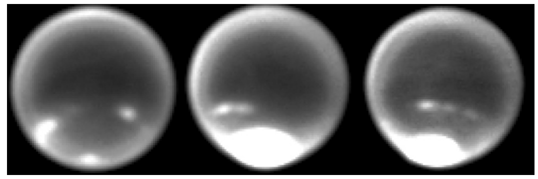
Titan

Titan, 5150 km (3200 mi) in diameter, is Saturn's largest moon and the second largest satellite in the solar system. In the last few years there have been significant advances in our knowledge of Titan's atmosphere and surface, aided by the *Cassini-Huygens* mission of the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA). NASA's *Cassini* Saturn orbiter has flown by Titan every few weeks since October 2004 (three dozen times by mid-2007). In January 2005, *Cassini* released the ESA-built *Huygens* probe, which descended by parachute through Titan's atmosphere and landed on its surface.



(a) (b) (c)

Fig. 1. Images of Titan's clouds taken with the Keck 10-m (400-in.) and Gemini 8-m (320-in.) telescopes using adaptive optics on (*a*) September 2, (*b*) October 2, and (*c*) October 7, 2004. They were taken using a carefully chosen near-infrared filter that blocks light reflected from Titan's surface and allows observations of atmospheric features. The background halo is reflection off of the stratospheric haze. These images show three classes of Titan's clouds: small, long-lived south polar clouds (part *a*); rare, enormous south polar storms (parts *b* and *c*); and sporadic linear clouds at 40° south latitude (all three images). (*Courtesy of H. Roe*)

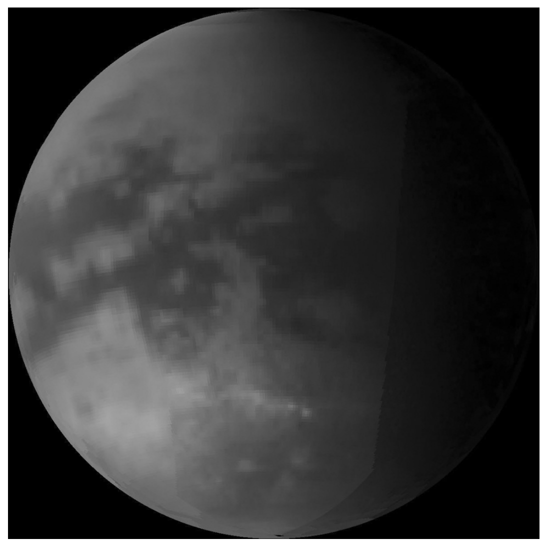


Fig. 2. Image of Titan as seen by *Cassini* during the July 22, 2006 flyby. Most of the visible details are surface features, but the features at lower center are clouds of the midlatitude linear type. (*Courtesy of NASA/JPL/University of Arizona*)

Atmosphere and Methane Weather

Titan stands out in the solar system as the sole moon with a substantial atmosphere. This atmosphere hosts a methane-based meteorology that we have just begun to understand in the past decade. While Titan was discovered in 1655 by Christiaan Huygens, it was not until 1943–1944 that Gerard Kuiper made the definitive discovery of Titan's atmosphere with spectral observations that revealed the signature of gaseous methane. (Earlier observational evidence for the presence of an atmosphere, dating from 1907, is controversial.)

The *Voyager 1* spacecraft flyby of Titan in 1980 returned a wealth of information on Titan's atmosphere, including basic information about atmospheric composition and structure. Because of its design, *Voyager 1* could observe only at shorter wavelengths where Titan's surface and lower atmosphere are obscured by a thick stratospheric haze layer. This circumstance contributed to the idea, held by most astronomers until just a few years ago, that Titan's lower atmosphere was quiescent, with little activity or weather. Observations by Caitlin Griffith in the late 1990s showed otherwise. Unlike *Voyager 1*, Griffith observed at near-infrared wavelengths that are long enough to penetrate through the stratospheric haze. Her observations revealed reflectivity variations in the lower atmosphere on time scales of hours to days. The most likely, and now accepted, explanation was that clouds of methane were forming and dissipating.

Since the time of Galileo the resolution of telescopic observations has been limited by the distortions induced by Earth's atmospheric turbulence. Even at the best sites in the world the best resolution ever achieved is about 0.25 arcsecond, and 1 arcsecond is much more typical at major observatories. Unfortunately, as viewed from Earth, Titan is never more than 0.9 arcseconds across. While Titan can be easily seen with even a modest pair of binoculars (it is only about 20 times fainter than what can be seen with the unaided eye), it is nearly impossible to see any spatial detail of Titan with a traditional ground-based telescope. The launch of the *Hubble Space Telescope*, which sits in orbit above Earth's atmosphere and therefore receives an undistorted view of Titan, and the development of the new technology of adaptive optics, which allows for the real-time correction of the distorting effects of Earth's atmosphere on large Earth-bound telescopes, finally gave astronomers the high spatial resolution necessary to study Titan's surface and lower atmosphere. The combination of this high spatial resolution with the ability to observe in the near-infrared first revealed hints of Titan's clouds in data taken in the mid-to-late 1990s and has been used regularly since 2001 to study in detail how Titan's clouds and weather form, dissipate, and evolve with the changing seasons (**Fig. 1**).

Since its arrival in orbit about Saturn in 2004, the *Cassini* spacecraft has sent back extremely high-resolution images of Titan's clouds during its fly-bys of the satellite (**Fig. 2**). The *Huygens* probe returned spectacular images of Titan's surface and the best-yet information about the composition and structure of Titan's atmosphere.

Structure and composition. The physical structure of Titan's atmosphere resembles that of Earth's

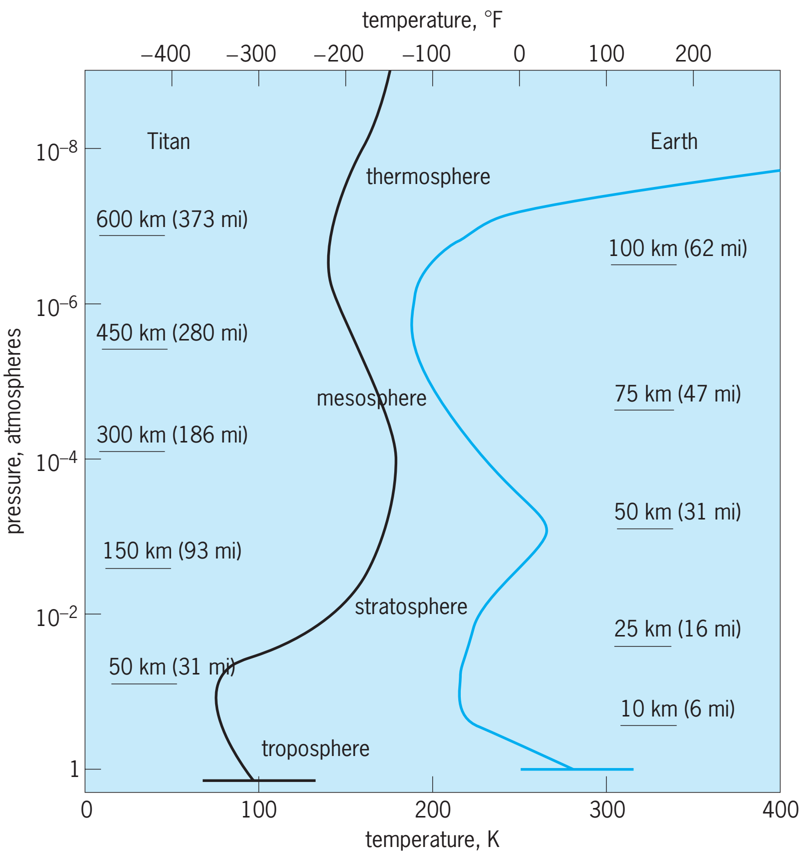


Fig. 3. Physical structures of the atmospheres of Titan and Earth. The vertical axis is logarithmic pressure. The two atmospheres appear similar, except offset in temperature. Also marked are the corresponding altitude levels in each atmosphere, showing Titan's atmosphere to be about six times more extended than Earth's. (*After H. Roe*)

(**Fig. 3**). At first glance the two atmospheres appear quite similar, except offset significantly in temperature. At Titan's surface the pressure is about 1.5 times greater than at Earth's, but the temperature is only 93 K (−180°C or −292°F), about 200 K (200°C or 360°F) colder than is typical on Earth. In both atmospheres the lowest layer is the troposphere, where most of the weather occurs. Because of the low temperature and Titan's low surface gravity (about 14% that on Earth), the density of Titan's atmosphere at the surface is almost five times greater than the atmospheric surface density on Earth. A further consequence of Titan's low surface gravity is that the atmosphere is greatly extended compared to Earth's. In spite of Titan's smaller diameter (5150 km or 3200 mi, compared to Earth's 12,800 km or 7950 mi), the mass of Titan's atmosphere is about twice that of Earth's.

Titan's atmosphere is composed primarily of molecular nitrogen (N_2), as is Earth's. The second most abundant species is methane (CH_4) at 1.4%. As on Earth, methane is a potent greenhouse gas in Titan's atmosphere, raising the surface temperature of Titan more than 10 K (10°C or 18°F) above equilibrium. Methane is broken apart high in Titan's atmosphere by ultraviolet photons, primarily from the Sun, which leads into a complicated network of chemical and photochemical reactions. The end products are numerous heavier hydrocarbons such as ethane (C_2H_6), acetylene (C_2H_2), propane (C_3H_8), and benzene (C_6H_6); nitriles such as hydrogen cyanide (HCN) and dicyanoacetylene (C_2N_2); and a thick stratospheric organic haze layer.

In Earth's lower atmosphere, temperature and pressure conditions lie near the triple point of water, the temperature and pressure at which all three phases of water (solid, liquid, and gas) can coexist in equilibrium. The combination of the driving force of energy deposited by sunlight with the easy phase transitions between the different states of water are what lead to all of the interesting weather phenomena that are familiar on Earth. On Titan conditions in the lower atmosphere are far too cold for water to exist as anything but solid. However, conditions in Titan's atmosphere are near the triple point of methane. In direct analogy with the water-based weather seen on Earth, there is a methane-based meteorology in Titan's lower atmosphere.

Source of methane. The loss of methane to photochemistry at the top of Titan's atmosphere is significant. Without some replenishing source, the methane in Titan's atmosphere would be depleted within a few tens of millions of years (much less than the 4.5×10^9-year age of the solar system). Comet impacts are far too infrequent to supply enough methane to explain the present-day abundance. The source of Titan's atmospheric methane must be the interior of Titan. Images and radar scans from the *Cassini* spacecraft show surface features that appear to be the remains of cryovolcanoes, where the "lava" would be a water-ammonia mixture with dissolved methane gas. During eruptions these cryovolcanoes should release significant quantities of methane into Titan's atmosphere.

A further problem is to explain where the methane inside Titan came from originally. If the methane is primordial and simply condensed with the rest of Titan out of the proto-Saturnian nebula (which certainly had plenty of methane gas), then the noble gases xenon and krypton should also be present in Titan's atmosphere. The *Huygens* probe found no trace of these two gases in the atmosphere, suggesting that the methane must have formed inside Titan after the satellite condensed. Earlier in Titan's history, there was a subsurface liquid ocean of water and ammonia in contact with Titan's inner solid rocky core. [This ocean may still exist, but 100 km (60 mi) under Titan's surface or even deeper.] The most likely place for producing Titan's methane was at this ocean-rock interface where a reaction between water and rock, known as serpentinization, would have occurred. Serpentinization creates hydrogen gas, which in turn reacts with carbon to form methane.

Seasons and time scales. Titan is tidally locked to Saturn and orbits once every 16 days. Thus, Titan's rotation period, and its "day," are 16 days long as well. Saturn takes 29.5 years to orbit the Sun and thus Titan, which is itself in orbit around Saturn, has a 29.5-year-long annual seasonal cycle. Seasons on Earth arise because Earth's rotation axis (the line running through the North and South poles) is not perpendicular to the plane of Earth's orbit about the

Sun. Titan's rotation axis is similarly tilted over (26.4°, compared with Earth's 23.5° tilt) with respect to its motion about the Sun. Thus, Titan's year is 29.5 times longer than Earth's. Titan has seasons similar to those on Earth, including long periods of total darkness and continuous daylight in the polar regions. The northern winter solstice occurred on Titan in October 2002 and the northern spring equinox will be in August 2009.

Because Earth's orbit around the Sun is nearly circular, its distance to the Sun varies only a small amount and Earth's seasons arise almost entirely due to the tilt of its rotation axis. Similarly, the dominant reason behind Titan's seasons is its rotation axis tilt. However, on Titan a second effect comes into play. Saturn's orbit about the Sun (and therefore Titan's) is somewhat eccentric. The distance between Titan and the Sun varies between 9.02 and 10.05 astronomical units (the mean distance between the Sun and Earth). An important implication of this is that the flux of sunlight hitting Titan varies with the season. When Titan is closest to the Sun (roughly in Northern winter) the Sun appears 1.23% as bright as what is seen from Earth, while when Titan is furthest from the Sun this drops to 0.99%. The combined effect of Titan's tilt and Saturn's eccentricity is that the South Pole at southern summer solstice receives 53% more sunlight per square meter than the annual average for a square meter on the equator. Because Titan's northern summer coincides with being further from the Sun, the North Pole at northern summer solstice receives only 35% more sunlight than the equatorial mean.

Clouds and circulation. Titan's tropospheric methane clouds that have been observed thus far divide into three general categories: smaller long-lived south polar clouds, giant south polar storms, and sporadic linear midlatitude clouds (Fig. 1). A fourth category of cloud composed of ethane particles has also been identified.

The smaller south polar clouds were present almost continuously from their discovery in 2001 until 2005 and have been sighted only occasionally since then. This corresponds with the period of late southern spring and early southern summer on Titan. The current understanding of these clouds is that they are a seasonal phenomenon. During this period the south polar region is in constant sunlight and experiences the maximum mean daily solar heating of any region on Titan's surface at any time of year. (That the pole receives more heating than the equator at the summer solstice may be counterintuitive, but is the result of the pole being in continuous sunlight while a point on the equator receives sunlight for only about half of the diurnal cycle.) Meanwhile the north polar region is in constant darkness. This north-south imbalance in heating is thought to drive a single pole-to-pole circulation cell, with an upwelling zone at the South Pole and downwelling at the North Pole. This upwelling zone leads to the formation of localized convective clouds in the south polar region, much as the equatorial upwelling zone on Earth of the Hadley cells leads to clouds.

Occasionally, during this same time period, the small south polar clouds erupted into enormous storms covering much of the south polar region. The triggering mechanism for these storms is unknown. After several of these storms the smaller south polar clouds disappeared or were significantly reduced for several months. These storms probably result in significant rainfall to the surface. *Cassini* images show several possible methane lakes in the south polar region, which fits with this scenario.

In 2003 observations from the 10-m (400-in.) Keck and 8-m (320-in.) Gemini telescopes on the island of Hawaii revealed a third class of methane clouds, which always appear near 40°S latitude, are often long and streaky, and are most often seen over the region around 350°W longitude. (Titan is tidally locked to Saturn, as noted above, and 0° longitude is defined as the sub-Saturnian longitude.) The strong clustering of these clouds over a small region on Titan's surface strongly suggests some process related to the surface is driving their formation. One possible explanation is that these clouds are being formed by release of methane from a region of geologic activity, possibly active cryovolcanism. Curiously, *Cassini* recently discovered the largest, highest mountain range yet seen on Titan [32 km (20 mi) wide by 145 km (90 mi) long by 1.6 km (1 mi) high] directly under this region of cloud activity. An additional factor driving the formation of these clouds may be the breakdown of the seasonal pole-to-pole circulation cell.

As Titan moves further into northern winter, *Cassini* has discovered a thin cloud made of ethane particles in the upper tropopause covering much of the north polar region. The formation of this cloud is likely due to the seasonal downwelling in this region leading to supersaturated concentrations of ethane. Henry Roe

Surface

Although Titan's surface remained largely hidden for 350 years after the satellite's discovery, it is now known to be the most Earth-like landscape in the solar system. Although *Voyager 1* flew close past Titan in 1980, its cameras barely managed to penetrate the thick haze in Titan's dense atmosphere, and scientists could only guess that it might be like other icy satellites underneath. However, the presence of large amounts of methane in Titan's atmosphere, and the surface temperature of 93 K (−180°C or −292°F, which is, as noted above, near the triple point of methane, much as Earth's temperatures are close to the triple point of water) led to speculation that Titan's surface might be covered in a deep ocean of that liquid. The first revelations about Titan's surface came in the early 1990s. First, radar echoes (using large radio telescopes on Earth) showed a somewhat reflective surface, more so than a liquid methane ocean would be. Soon thereafter, telescopic measurements showed selected "windows" of wavelengths that could penetrate the haze and detect the surface, which had both bright and dark areas of infrared reflectivity.

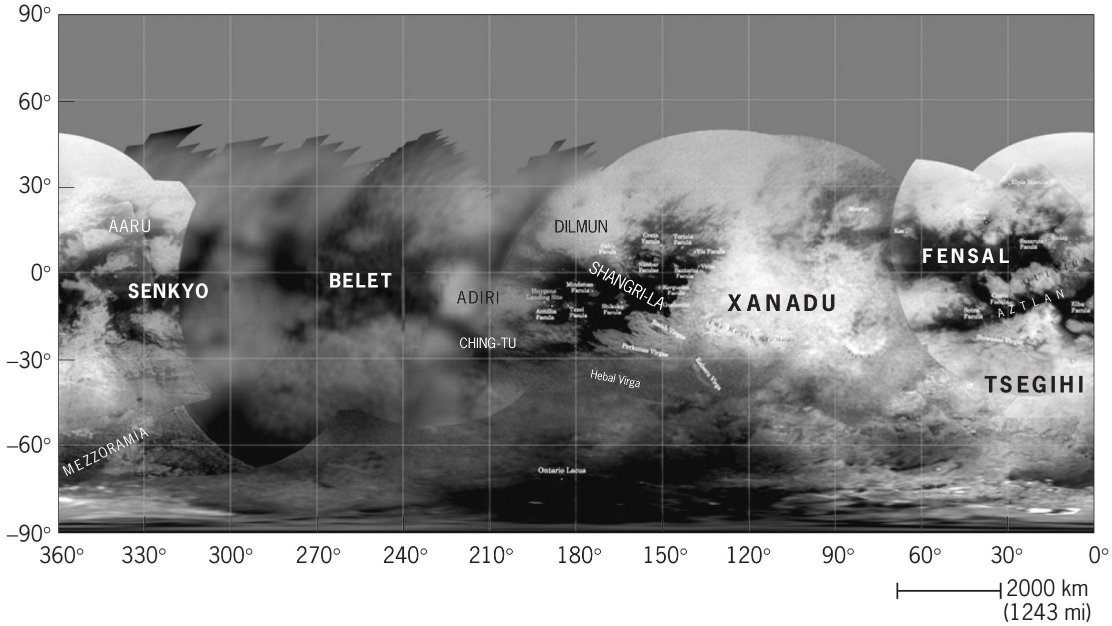


Fig. 4. Map of Titan, with names indicated for major regions, compiled in October 2006 from images of the *Cassini* Imaging Science System (ISS) at a wavelength of 940 nm. Some areas are mapped at rather higher resolution than others, and latitudes 50°N and higher are insufficiently illuminated in the present season to map. (*Courtesy of NASA/JPL/Ciclops*)

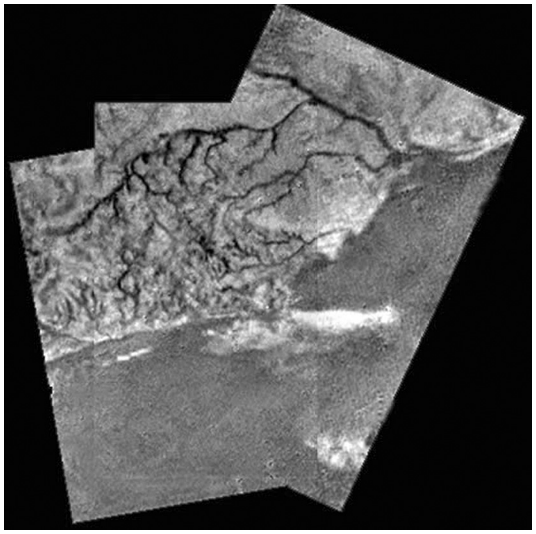
These were disk-integrated measurements; that is, they provided no surface resolution and effectively summed the radiation from the satellite's visible disk. They were followed in 1994 by images with the *Hubble Space Telescope* that allowed the first crude maps to be developed, notably showing a large bright region (named Xanadu) on Titan's leading face. (As noted above, Titan rotates synchronously, like Earth's Moon, always showing the same face to its parent planet.) Improving capabilities of large ground-based telescopes with adaptive optics systems allowed better maps to be made prior to *Cassini's* arrival, but even these telescopes show about as much detail on Titan as observers see on our Moon with the unaided eye, and so ideas about what the bright and dark regions might be remained speculative.

A planet's surface reflects the processes operating to shape it. Calculations of the possible rates of erosive processes, tectonics, cryovolcanism (that is, ice volcanism), and impact cratering suggested that unlike, for example, Io, which is dominated by volcanism, and smaller satellites dominated by impact craters, Titan should have a complex Earth-like balance of all of these processes. Measurements from the *Cassini* orbiter as it has flown past Titan, coupled with in situ measurements from the *Huygens* probe, have revealed most of what is known about Titan. This torrent of data has borne out the prediction: Titan's landscape is incredibly diverse and Titan appears to be the most Earth-like body in the solar system, despite being made of different material (ice and organics instead of rock) and shaped by a different fluid (liquid methane rather than water).

Cassini results: A young surface. *Cassini's* cameras, sensitive to near-infrared light and able to make maps with a resolution of a few kilometers (1 km = 0.6 mi), show Titan's surface to be varied at all scales (**Fig. 4**). The strongest bright-dark contrasts appear so far at the equator, with more muted features at midlatitudes. So far there are only distant views of the polar regions. (Because *Cassini's* arrival at Saturn in 2004 occurred during late southern summer, the high northern latitudes are in winter darkness until the equinox in 2009.) The first near-infrared images and the first *Cassini* radar observations (which are able to penetrate the haze and map the surface with resolutions down to 350 m or 1150 ft) showed a striking lack of impact features. Since impact features are continuously generated throughout the solar system, hundreds of craters should have been seen if the surface were old. Thus the lack of craters suggested that, like Earth, Titan's surface is young, being continuously shaped by processes such as erosion or cryovolcanism; analysis suggests an effective age for the surface of about 500 million years, rather similar to that for Venus or the Earth.

Spectral mapping by *Cassini's* Visual and Infrared Mapping Spectrometer (VIMS) has found several distinct terrain compositions. 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 what chemical composition is responsible for these different units. A few patches on Titan are particularly bright at 5 μm wavelength (spectral identification of materials from orbit is complicated on Titan by the thick atmosphere), suggesting a distinct composition, perhaps related to cryovolcanism. The possible interaction, albeit short-lived, of cryolava (that is, water) with the organic haze material on Titan's surface is of particular interest in studies of the origin of life, as laboratory studies show that such reactions can produce prebiotic molecules such as amino acids and pyrimidines, which living things on Earth use in proteins and in DNA.

Huygens probe: Titan up close. The descent of the *Huygens* probe in January 2005 gave close-up images of an area about 30 km (19 mi) across just south of Titan's equator. A surprising and immediate result was that this area had been shaped by fluvial processes—rain and rivers (**Fig. 5**). Not only were some bright highlands and dark plains dissected with networks of steep-sided dark channels, but the images from knee-height by the probe after its impact (although not designed explicitly to survive impact, the probe's landing was quite soft) showed a broadly flat plain with a fine-grained dark substrate on which sat rounded bright cobbles between 5 and 15 cm (2 and 6 in.) in diameter; in other words, *Huygens* had landed in a stream bed. The rounding of the cobbles and the absence of small pebbles suggested the area had been last shaped by a rapid flow of liquid, most probably the result of a methane thunderstorm.



(a)

(b)

Fig. 5. Images obtained by the *Huygens* probe. (*a*) Descent image, about 7 km (4.3 mi) across. (*b*) Side-looking image acquired after impact, showing rounded cobbles between about 5 and 15 cm (2 and 6 in.) across. (*NASA/JPL/ESA/University of Arizona*)

The impact force on the probe suggested the surface texture was like wet sand (except here the "sand" means sand-sized particles of organic materials and ices). The impact also embedded the heated inlet of *Huygens's* gas analyzer into the ground, and this fortuitous surface sampling revealed methane and ethane, showing that the ground was damp with these liquids. Tracking of the probe just prior to impact showed that the near-surface winds were gentle, less than about 0.5 m/s (1 mi/h).

Dunes and lakes. A surprising finding in radar images in late 2005 was that large dark areas near Titan's equator were not (as was once thought) liquid, but rather are giant sand seas. These sand seas are filled with massive linear dunes, tens of kilometers long, a couple of kilometers apart, and up to 150 m (500 ft) 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 winds 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 may be 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 that heats and cools on a daily time scale. On slowly rotating Titan with its massive atmosphere so far from the Sun, the response to changing sunlight is heavily damped, and the comparatively large tidal effects may dominate.

In summer 2006, the first radar images at high northern latitudes showed dozens of lakes (**Fig. 6**). Some of these were simply round, while others had the irregular appearance of flooded river valleys. The lakes were the darkest things seen to radar on Titan's surface, consistent with a liquid hydrocarbon composition. It remains to be seen whether the lakes are concentrated at high latitudes because of lower surface temperatures there, or because liquid ethane is preferentially deposited near the poles, or because the poles are lower in elevation.

Exploring a diverse, dynamic landscape. River channels, running for several hundred kilometers, have been observed in radar and near-infrared data. Some have the characteristics of rough desert washes, formed by rare but heavy downpours. [Models of methane thunderstorms on Titan show they can deposit several tens of centimeters (1 cm = 0.4 in.) of liquid in only a few hours, much like the heaviest

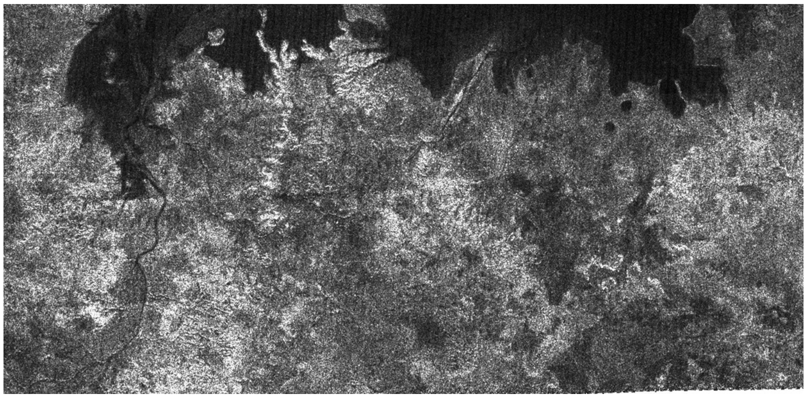


Fig. 6. ***Cassini*** **radar image (300 × 140 km or 186 × 87 mi) showing a large dark lake of liquid methane and ethane at top. A meandering river drains into the left end of the lake. (*NASA/JPL*)**

downpours on Earth.] Some others are more heavily incised valleys, and yet others are shallow and meandering, suggesting they deposit fine-grained sediment.

Although many areas of Titan appear quite flat (as indicated by radar altimetry) with elevation changes of only a few tens of meters (1 m = 3.3 ft) over hundreds of kilometers, there are steep mountains over a kilometer high in patches or chains all over Titan. The Xanadu region is particularly rugged. How the mountains form is not yet known.

The *Cassini* mission is still ongoing, and new data come in regularly; in mid-2007, only about 20% of the surface had been mapped by radar. Expected forthcoming results include more infrared and radar mapping, perhaps to show surface changes, as well as gravity measurements which will probe Titan's internal structure. (As noted above, Titan, like Europa, may have an internal water ocean beneath its ice crust.) Plans are already under way for a future mission to explore Titan, perhaps with a balloon and long-lived lander as well as an orbiter, able to make more complete and detailed maps, to measure the composition of Titan's surface, and to observe wind patterns and seismic activity.

For background information *see* ADAPTIVE OPTICS; ATMOSPHERE; ATMOSPHERIC GENERAL CIRCULATION; DUNE; GREENHOUSE EFFECT; HUBBLE SPACE TELESCOPE; METHANE; PREBIOTIC ORGANIC SYNTHESIS; RADAR ASTRONOMY; SATELLITE (ASTRONOMY); SATURN; SEASONS; SPACE PROBE; TRIPLE POINT in the McGraw-Hill Encyclopedia of Science & Technology.

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