made of something other than water.

Another Dutchman, Gerard Kuiper, working in the United States in 1944, discovered this other something on Titan: dark bands in the spectrum of sunlight reflected by Titan matched those of methane measured in the laboratory. This immediately made Titan unique among the satellites in the solar system—it had an atmosphere.

Even through the 1970s, with the first space-borne observations of Titan (in the UV by the Orbiting Astronomical Observatory-2) together with thermal IR observations from the ground, the thickness of this atmosphere was unknown. The early observations seemed mutually

contradictory: a thick atmosphere would reflect blue and UV light more brightly than the space-borne observations (just as our own sky is blue), but the warm temperatures implied by the ground-based thermal data required a thick atmosphere.

Observations from the Voyager 1 spacecraft as it flew by Titan in 1980 resolved the matter, showing both “end members” to be partly correct. Voyager showed Titan’s atmosphere to be like Earth’s, made predominantly (>90%) of molecular nitrogen and having a surface pressure of 150 kPa and a temperature around 94 K, indicating its “sea-level” air density to be 4 times higher than Earth’s.

Methane makes up about 1.5% of Titan’s stratosphere, although (much like water vapor in the Earth’s troposphere) its abundance increases somewhat nearer the ground. Indeed, the temperature profile indicated by Voyager showed Titan to have a very Earth-like atmospheric structure, but one that was colder and vertically stretched in the low gravity, i.e., temperatures slowly fall with altitude from the surface upward to the chilly tropopause at 40 km. And just as with water vapor on Earth, Titan’s tropopause acts as a “cold trap” for methane, which is a condensable greenhouse gas. At higher altitudes, local absorption of sunlight (on Earth by ozone, on Titan by the haze discussed below) causes temperatures to rise with altitude, forming a stable stratosphere. It is this warm, stable stratosphere that causes the large thermal fluxes observed from Earth.

It had been suspected from Titan’s reddish color and the polarization of its light that its atmosphere might be hazy, and indeed it is this haze that prevents Titan’s sky from being blue. Because it absorbs around half of the sunlight incident on Titan, the haze is a major factor in controlling Titan’s climate: together with the condensable greenhouse gas (methane), the haze opens Titan to many interesting climate feedback processes.

A further intriguing analogy with Earth is the “polar hood” observed by Voyager (and also by Cassini; see Fig. 2). There is a seasonally variable enhancement of haze opacity over the winter polar regions, which are dynamically isolated from the rest of the atmosphere by a circumpolar vortex. A similar effect occurs on Earth where polar stratospheric clouds form in the cold winter darkness but are kept from dispersing by the circumpolar winds, especially around Antarctica. On Earth, these clouds are instrumental in the catalysis of ozone destruction, and so are responsible for the formation of the ozone hole. Titan’s chemistry is very different, but the physical setting and the peculiar processes occurring in its polar night may have much to teach us about Earth.

Titan’s haze is produced by the destruction of methane by solar UV light and the bombardment of the

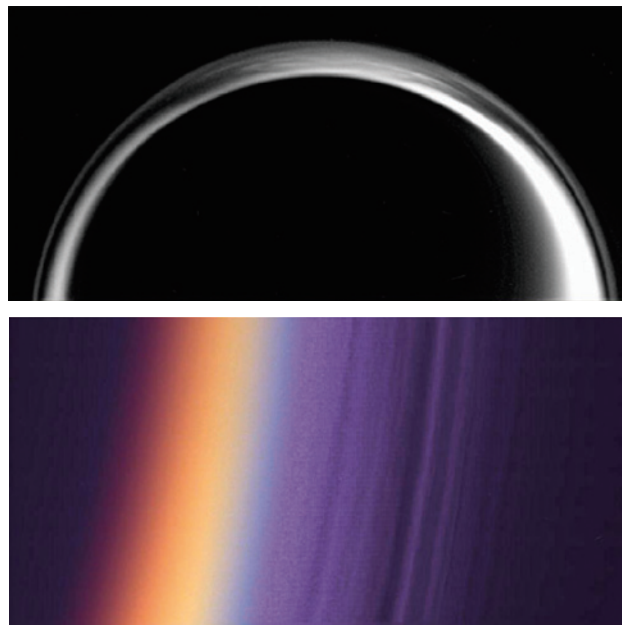


Figure 2. Cassini ISS images show striking structure in the atmospheric haze. The north polar region (top) features a particularly complex structure (the “North Polar Hood”). The main orange haze deck, as well as the “detached haze” (which appears dynamically connected to the polar hood), has somewhat different optical properties. The lower panel shows a close-up example of the rich, layered structure in the haze (“up” is to the right.) (Images courtesy of NASA/JPL/Ciclops.)

atmosphere by energetic particles in Saturn’s magnetosphere. Titan orbits 1.2 million kilometers from Saturn (20 Saturn radii) so that it is sometimes inside the magnetosphere but outside during periods of stronger solar wind. Titan’s ionosphere is therefore exposed to various combinations of sunlight, solar wind, and Saturn’s magnetospheric flow, making it a highly variable and dynamic region. These energy sources cause heating and drive winds, and also break methane and nitrogen molecules apart. These fragments recombine in myriad ways, producing a host of larger organic molecules, some of which make up the reddish haze.

Post-Voyager models predicted that ethane would be the dominant product of methane photolytic destruction: the process is irreversible, since hydrogen liberated from methane escapes into space. The amount of methane presently in Titan’s atmosphere would be depleted in only a few million years, a fraction of the age of the solar system. So for Titan’s methane presence today not to be a quirk, it must be buffered by a surface reservoir. Both methane and ethane are liquids at Titan’s surface temperature, and thus an intriguing possibility is that this reservoir was an ocean of methane, progressively being converted into ethane over geological time.

In response to these and many other mysteries of the Saturnian system (the spokes observed in its rings,

the bright/dark dichotomy on Iapetus, the fresh surface of Enceladus, and the E-ring, among others) a follow-on mission was proposed. That mission opened up two new dimensions compared with Galileo (the follow-on mission to Jupiter). First, while Galileo’s tour at Jupiter made multiple encounters with the planet’s four large satellites that orbit in a plane, Cassini’s orbital tour was three-dimensional—the inclination of the spacecraft’s orbital plane could be cranked upward to look down on the rings and Saturn’s polar regions. In the Saturnian system, only Titan is massive enough to usefully alter the spacecraft’s orbit (a “slingshot” or gravity assist), so Cassini’s orbital tour was constructed by chaining one Titan flyby after another, with each flyby changing the orbital period, the orientation in its plane, or its inclination. With a 4-year tour making many dozens of orbits, the number of possible tours was enormous.

The second added dimension, that is, international participation, has been more significant. Although NASA had studied follow-on Saturnian and Titan missions, notably SO2P (Saturn Orbiter with Two Probes, one for Titan and one for Saturn), the Cassini mission in its modern form originated in an international proposal to the European Space Agency (ESA). Several years of joint studies followed, culminating in a new start for Cassini as part (subsequent cancellations were to make it the only part) of the Mariner Mark II series in NASA’s program in 1989, and the selection of a Titan probe for Cassini, to be named Huygens, as ESA’s second medium-class mission.

In addition to the ESA contribution of the probe and its support systems, its member states and the United States provided instruments for both the Huygens probe and the orbiter spacecraft, making both elements truly international endeavors. In addition, Cassini’s 4-m-wide high gain antenna, together with its four-wavelength feed structure, was supplied by the Italian Space Agency.

By the time Cassini was launched in 1997, the Hubble Space Telescope (HST) had been refurbished, enabling it to image Titan in near-IR wavelengths where the haze was less opaque. These images showed Titan to have a variegated surface, notably with a large, bright region named Xanadu on its leading face. This near-IR map—soon supplemented by others made from larger ground-based telescopes equipped with ever-improving adaptive optics systems as well as radar observations made with large radio telescopes—showed that Titan did not have a global ocean after all. Yet something was making, or keeping, part of its surface brighter than other parts, despite an expected slow drizzle of photochemical debris all over its surface.

HST images showed Titan’s haze to be changing seasonally: it was thicker in one hemisphere than the other. In 1980, Voyager showed Titan’s northern hemisphere to be optically brighter, indicating less haze. In the

mid-1990s, the HST saw the opposite, as might be expected half a Titan year later. (Saturn and Titan are inclined at 26° to the Sun, giving them strong seasonal forcing, albeit much slower than Earth, since they orbit the Sun only every 29.6 years.) It seems that air rises in the summer hemisphere, blowing haze toward the winter side.

Rising air, much like in the Earth's tropics, creates large cumulus clouds on Titan. Indications of cloud activity were first observed in ground-based spectra and more tentatively in HST images in 1995. But in the first years of the new millennium, large ground-based telescopes with adaptive optics showed massive methane cloud systems around Titan's south pole. The southern summer solstice on Titan was in 2003.

Thus our understanding of Titan, and our appreciation of it as an active place, grew as Cassini-Huygens steadily cruised to Saturn. Even with its formidable Titan IV launch vehicle, Cassini required flybys of Venus (in 1998 and 1999), Earth (in 1999), and Jupiter (in 2000) to gain enough energy to reach Saturn in July 2004.

THE EMERGING PICTURE

Before Cassini, expectations of Titan's surface ranged from a global ocean of liquid hydrocarbons to a dead, cratered landscape like Callisto. One leading idea as to what made Xanadu (a region on Titan comparable in size to Australia) bright was that it might be mountainous and that methane rainfall might wash it clean of dark organics. This explanation, however, was considered speculative. The source of the methane remained a puzzle. Perhaps it was from lakes, seas, or subsurface "aquifers," or perhaps it was supplied by eruption in cryovolcanos.³ In fact, the latter idea does not allow an easy escape from the notion that there should, at least sometimes, be surface liquids: unless the methane supply rate to the atmosphere was exquisitely finely tuned to just balance the loss by photolysis, the atmosphere would in time run dry or would periodically become saturated, allowing lakes and seas to form anyway. Only observations near Titan would offer the hope of solving the riddle.

Cassini's ISS (Imaging Science Subsystem) can observe in the near-IR, like HST, but the haze is still thick enough at this wavelength (940 nm) to blur images somewhat. The first ISS images showed a complex surface with bright and dark regions (Fig. 1). In some cases the boundaries between these regions were irregular, reminiscent of terrestrial coastlines, while some other dark patches had straight edges.⁴ An interesting observation was that the western margins of bright terrain seemed to be consistently sharp while the eastern margins were often diffuse, suggesting that bright material might be transported eastward by winds or other fluid flow.

The discovery of dozens of features on Titan's surface required that they be named. Mediated by

the International Astronomical Union (IAU), the naming scheme evokes mythology and geography. Bright regions are named after places of enchantment, paradise, or celestial realms, and craters are named after deities of wisdom. Lakes are named after actual terrestrial lakes, and rivers are named after mythical or imaginary rivers. Many of these names, such as Mare Crisium on Earth's Moon or Meridiani Planum on Mars, are becoming familiar to planetary scientists. Figure 3 shows a map made from Cassini ISS images with major features noted.

With Titan's haze in mind, Cassini is equipped with a multimode radar instrument. In addition to large-scale scatterometry and passive radiometry measurements, it can perform altimetry and synthetic aperture radar (SAR) imaging. During close flybys of Titan, SAR allows Cassini to map long strips covering over a million square kilometers (about 1% of the surface) on each pass with resolutions down to 300 m.

The first radar image⁵ in October 2004 showed an inscrutable region well north of Xanadu, apparently containing cryovolcanic and perhaps fluvial features. Remarkably, no impact features were seen in the above strips. Since impact features are continuously generated throughout the solar system, hundreds of craters should have been seen if the surface was old. Thus the lack of craters suggested that, like Earth, Titan's surface is young, being continuously shaped by processes such as erosion or volcanism.

HUYGENS

Much anticipation accompanied the descent of the Huygens probe (Fig. 4). The probe was released on Christmas Eve, 2004, before making a 21-day dormant coast initially away from Saturn and then arcing back inward to enter Titan's atmosphere at 6 km/s on 14 January 2005. Cassini fired its engine to trail behind the probe as it flew past Titan to act as a communications relay during the probe's descent.

Protected by its heat shield, Huygens decelerated to Mach 1.5 at an altitude of 160 km, at which point it deployed its parachutes to make a 2.5-h descent to the surface. The peak deceleration was only ≈ 14 (Earth) g; the large-scale height of Titan's atmosphere makes hypersonic entry easier there than anywhere else in the solar system.

The probe profiled the optical properties of the haze, finding⁶—in contrast to most pre-Huygens models—that the haze extended all the way down to the surface. The atmospheric temperature structure, which resembles a cold but vertically stretched version of that of the Earth, was much as had been predicted from Voyager radio-occultation data: the surface temperature was 94 K, while a temperature minimum of 71 K at an altitude of 40 km defines the tropopause.

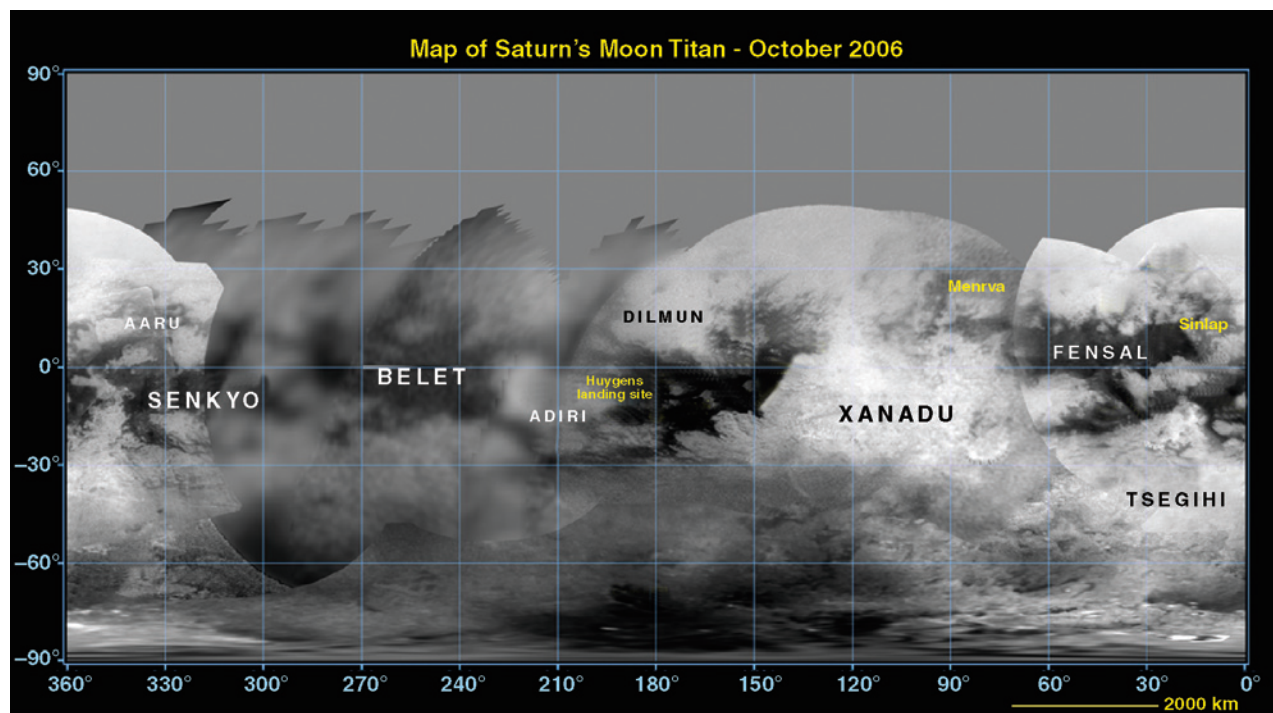


Figure 3. A map of Titan from Cassini ISS images at 940 nm, with names indicated for major regions (names are selected by a committee of the IAU). Some areas are mapped at rather higher resolution than others; latitudes 50°N and higher are insufficiently illuminated in the season shown to map. (Image courtesy of NASA/JPL/Ciclops.)

As predicted, the probe drifted some hundreds of kilometers eastward in the zonal winds, although a striking region of wind shear was discovered at an altitude of ≈ 80 km, where the wind declined to near zero. Somewhat unexpected was a reversal in the drift direction in the

lowest few kilometers of descent. Electric field investigations found no definitive evidence of lightning, which was, in any case, considered unlikely since there is little sunlight to drive convective activity, and unlike water, methane is a nonpolar molecule and so is less effective at charge separation. However, an increase in atmospheric ionization was observed around a 90-km altitude due to cosmic rays (whose interaction with nitrogen will also produce a small amount of radiocarbon, as in the Earth's atmosphere).

A much-anticipated moment was the impact of Huygens with the surface—an event for which survival was never guaranteed. The probe hit the surface at 5 m/s (about the speed of a laptop dropped from a table on Earth), encountered a fairly soft surface (mechanically resembling sand or mud), and continued to operate quite happily.

Images (taken from knee-height!) of the surface showed a fluvial landscape, broadly flat with a fine-grained dark substrate on which sat rounded, bright cobbles between 5 and 15 cm in diameter. The rounding of the cobbles and the absence of small pebbles suggested the area had last been shaped by the rapid flow of liquid, most probably the result of a methane rainstorm.

The impact embedded the heated inlet of a gas chromatograph/mass spectrometer into the ground. This fortuitous surface sampling allowed the detection of methane, ethane, carbon dioxide, and benzene in the surface material, which doubtless contained a host of

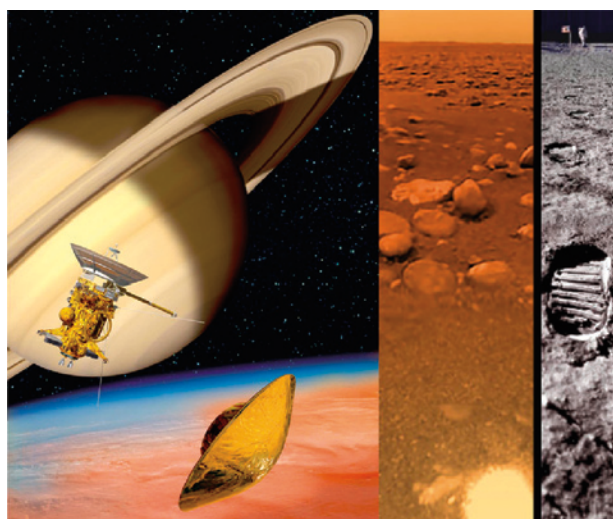


Figure 4. (Left) Artist's impression of the Huygens probe released from the Cassini orbiter. (Center) The knee-high view of Titan's surface acquired by Huygens' camera after impact. (Right) The lunar surface shown at the same perspective. (Images courtesy of ESA/NASA/JPL/University of Arizona.)

other unmeasured organic compounds. An analysis of the inlet temperature suggested that the ground had to be physically damp with liquid methane.

An hour after its historic landing, Huygens was continuing to transmit, but the Cassini spacecraft, acting as Huygens's data relay, set in the western horizon. Analysis of the irregular fading of signal strength due to interference of the direct radio signal with a grazing reflection from the ground showed that the terrain to the west was similar in roughness to that seen to the south by the camera. Radio telescopes on Earth were able to detect continuing transmission for another 2 h: models of battery depletion suggest that probe operations ceased very soon thereafter.

NOT EVEN THE BEGINNING OF THE END

While clearly a highlight of the Cassini mission, the Huygens descent merely marked the end of the beginning of a new era of Titan exploration. Cassini is scheduled to make 44 close flybys of Titan during its 4-year nominal mission, with an additional ≈ 20 planned for a 2-year initial mission extension.

In terms of revealing details of the landscape (Fig. 5), radar observations have been instrumental. Radar measurements are made on only about a third of the flybys, since Cassini lacks a scan platform to independently point its instruments, which cannot all observe at once. The massive Cassini spacecraft must therefore be slewed around as it whips by a target to point its instruments. The first six radar passes seemed to show a different body each time! Only a handful of impact craters have been found, indicating an overall young surface.

River channels running for several hundred kilometers have been observed. Some have the characteristics of desert washes, formed by rare but heavy downpours. (Models of methane thunderstorms on Titan show they can deposit several tens of centimeters of liquid in only a few hours, much like the heaviest downpours on Earth.) Other channels are more heavily incised valleys, while still others are shallow and meandering.

A surprising finding⁷ was that large, dark areas near Titan's equator were not (as was once thought) liquid, but rather giant sand seas. These sand seas are filled with massive linear sand dunes, tens of kilometers long, a couple of kilometers apart, and up to 150 m high—exactly the size and style of linear dunes seen in the Namib or Arabian deserts on Earth. Linear dunes, which run along the vector mean wind direction rather than across it, form in wind regimes that alternate between two general directions. On Earth this fluctuation is usually seasonal, relating to monsoonal flows, but on Titan the fluctuation in wind direction is more likely due to Saturn's massive gravitational tide in Titan's atmosphere. These tidal currents of air exist on Earth, but are tiny compared with the solar-driven winds on

our rapidly rotating planet, which heats and cools on a daily timescale. On slowly rotating Titan, with its massive atmosphere so far from the Sun, the response to changing sunlight is heavily damped, and the tidal effects may dominate.

In summer 2006, the first radar images at high northern latitudes revealed dozens of lakes,⁸ some of which were simply round while others had the crenellated appearance of flooded river valleys. The lakes were the darkest areas in radar images of Titan's surface and also showed a high microwave emissivity consistent with a liquid hydrocarbon composition. Whether the lakes are concentrated at high latitudes because of lower surface temperatures there, or because liquid ethane is preferentially deposited near the poles, is not yet clear. Nor is it known whether the lakes are mostly methane or ethane, although a large ethane cloud deck has been observed by Cassini at high northern latitudes, possibly related to the polar hood, which may supply the lower atmosphere with condensation nuclei to aid in cloud formation.

Spectral mapping (Fig. 6) by the Visual and Infrared Mapping Spectrometer (VIMS) has found several distinct terrain compositions.⁹ In addition to the bright terrain making up Xanadu, there seem to be two types of dark terrain: a "brown" unit characteristic of dune-covered areas and a "blue" one apparently associated with river channels. Work is under way to determine the chemical composition responsible for these different units. A further spectrally distinct surface type is associated with a few patches on Titan, which are the brightest regions in a window at a $5\text{-}\mu\text{m}$ wavelength. Spectral identification of materials from orbit is complicated on Titan because of scattering by the haze and absorption of much of the near-IR spectrum by methane gas, the very absorption bands that permitted the discovery of Titan's atmosphere in the first place. Relatively few materials are bright at this wavelength; water ice, for example, is not. One intriguing possibility is carbon dioxide ice, which might be associated with cryovolcanism. Active jets have been observed spewing water vapor and traces of other gases, including carbon dioxide, on Enceladus, one of Saturn's smallest moons.

CASSINI CONTINUES

At the time of writing, Cassini is halfway through its 44 nominal mission flybys, and its orbital plane is being flipped over to change the viewing geometry of the many scientific targets at Titan. Toward the end of the nominal mission in July 2008, the inclination of the orbit will be progressively increased, allowing Cassini to look down on the rings and onto Saturn's high latitudes where aurora occur.

Overall, the spacecraft—already in space for a decade—is in good health and has ample propellant to support further operations. As noted earlier, a 2-year

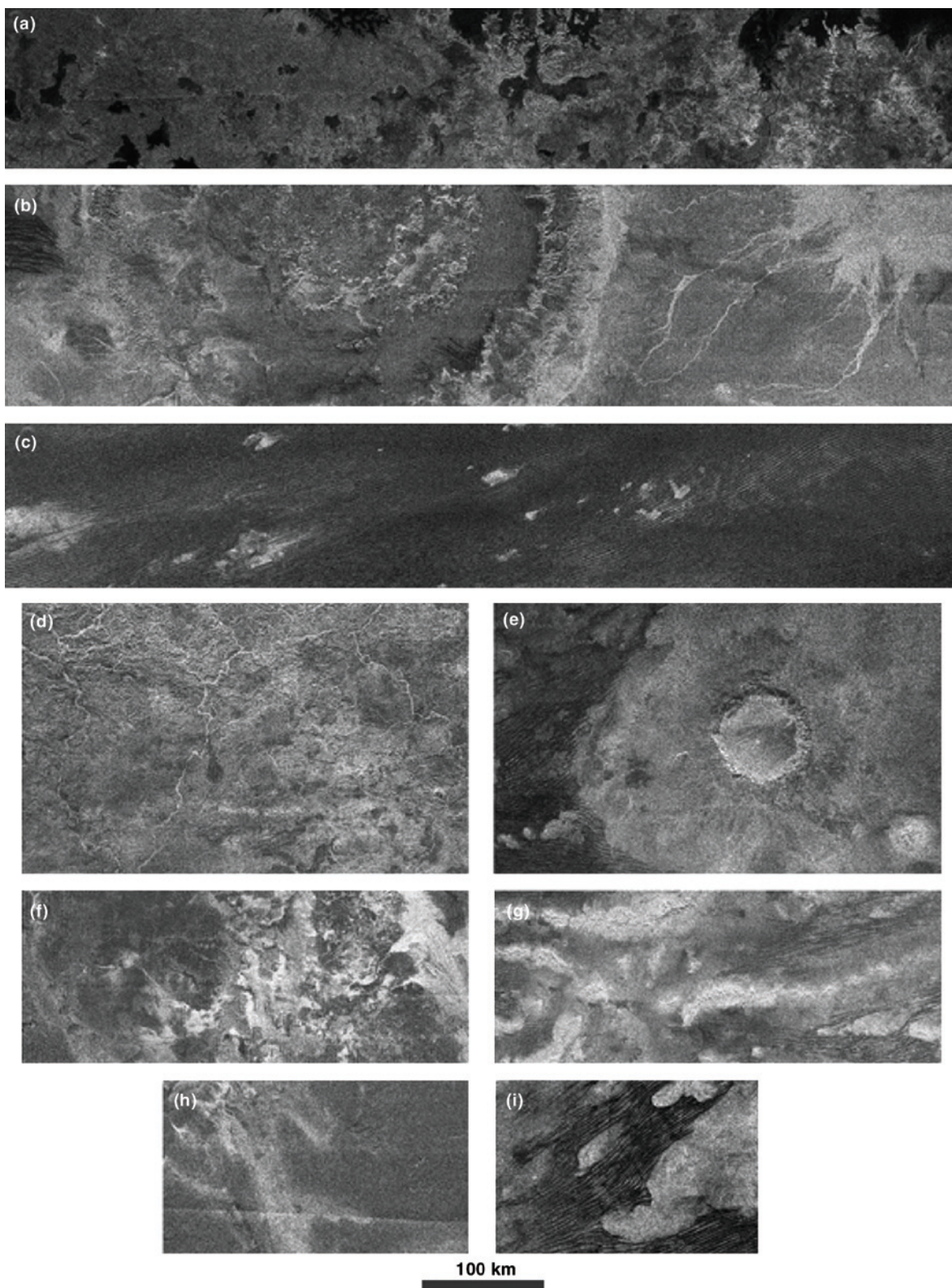


Figure 5. A montage of Cassini radar images showing the diversity of landforms on Titan's surface at a common scale (most locations are indicated in Fig. 3). North is roughly upward in all cases: (a) Lakes near 80°N latitude, (b) the 440-km impact structure Menrva and network of braided river channels to the east, (c) giant linear sand dunes in the near equatorial region Belet, (d) a dendritic river channel network in the western end of Xanadu, (e) the 80-km impact crater Sinlap, (f) Ganesa Macula, a possible cryovolcanic dome, with bright fans to the west, (g) bright mountain chains in Adiri forming a chevron pattern, (h) a lobate structure, possibly a flow, seen on the first close flyby, and (i) dunes sweeping around lobate topography in northwestern Belet. (Images courtesy of the author and the Cassini Radar Team.)

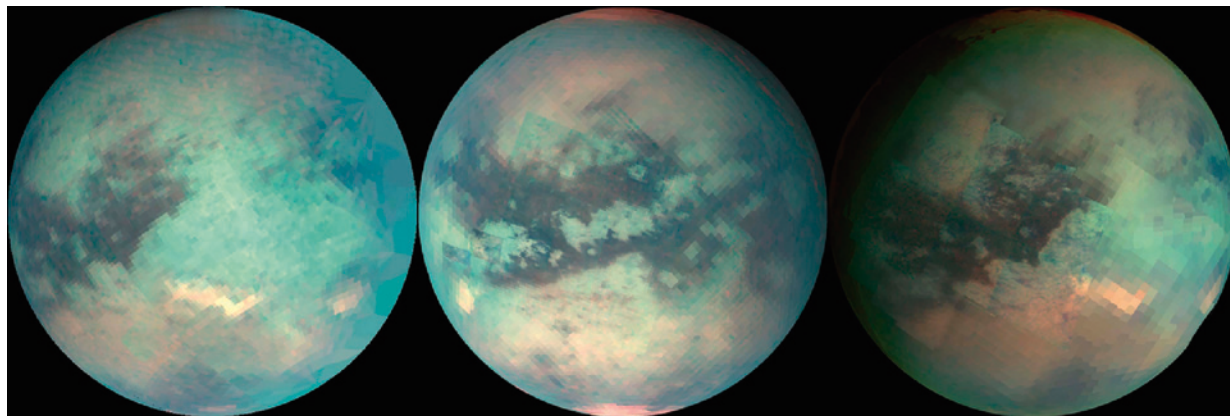


Figure 6. A mosaic of VIMS data showing the spectral diversity of Titan's surface. The bright orange areas, notably Tui Regio and inside Hotei Arcus, are particularly reflective at $5\ \mu\text{m}$, perhaps indicating CO_2 -rich deposits that might be associated with cryovolcanism. In this mosaic, bright clouds are present around the south pole. (Image courtesy of NASA/JPL/University of Arizona.)

extended mission is presently being planned, permitting over 20 more Titan flybys as well as much other science in the Saturnian system as a whole.

In addition to building up mapping coverage at all wavelengths, the Cassini encounters aim to determine Titan's internal structure from its gravity field via precise radio tracking and perhaps to discern hints of an internal water ocean. Beyond observations of cryovolcanic features, clues to such an ocean might include a change in shape and gravity field through flexing of the crust through one tidal cycle as well as measurements of any induced magnetic field. Those measurements (which were used by Galileo to indicate water oceans on Europa and Ganymede) are more challenging at Titan because of weaker changes in the Saturn field there (the inductive detection of a conducting interior, by implication liquid water, requires modulation of the applied field) and because the ionosphere above Titan's thick atmosphere blocks the internal signature.

While Cassini's flybys have predominantly imaged Titan's northern hemisphere, the extended mission will allow much more of the south to be mapped. An exciting prospect is to observe Titan around its northern spring equinox in 2009: the atmospheric circulation may undergo a convulsive change from the gentle Hadley circulation that transports haze from the summer to winter hemisphere. Models suggest that for a year or two a double-cell equator-to-pole symmetric circulation may develop before being replaced by the new (reversed) pole-to-pole circulation.

One possibility being considered is to introduce particularly low-altitude encounters to get beneath the ionosphere and sample the atmospheric chemistry at higher densities than has been dared in the nominal mission. This chemistry (Fig. 7, Table 1) has been found to be much more complex than anticipated, showing an abundance of compounds with masses of 70 and above such

as benzene.¹¹ Although some 20 or so different molecules had been detected on Titan (principally with mid- and far-IR spectroscopy by Voyager and from Earth) before Cassini arrived, it had been assumed that only simple molecules would be present at the $\approx 1000\text{-km}$ altitudes where Cassini flies past.

Clearly, Cassini's findings have found our understanding of this chemistry to be wanting. The richness of the upper atmospheric chemistry may be connected with the surprising balance of surface materials. A relatively modest coverage by surface liquids has been observed so far, although some lakes (Fig. 8) are several hundred kilometers across and thus may qualify as "seas." In

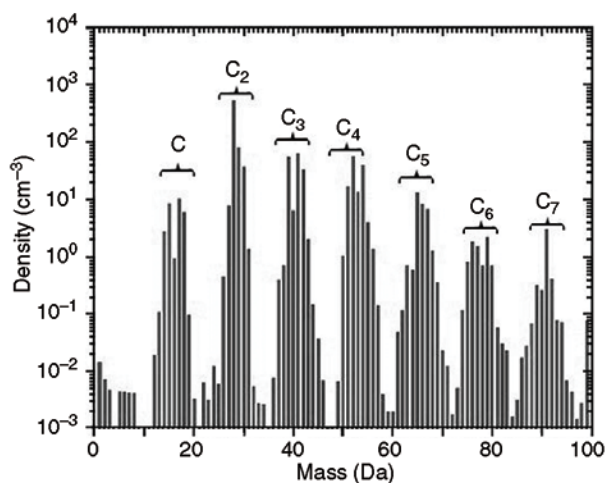


Figure 7. A mass spectrum acquired by Cassini's Ion and Neutral Mass Spectrometer between an altitude of 1100–1300 km as it flew through the upper atmosphere. The spectrum shows the surprising abundance of large hydrocarbon molecules, even at altitudes above 1000 km. This material forms Titan's haze and, perhaps growing in complexity as it descends, is deposited on Titan's surface. (Data courtesy of NASA/SwRI.)

Table 1. Composition of Titan's atmosphere (after Ref. 10).

Common (official) name	Formula	Amount (in stratosphere unless otherwise indicated)
Nitrogen	N ₂	95% near surface ≈98%
Methane	CH ₄	4.9% at surface near equator 1.4% in lower stratosphere ≈2% at ≈1000 km
Hydrogen	H ₂	0.1–0.2% in lower atmosphere ≈0.4% at ≈1000 km
Argon	Ar ⁴⁰ Ar ³⁶	43 parts per million (ppm) 28 parts per billion (ppb)
Ethane	C ₂ H ₆	≈20 ppm
Carbon monoxide	CO	≈45 ppm
Acetylene (ethyne)	C ₂ H ₂	3.3 ppm 19 ppm at ≈1000 km
Propane	C ₃ H ₈	700 ppb
Hydrogen cyanide	HCN	800 ppb in winter stratosphere ≈100 ppb in summer stratosphere
Ethylene (ethene)	C ₂ H ₄	160 ppb
Carbon dioxide	CO ₂	15 ppb
Methyl acetylene (propyne)	C ₃ H ₄	10 ppb
Acetonitrile	CH ₃ CN	a few ppb
Cyanoacetylene	HC ₃ N	>5 ppb in winter stratosphere <1 ppb in summer stratosphere
Methyl acetylene	CH ₃ C ₂ H	5 ppb
Cyanogen	C ₂ N ₂	5 ppb
Water vapor	H ₂ O	8 ppb
Diacetylene (buta-1,3-diyne)	C ₄ H ₂	1.5 ppb (slightly higher in winter)
Benzene	C ₆ H ₆	1.4 ppb at winter pole, <0.5 ppb elsewhere

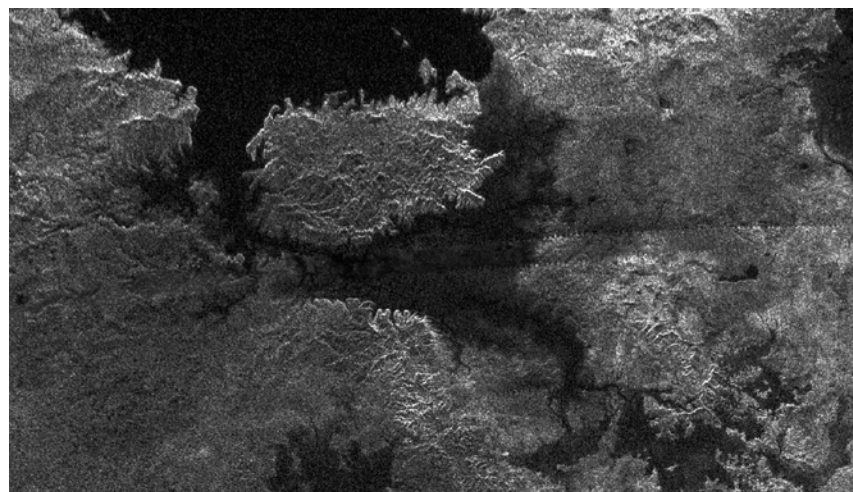


Figure 8. This radar image shows a lake/coastline region at around 79°N, 310°W. An island (90 × 150 km) is mountainous (as evidenced by the “layover” of the peaks toward the top of the image, from which direction the radar observation was made). It is bounded at the top by a pitch-black area that is probably liquid and on the lower side by a lighter-shaded channeled area, perhaps a tidal mudflat.

contrast, vast sand seas of dark dunes cover some 40% of low-latitude terrain, perhaps a fifth of the entire surface area of Titan.

At the end of a 2-year mission extension, Cassini could easily be introduced into a low-maintenance cyclor orbit between Titan and Enceladus. With minimal intervention, it would make repeated flybys of both bodies, yielding an efficient science return as long as its systems, propellant, and ground support hold out.

OUTSTANDING QUESTIONS AND FUTURE MISSIONS

Cassini is a mission to the Saturnian system, not to Titan. Even with the outstanding return from Cassini's formidable array of instruments on its Titan flybys, Cassini spends only an hour within 10,000 km of Titan on each flyby. It is likely that radar imaging after the 2-year extended mission will only reach 30–40% coverage, and high-resolution spectral mapping will have sampled only small areas. Much is left to discover at Titan, and the long gestation and delivery time of missions to the outer solar system is such that it is already time to consider what future missions might accomplish.

There are many isolated scientific questions to consider, but above all is the notion of how Titan functions as a system. A nested cycle fluxes carbon atoms around. In an inner hydrological cycle, methane forms clouds and rain, carving channels on the surface and perhaps accumulating in polar lakes before evaporating again. Over longer periods, the methane must come from Titan's interior, released perhaps from clathrate ice reservoirs through vents or cryovolcanos. In the upper atmosphere, the methane and nitrogen are destroyed and converted into heavier organic molecules which ultimately are deposited on the surface. Identifying the sources, sinks, and pathways in this complex system requires Titan to be studied at a range of scales from top to bottom, from its ionosphere to its interior.

Orbiting Titan, rather than flying past, would allow a future mission to get more than fleeting glances at the body. Indeed, within the first 3 days of a dedicated follow-on mission to Titan, the mission would spend longer at Titan than Cassini. An orbiter with modest capabilities could, over only a couple of years, conduct radar and near-IR mapping with 3–10 times

better resolution than Cassini and with much more complete coverage. A global topographical dataset, to which Cassini will contribute little, could be generated by an orbiting altimeter and would enable a quantitative study of Titan's meteorology and hydrology, measuring the slopes that drive winds and river flow, and perhaps even detecting the ebb and flow of tides in the polar lakes. Prolonged immersion in the near-Titan environment would allow a full exploration of the variations of composition and structure in the upper atmosphere with latitude, altitude, and orbital position and permit the unraveling of the various contributions to the atmospheric "chemical factory" from magnetospheric electrons, the solar wind, and UV light.

An important enhancing, if not enabling, technology for an orbiter is aerocapture. To brake into orbit around Titan requires a substantial velocity change (ΔV) of some 3–4 km/s, which would entail a formidable propulsion system but can be readily achieved by dipping into the atmosphere upon arrival. This is a natural extension of the aerobraking procedure that is now routinely used at Mars. The large-scale height at Titan makes the navigational accuracy for safe aerocapture easily achievable and keeps deceleration and heat loads down to modest values.

Despite the formidable science return possible from an orbiter, it is *in situ* exploration that is likely to capture the imagination at Titan, much as the Huygens probe did. A lander (Fig. 9) would be a natural way to measure the composition of the surface material, which the Huygens probe showed to be rich in organic matter. Huygens' instrumentation was not designed for detailed surface measurements, yet it is on the surface that the



Figure 9. Artist's impression of a lander sitting amid Titan's dune fields. The sampling arm is equipped with a UV lamp to excite fluorescence in specific organic compounds. A seismometer/magnetometer package lies in the foreground, connected to the lander by a tether, and a meteorology mast is at left. (Artwork by James Garry [www.fastlight.co.uk]; used with permission.)

most complex astrobiological materials are likely—perhaps where cryovolcanic materials have interacted with the organic haze. Measurements might include gas or liquid chromatography and mass spectrometry to look for prebiotic molecules such as pyrimidines (found in DNA) and amino acids (found in proteins), which laboratory experiments show might be made on Titan. Another important task for the onboard chemical laboratory is to assess how enantiomeric the surface organics are, i.e., whether left- and right-handed stereochemicals are produced in equal proportion or (as in living matter on Earth) one stereoisomer predominates. Another goal might be to measure the radioactivity of the material, since cosmic ray interactions with nitrogen in the lower stratosphere will produce (as on Earth) radiocarbon. It may therefore be possible to determine how “fresh” the haze material is.

A simple seismometer could probe Titan’s internal structure and would probably find a substantial excitation of crustal flexing by the changing tidal potential over a 16-day orbit of Titan around Saturn. A small meteorological package could also monitor changes in the winds, which likely also have a substantial tidal component.

Titan’s surface is diverse, and no practical number of landers can catalog all of its different surface types. Large-scale mobility is the obvious solution, and as experience with Mars rovers has shown, engages the public in ways that remote sensing does not. Titan’s environment allows one to consider many possible vehicle types,¹² most notably aerial platforms, that permit mobility over long distances. Suggestions of balloons at Titan date back to 1978, and serious studies have been made since 1983.

A leading idea to tackle this diverse surface is a montgolfière (a hot air balloon). Buoyancy via warmth is a particularly efficient strategy on Titan with its cold, dense atmosphere, and is easily achieved. A radioisotope power source, which is in any case necessary for a long-duration mission so far from the Sun, tends to have a modest conversion efficiency of 5% or so. Thus to produce 100 W of electricity, around 2 kW of heat must be rejected from the source, but this heat can be exploited to warm the balloon gas. By modulating the heat flow, the altitude of the balloon could be controlled, much as is done with ballast and propane burners on terrestrial hot air balloons. And as knowledge of Titan’s wind improves, it may be possible (as on Earth) to exploit different wind speeds and directions at different altitudes to develop some control over where the balloon drifts (Fig. 10).

Over a likely lifetime of a year floating at an altitude of a few kilometers, the balloon would circumnavigate Titan two or more times. Key science on a balloon would be imaging of the surface and lower atmosphere. The “airplane window” perspective afforded by the balloon

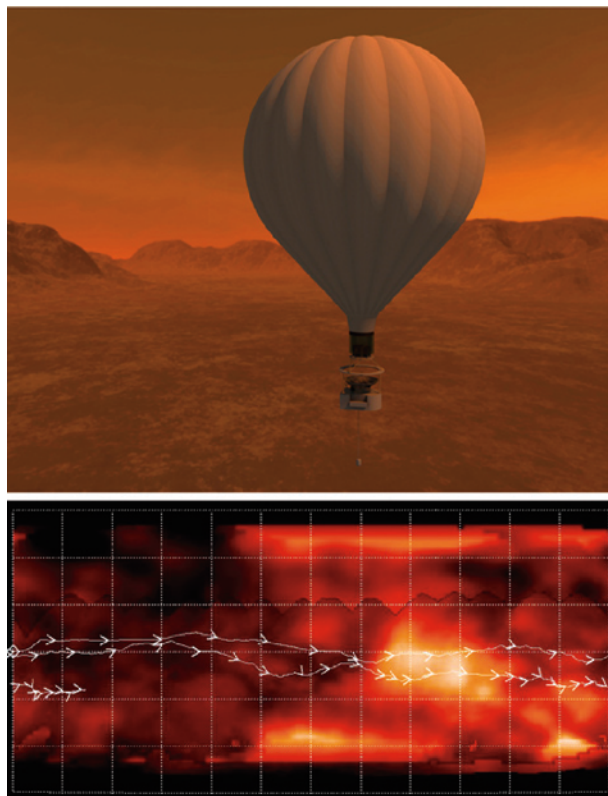


Figure 10. (Top) Artist’s impression of a hot-air balloon at Titan. (Bottom) A simulation of the trajectory of a balloon floating at a fixed 8-km altitude simulated using a general circulation model of Titan’s winds. The plot shows the trajectory over several months overlaid on a low-resolution map of Titan.

would give a high-resolution stereo view of hundreds or thousands of locations. High resolution is not as easy to achieve from an orbiter high above Titan’s hazy atmosphere, as has been done at Mars, and imaging from a balloon fills an important scale gap between orbiter and lander observations. A subsurface radar sounder could measure topography and detect subsurface layers, such as the depth of the sand in the sand seas or the depth of lakes, and perhaps detect any subsurface liquid water ocean. It would, furthermore, be a tremendously exciting platform for education and outreach. Plotting updates on its location on a wall-chart map of Titan could become a daily activity in schools, together with launching balloons.

In fact, a Flagship-class mission might include all of these elements. There are significant technical advantages to such a combination: a lander acting as a fixed point can provide an important navigational reference, and an orbiter can dramatically improve the data volume returned from a balloon and/or lander by acting as a relay. The scientific synergies are no less important; for example, the drifting of the balloon and the changing winds at a fixed lander location provide powerful

independent constraints on the meteorology, while the lander/orbiter combination gives a top-to-bottom picture of the production and deposition of organic material. Such a multipronged approach gives a substantial robustness to what must be a long-duration mission, since each element by itself can provide a significant return. Also, the opportunity for cost-sharing with international partners exists, and through Cassini there is already an established community of European scientists with interests in Titan.

CONCLUSIONS

In addition to the ice geology and space physics that Titan shares with other outer planet satellites, it also shares many other fields. Hydrologists and Aeolian sedimentologists can engage Titan as well as Earth and Mars, and limnology and oceanography are now no longer just Earth sciences. Titan's weather—with its methane downpours in a greenhouse climate and peculiar polar photochemistry—may offer some significant and relevant insights into processes that affect us here on Earth. Titan is also the chemically richest place in the solar system, and thus promises to give important insights into the generation of chemical complexity in the universe, a set of processes that ultimately led to the formation of life.

Titan kept many of its secrets shrouded in haze through the first decades of space exploration but is now beginning to reveal itself as one of the most diverse, complex, and Earth-like places in the solar system.

NASA has recently initiated a study at APL to examine what a Flagship-class mission dedicated to Titan could accomplish. This bizarre orange-colored world has a rosy future.

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