Rivers, Lakes, Dunes, and Rain: Crustal Processes in Titan’s Methane Cycle

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Abstract

Titan exhibits ample surface and crustal processes including lakes and seas, fluvial erosive features, possibly subsurface reservoirs of liquid, and rainfall. Together these constitute strong evidence for a multicomposition hydrological system, composed mostly of methane and ethane as well as trace amounts of other alkanes. Estimates of the volume of liquid methane required in streams and rainfall to produce erosional features suggest that these could be relatively recent phenomena, perhaps periodically renewed as the overall climate cycles between dry and wet periods. The end state of the long-term chemical processing of methane in the upper atmosphere is expressed on the surface in the form of deposits of solid organics organized into dunes, and lighter hydrocarbons such as ethane (in the lakes), acetylene, and other hydrocarbons and nitriles. The long-term evolution of the methane cycle may have involved episodic resupply of methane to the surface or gradual depletion of a larger surface reservoir of methane, but in either case, removal of large amounts of ethane from the surface remains an unresolved problem.
1. INTRODUCTION: THE HISTORICAL SETTING FOR A METHANE CYCLE ON TITAN

Titan is Saturn’s largest natural satellite and the second-largest moon in the solar system. Virtually identical in mass and size to Jupiter’s moon Ganymede, Titan’s bulk composition is inferred from its density and comparison with Ganymede to consist of about 60% rock, 40% ice, with the latter forming a mantle and crust overlying the rock (Sohl et al. 1995). Discovered in 1655 by the Dutch astronomer Christian Huygens, little was known about this moon until the turn of the twentieth century, when hints of an atmosphere appeared in telescopic studies (Comas Solá 1909). Methane was seen spectroscopically in the 1940s (Kuiper 1944) confirming that at least a thin atmosphere existed; subsequently, a few other hydrocarbons including ethane and acetylene were detected in the atmosphere (Danielson et al. 1973) that were understood to be the product of chemistry on methane energized by UV light from the Sun (Strobel 1974). Little else could be determined beyond that Titan’s visible surface was an optically thick layer of haze standing an indeterminate distance above Titan’s surface.

Whether Titan’s atmosphere was pure methane and, hence, thin (dictated by the vapor pressure and the low temperatures at Titan’s 9.5-AU distance from the Sun), or contained a spectroscopically inert gas such as nitrogen and could be much denser (Hunten 1978), was resolved finally through remote sensing measurements by Voyager 1 as it flew by Titan in 1980. Nitrogen was indeed found to be the principal gas in the atmosphere, comprising over 90%, with methane largely constituting the rest, supporting a surface pressure of 1.4 bars at 94 K (−179°C). The temperature was measured by Voyager 1 to decline toward a minimum value of 72 K at about 50 km, and then increase again (Lindal et al. 1983). Hydrocarbons and nitriles in the stratosphere confirmed the idea that methane—along with nitrogen—was being converted into higher hydrocarbons and nitriles, with escape of hydrogen making the photochemical destruction of methane irreversible.

Because models showed the process to be limited only by the solar UV flux at energies high enough to break the carbon-hydrogen bonds within the methane, the lifetime of Titan’s atmospheric methane was straightforwardly calculated to be a few percent of the age of the solar system (Yung et al. 1984). This, in turn, implied that methane must be supplied externally to the atmosphere, from space, from Titan’s surface, or from its interior. The first of these sources can be eliminated on the basis of reasonable estimates of the current flux of methane-bearing icy impactors in the outer solar system, without eliminating this as a possible initial source of methane early in the solar system’s history (Zahnle et al. 1992).

The second source, a surface reservoir of methane two orders of magnitude more massive than that in the atmosphere, was an elegant solution that allowed incorporation of methane’s primary photochemical product, ethane, as a dissolved component of the surface reservoir (Flasar 1983), because both are liquid at the conditions found in the Voyager data at Titan’s surface. The resulting model was of a deep surface ocean of methane and ethane, hundreds of meters in thickness, residing over the entire surface of Titan and existing as the source and the sink of methane photolysis (Lunine et al. 1983).

Although the photochemical haze renders the atmosphere largely opaque to imaging in the wavelength range of the human eye, charge-coupled devices (CCDs) operating near 1-micron wavelength on the Hubble Space Telescope (Smith et al. 1996) and detectors at 2 microns on large ground-based telescopes with adaptive optics (Roe et al. 2002) indicated a variegated surface with bright and dark regions, while radar data suggested a relatively reflective surface (Muhleman et al. 1990). Although higher signal-to-noise radar observations suggested the presence of specular reflection points on the surface (Campbell et al. 2003), the general consensus regarding the ground-based data was that it militated against the presence of a global surface ocean of methane and ethane.
A variant of this model, that much of the methane and ethane might be trapped in a porous or fractured crust (Stevenson 1992), was still in play. Spectroscopy of the surface at 5 microns from Earth-based telescopes hinted at a global mixture of water ice with a second, dark component (Lellouch et al. 2004), but again no evidence was found of vast regions of liquid methane and ethane.

Once it arrived in Saturn orbit in mid-2004, Cassini orbiter imaging and VIMS data showed no specular reflection at 1-micron wavelength (West et al. 2005), indicating that surface liquid was not present. Spectroscopic VIMS data (McCord et al. 2006) showed large areas of nonliquid materials, and radar images revealed that the vast equatorial dark areas were, in fact, seas of “sand”—likely of organic or organic-coated water-ice composition (Lorenz et al. 2006a, Radebaugh et al. 2008). The descent probe it carried—Huygens—landed in January 2005 on a cobble-strewn plain (Tomasko et al. 2005), where it measured a methane humidity of 45% (Niemann et al. 2005, Fulchignoni et al. 2005).

Although it was evident from Cassini-Huygens data that a global methane-ethane ocean did not exist and that the remaining possible reservoirs were subsurface crustal or subcrustal, it also became clear that methane was not restricted to a gaseous component of the atmosphere at present or in the recent past. Huygens probe descent images of dendritic and possibly ground-sapping features near the landing site (Tomasko et al. 2005), terrains cut by fluvial features at a variety of latitudes seen in Cassini radar data (Lunine et al. 2008), northern hemisphere radar-dark features that have the morphology and radiometric response of hydrocarbon liquid basins (Stofan et al. 2007), convective cloud structures at the south pole tied to very dark spots observed during that hemisphere’s early spring (Porco et al. 2005), a methane cloud base at 8-km altitude, and the detection of methane and ethane vaporizing (Niemann et al. 2005) from a relatively high thermal-conductivity surface (Lorenz et al. 2006b) are all consistent with an environment in which methane is present in both gaseous and liquid phases acting as an erosional agent on a water-ice crust. The progressive decline of surface temperature from equator to pole as determined by radio science and Cassini infrared observations (Flasar et al. 2007) [RSS: Radio science subsystem (Cassini), CIRS: Cassini Infrared Radiometer and Spectrometer] is also consistent with the bulk of the condensed phase methane present in the polar regions, but possibly moving seasonally from pole to pole (Stevenson & Potter 1986, Mitri et al. 2007). Finally, observations of thermal emission at radio wavelengths hint at a porous crust where large amounts of methane and ethane might be stored.

In this review we focus on the surface and subsurface but crustal manifestations of the methane hydrological cycle. The authors eschew alternative nomenclatures to “methane hydrological cycle” such as “alkanologic cycle,” “methanological cycle,” etc., because “hydro” is widely used to describe fluid behavior in general (for example, the term hydrodynamics is applied to nonaqueous fluids) and the physics and chemistry is in many respects analogous to the hydrologic cycle familiar to Earth.

A striking difference between the water hydrological cycle on Earth and the methane cycle on Titan is that, in the latter case, two liquids are involved: methane and its photochemical product ethane. The two form nearly ideal solutions with each other under Titan conditions, obeying Raoult’s law (Prausnitz 1969). The difference between the two is that the vapor pressure of ethane is more than three orders of magnitude lower than that of methane at the surface temperature of 94 K. This means that, while ethane mechanically behaves as a fluid identically with methane, and is fully mixed with it, it does not participate in the gaseous phase of the hydrological cycle through evaporation and condensation on the same timescales and with the same mass flux as methane. The full implications for the behavior of the surface liquids and their atmospheric transport have yet to be explored.

Additionally, unlike the Earth—where atmospheric nitrogen hardly dissolves in liquid water—on Titan, the atmospheric nitrogen is soluble in the hydrocarbon liquids such that in pure methane under 1.4 bars of gaseous nitrogen 20% of the solution is N₂, but it is much less for an
ethane-methane mixture (Lunine et al. 1983). Given the depth and extent of the lakes as discussed below, this is unlikely to result in a large change of the surface pressure at present.

2. FLUVIAL FEATURES

Once the Voyager data had suggested the possibility of methane liquid on Titan’s surface, it was only a small intellectual step to postulate that methane might participate in an active hydrological cycle. However, especially because Voyager data indicated only modest humidity in the atmosphere, and there were no robust indications of clouds, this was purely speculative.

Rainfall was suggested as a cleansing mechanism that might render elevated terrain optically brighter than lowlands (Smith et al. 1996, Griffith et al. 1991), especially because elevated terrain might receive more rainfall (Lorenz 1993). Noting that methane raindrops on Titan would fall slowly (and might not reach the ground at all, evaporating in the unsaturated lower atmosphere; Lorenz 1993) Lorenz & Lunine (1996) initially argued that pluvial erosion would be weak on Titan, especially because the meager sunlight does allow a vigorous hydrological cycle, amounting to only ~1 cm of methane rainfall per earth year. However, it was subsequently noted (Lorenz 2000) that even though desert regions on Earth receive little rainfall on average, rain and rivers can substantially erode the landscape if that rainfall is expressed in rare but violent storms. That revised paradigm appears to have been borne out. Furthermore, more sophisticated microphysical modeling by Graves et al. (2008) shows that raindrops are sufficiently out of temperature equilibrium during their descent (largely due to evaporative cooling not taken into account in Lorenz 1993) that they may reach the ground before evaporating.

Griffith et al. (1998) noted that the Titan atmosphere holds a massive amount of precipitable methane, and indeed the first simulations of Titan rainstorms (Tokano et al. 2001; actually few of the precipitation results are reported, because that particular study was devoted to assessment of possible lightning) showed that tens of centimeters of rain could fall within a few hours, a result confirmed by subsequent modeling (e.g., Hueso & Sanchez-Lavega 2006; see also Barth & Rafkin 2007) Awal & Lunine (1994) calculated updrafts in convective plumes and found that while such plumes were little less energetic than those on Earth, the overall flux limitation due to the weak insolation meant that such convection (and by implication, rainfall) had to be rare.

The first robust detection of tropospheric clouds on Titan was reported by Griffith et al. (1998), who spectroscopically inferred the presence of a cloud covering about 10% of Titan’s disk at an altitude of 10–20 km, a range where methane condensation might be expected to occur. This cloud (in data acquired in October 1995) was probably the same one seen in images acquired by the Hubble Space Telescope only a few days later (Lorenz & Mitton 2002, Lorenz 2008), which indeed occupied about 10% of the disk and could be localized to near the prime meridian at about 40° N latitude. Subsequently, further spectroscopic analysis (Griffith et al. 2000) indicated some smaller cloud patches (<1% disk coverage) but varying on timescales of the order of 1 h, suggesting that these were indeed convecting and probably precipitating clouds.

The improving capability of groundbased adaptive optics (AO) telescopes, and more importantly, the increasing amount of observing time devoted to monitoring Titan, yielded dividends in 1999–2001, with the direct observation of large cloud systems brewing over the south (summer) pole (e.g., Brown et al. 2002, Roe et al. 2002, Schaller et al. 2006a).

Even small (14-inch) telescopes are able to detect the presence of clouds on Titan, and such monitoring has been used to cue observations with larger facilities, such as the Keck AO. These monitoring efforts (e.g., Schaller et al. 2006b) found that the abundant convective cloud activity seen near the south pole since 2001 abruptly disappeared soon after Cassini’s arrival. Although these clouds were seen by Cassini in July and October 2004 (Porco et al. 2005), sporadic clouds at...
southern midlatitudes have been observed on many occasions (e.g., Roe et al. 2005), and the cloud-top heights were measured to be rising at a few meters per second by VIMS (Griffith et al. 2005).

Hints of possibly fluvial channels were seen in both the first optical (Porco et al. 2005) and radar (Elachi et al. 2005) images of Titan’s surface. However, the pictures from the Huygens probe (Tomasko et al. 2005) left no doubt whatsoever that fluvial action had modified Titan’s surface (Figure 1). Not only were dendritic channels draining from the bright highlands into the darker plains on which Huygens landed very obvious and reminiscent of terrestrial river networks, but the images fortuitously returned by the probe after landing showed a surface littered with cobbles, rounded by tumbling in vigorous streamflow. Although no liquid was observed directly at the landing site, the thermal properties of the ground in contact with a heated inlet of the Huygens gas chromatograph and mass spectrometer (GCMS) (Lorenz et al. 2006b) and the evolution of methane postimpact (Niemann et al. 2005) indicate that the ground was damp with methane-bearing liquid.

Radar images acquired after Huygens have shown (Elachi et al. 2006, Lorenz et al. 2008a) a variety of fluvial channels at rather larger scales than those seen by Huygens. One network (now named Elivagar Flumina) is a set of anabranching and braided radar-bright channels, apparently not deeply incised, just to the east of the Menrva impact structure (Figure 2). Such branching, shallow channels are characteristic of violent flows associated with heavy rains (i.e., flash floods). Some other channels are more conventional branched networks, with the largest so far seen in Xanadu and extending over more than 500 km.

Although it is not known whether the dark channels seen by Huygens are dark because they have dark material in their floors, or the steep-sided walls (Soderblom et al. 2007a) of the channels are enough to cause darkening by topographic shading alone, on the larger scale a number of channels seen in radar can be picked out in ISS images and are optically dark, suggesting dark sediment on their floors. Correlations with VIMS data (e.g., Barnes et al. 2007, Jaumann et al. 2008, Soderblom et al. 2007b) show that the margins of bright units, and fluvial channels in

**Figure 1**

(Left) Mosaic of images of the surface of Titan taken by the Huygens probe DISR from several different altitudes below 10 km and projected to a common altitude of 6.5 km, showing a network of dark dendritic channels. The elongated bright “island” to the center-right of the mosaic is about 2 km in length. (Right) DISR image of the surface. The largest rocks in the image are about 15 cm across. Images courtesy of NASA/ESA/University of Arizona.
Figure 2

(a) The center left of this Cassini radar image form the T3 flyby is dominated by the impact crater Menrva, some 440 km in diameter. To the west (left) of the crater is a limited set of fluvial channels, whereas to the east is the more extensive fluvial network Elivagar Flumina. (b) Sketch of the same region showing Elivagar Flumina in black. From Lorenz et al. (2008a).

In particular, appear associated with the so-called blue spectral unit, which may have a higher water ice content than other surface materials.

Mapping coverage is only now becoming extensive enough to permit meaningful characterization of the geographical distribution of channels. One pattern noted in Lorenz et al. (2008a) is that many channels have a generally poleward trend, perhaps suggesting a systematic variation of terrain height with latitude. Terrain heights are generally poorly known on Titan, because altimeter coverage and radar stereo coverage are limited (Kirk et al. 2008).

For the most part, the channels observed to date by Cassini (and at a smaller scale by Huygens) are dendritic with acute branching angles, suggesting an origin in rainfall. However, one set of channels in the Huygens images appears to link a straight channel with several near-circular patches that may indicate another origin, perhaps as spring-fed streams. A few similar features are seen in radar imagery in the north-polar regions, but as yet no detailed studies of these features have been made.

Rain Rates and Erosion

Modeling studies by Burr et al. (2006), substituting Titan environmental parameters into conventional terrestrial sediment transport relations, show that the sediment movement indicated by the radar properties of the surface and by the Huygens images can be effected by the flow rates associated with models of methane rainstorms that are consistent with cloud observations to date. Perron et al. (2006) consider the Huygens landing site streams in particular (with a drainage area of about
and find that indeed rainfall of a few centimeters per hour would be enough to mobilize the cobbles seen (and more particularly, the smaller pebbles NOT seen) at the landing site.

However, a separate problem is how the sediment is generated in the first place (i.e., how a flowing stream cuts into bedrock). Even on Earth, the different roles of solution, cavitation erosion, and erosion by the abrasive action of bedload in river incision can vary widely (e.g., Sklar & Dietrich 2001). Collins (2005) showed in some simple experiments that water ice at cryogenic temperatures has a percussive strength comparable with that of soft terrestrial rocks, but more data on the geotechnical properties of Titan surface materials at the relevant conditions are needed.

In sum, it is clear that rainstorms have occurred in Titan’s past and left their scars on the landscape. The dampness of the Huygens landing site suggests that such fluvial activity is geologically recent, even at the dry low latitudes. Cloud systems have been observed on Titan, predominantly at the summer pole, but a constraining record extends only for a Titan season, and it is likely that low latitude weather may occur preferentially near equinox. That season is about to be observed.

Finally, whereas some observed features can be explained with models of present-day rainstorm precipitation, it is not clear that all can. There is evidence at the Huygens site of larger-scale features, and radar imagery is revealing progressively larger areas of heavily dissected terrain (badlands). Cloud models by Hueso & Sanchez-Lavega (2006) indicate that a relative humidity of 80% is required for spontaneous development of convectively driven methane rainstorms on Titan, about twice the present-day relative humidity. If these models are correct, they imply that the features seen at the Huygens site were formed in a substantially wetter climate than that observed today (Griffith et al. 2008). The source of the additional methane—if it still exists—remains unidentified.

3. LACUSTRINE FEATURES

Beginning in July 2006, a series of flybys of the high northern latitudes of Titan began in which the Cassini Orbiter radar imaged a variety of very dark features that have been interpreted to be liquid-filled basins, or lakes (Stofan et al. 2007). The features range in size from less than 10 km² to at least 100,000 km². They are confined to the region poleward of 55° N, although the largest sea may extend equatorward based on imaging (ISS) data from Cassini, which is heavily affected by haze scattering. To date some 655 such features have been identified and mapped over seven Titan flybys (Hayes et al. 2008) (Figure 3).

Mapping by Hayes et al. (2008) indicates that above 65° N the dark lakes occupy 15% of the imaged surface (which to date is about one half of the total surface area of that part of Titan). Bright lakes—features that appear similar to the radar-dark lakes but have little or no brightness contrast with their surroundings—replace the dark lakes equatorward of 70° N. An intermediate class of granular lakes has a latitudinal distribution similar to that of the bright lakes. Neither is seen above 77° N, where the dark lakes predominate. Size selection does not appear to be present in the dark lakes; both very large and very small examples exist.

The hypothesis that the dark lakes are filled with liquid is advanced (Stofan et al. 2007) based on several arguments. First, the dark lakes are in many—but not all places—extremely dark, with reflectivity values below the noise level of the radar system. Because the radar never operates in imaging mode at 0°—nadir—incidence, the lack of return indicates reflection off a surface smooth on the scales of the 2.16-cm wavelength of the radar system. A calm liquid surface or smooth solid surface would produce this result. The Huygens landing site was littered with 1–10-cm-scale pebbles and appeared bright to the radar system (Lunine et al. 2008); features as dark as the lakes do not appear at equatorial or midlatitudes. Evidently, then, the physical surface causing the coherent reflection away from the radar antenna is typical only of the high latitudes and not
simply of plains areas devoid of pebbles. Thus, either liquid or a recently frozen, smooth surface is required.

Second, radiometry measuring the natural thermal emission at the 2.16-cm wavelength of the Cassini radar indicates that the dark lakes emit more thermal energy than the surroundings, consistent with hydrocarbons and inconsistent with a smooth surface of water ice or ammonia ice (Paganelli et al. 2008), assuming the exposed surrounding crustal material is water ice. Third, the morphology of the boundaries between the largest of the dark lakes and the surroundings resembles a terrain flooded by liquid, with the dark material appearing to flood valleys between hilly terrain and in some cases occupying networks of channels that feed into or out of the lakes (Figure 4). Finally, the latitudinal restriction on the occurrence of the dark lakes is consistent with global circulation models that predict precipitation of methane onto both or at least the winter pole (Rannou et al. 2006, Mitchell et al. 2006), together with the decrease in surface temperature poleward (Flasar et al. 2007). Currently, the northern pole is experiencing spring equinox in an annual cycle that is 29.5 years in length.

These data 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. Methane is difficult to identify, given the large abundance of gaseous methane that dominates much of the near-infrared spectrum from 1–5 microns; liquid ethane features are potentially more detectable. Because the northern reaches are just now experiencing the onset of spring, the sun is low on the horizon above 64° N, given

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**Figure 3**

(a) Map of the more than 600 lake and sea features observed to date by the Cassini radar system in the high northern latitudes of Titan, from 60°–90° N latitude. (b) Mapped units in the northern hemisphere. Dark lakes are blue, granular lakes are cyan, and bright lakes are red. The colors outside the lakes indicate radar incidence angle from the vertical with green at 10° and pink 50°. A sketch of Lake Michigan in the center of the figure is to scale. From Hayes et al. (2008). SAR, synthetic aperture radar.
Figure 4

(a) Cassini radar image of an area around 70° N, measuring 160 km by 270 km, in which liquid—appearing dark to the radar—submerges a hilly terrain possibly dissected by fluvially generated valleys.

(b) Region around 79° N latitude with dendritic features feeding into and out of a lake. The “island” in the middle is 90 km by 150 km across.
Titan's axial tilt of 26° (Stiles et al. 2008). As the season progresses, spectra with progressively higher signal-to-noise on the larger lakes (which are large enough that the IAU has designated them “mare,” or seas) may test whether either of the two primary liquids in Titan's hydrological cycle are present in the lakes. Ethane was detected in the southern hemisphere lake Ontario Lacus (Brown et al. 2008).

Assuming that the darkest lakes are filled with liquid, it is of interest to know their depths, to understand both the total amount of liquid they contain, and the underlying geology that has formed them. Both methane and ethane are relatively transparent at 2-cm wavelength, with recent laboratory measurements suggesting absorption lengths (1/e diminution of the signal) of order meters (Paillou et al. 2008). The darkest lakes may therefore have depths that exceed of order 10 meters, whereas the granular lakes might be sufficiently shallow that we are seeing to the bottom. Features seen in the granular lakes, such as channels, are consistent with shallow features that periodically empty and are then subjected to channel formation through flow of methane from the surroundings.

With 35% of Titan’s surface now imaged by radar, and the lakes covering 2.4% of this area, roughly 0.6% of Titan’s surface is potentially covered by liquid methane and ethane if the remaining unimaged parts contain no lakes. Mitri et al. (2007) constructed a simple model of evaporation off high-latitude lake surfaces to show that this amount of surface coverage, coupled with advective rates consistent with plausible wind speeds of 0.1–1 m s⁻¹ (Tomasko et al. 2005), is sufficient to maintain the relative humidity of methane globally on Titan at its present value. However, for an average lake depth of 20 m the reservoir of methane in the lakes is between 1/30 and 1/3 the methane atmospheric inventory (Lorenz et al. 2008b), which is insufficient to account for the additional methane required to humidify the equatorial atmosphere and permit the convectively triggered rainstorms that appear to be required to form the dendritic features at the Huygens site (Section 3). Either the lakes are on average at least an order of magnitude deeper than the minimum inferred from the radar absorption lengths, or additional methane is present in subterranean porous or fractured media. Alternatively, the dendritic features might be a relic of a wetter recent past (see Section 6; Griffith et al. 2008).

Even if the average lake depth is only 20 m, the amount of liquid in the lakes is substantial: two orders of magnitude larger than the known oil and gas reserves on the Earth (Lorenz et al. 2008b). Equally impressive is the range of morphologies of the lake and sea features observed to date, from flooded canyonlands to what appear to be liquid-filled calderas (Figure 5).

In contrast to the extensive coverage by radar in the northern hemisphere, only one radar pass has been made of the southern hemisphere, revealing only two fairly small lakes. The rest of the terrain appears hilly (Figure 6), and there are no obvious dry lake basins as in the northern hemisphere. However, ISS images at much lower spatial resolution than the 350–1000 m achievable with the radar show a kidney-shaped dark feature about 200 km in length, named Ontario Lacus, that is outside the area of radar coverage and contains ethane (Brown et al. 2008). The observation early in the mission of extensive south polar convective clouds (Porco et al. 2005) that subsequently disappeared suggests that a source of condensed methane exists or existed very recently in that hemisphere; additional radar imagery of the southern hemisphere will perhaps reveal lakes or lake basins akin to those in the north (Figures 7 and 8).

4. AEOLIAN COMPONENT OF THE METHANE CYCLE

Pre-Cassini Expectations and Discovery

Pre-Cassini expectations were that dunes on Titan were unlikely (Lorenz et al. 1995), an expectation that has been proven wrong (Lorenz et al. 2006a) for interesting reasons. First, near-surface
winds on Titan were expected to be gentle, due to the low solar flux and the large mass of the atmosphere. This energy-flux argument, which correctly predicts windspeeds of a few meters per second on Earth, suggests windspeeds on Titan of only about 1 cm s\(^{-1}\). In contrast, despite Titan’s thick atmosphere and low gravity, which both favor transport of material by wind, the threshold windspeeds required to move sand are of the order of 0.5–1 m s\(^{-1}\). Second, it was not obvious what processes on such a stagnant world could generate sand-sized particles.

We now know that near-surface winds of the order of 0.5–1 m s\(^{-1}\) do occur and were measured by the Huygens probe during its descent (Bird et al. 2005, Tomasko et al. 2005). An unanticipated factor in controlling Titan’s near-surface winds in particular is the gravitational tide due to Saturn (Tokano & Neubauer 2002)—a feature that may be unique in our solar system, but important on extrasolar planets. Furthermore, it is now better appreciated that average conditions are not a reliable guide to surface modification, in that the landscape leaves a record of the most violent events (both dune-forming winds and the heaviest rainstorms) that affect it, rather than the average. Thus, fluvial erosion (and possibly the generation of sand-sized sediment by it) is more prominent than the average rainfall figure of 1 cm year\(^{-1}\) might suggest.
Figure 6

The south pole of Titan imaged at 350 meters resolution by Cassini radar. This area, 760 km by 170 km, shows only two dark lakes. Radar illumination is from the lower left with incidence angles from 22–38°.

Radar imagery in February 2005 (T3) found many radar-dark subparallel features, nicknamed cat scratches, which were interpreted (Elachi et al. 2006) as being possibly aeolian in origin, but other processes were recognized as being impossible to preclude. Before that, near-infrared mapping noted the existence of some “streaky” boundaries between light and dark terrain, suggesting possible surface transport. It could not be determined unambiguously whether these features were the result of aeolian or fluvial transport.

The situation became clear in the October 2005 flyby T8 (Lorenz et al. 2006a, Lunine et al. 2008), which featured radar mapping of the optically darkest region then known on Titan, Belet, near the equator. As well as showing dark streaks like T3, the larger dunes here, illuminated by the radar in a more favorable broadside-on geometry, showed topographic glints indicating that they had positive relief of some 100–150 m (Figure 7). The dunes were strikingly similar in morphology and size to the linear (longitudinal dunes) seen in the Namib, Sahara, and Arabian deserts on Earth.

The association of the radar-dark dunes with the optically dark regions straddling Titan’s equator was immediately obvious, and indeed subsequent radar mapping has found dunes covering...
Figure 7
A segment (North up) of the T25 radar swath, showing dunes in Aztlan. The bright interdune areas can be seen, as well as a few uprange glints on the dunes at upper left. Note the abrupt termination of dunes when they reach the western edge of topographic obstacles.

Figure 8
A compilation map of radar-determined dune directions overlain on an ISS base map. The radar coverage is quite incomplete, but dunes are seen on essentially all the optically dark low-latitude terrain imaged so far.
most of these dark areas. Radebaugh et al. (2008) document further observations of the dunes with radar data, counting several thousand individual dunes. In some areas (presumably where sand is more abundant), the dunes appear on a dark sand sea, whereas in others the dark dunes are superimposed on a brighter substrate, which indicates that the interdune areas are sand-free, or at least with a sand layer thinner than the radar penetration depth of some tens of centimeters. The dunes are almost invariably linear in form, and the pattern is overwhelmingly one of net sand transport from W to E (Figure 8). Dunes terminate abruptly at the western edge of obstacles and pick up gradually thereafter. Some obstacles have “tails” in this downstream direction. Only a few patches of network dunes are noted, suggesting some locally complex wind; remarkably, hardly any dunes are found outside the tropics (+/- 30° latitude).

Correlations of radar with VIMS data (Soderblom et al. 2007b) find that dunes are invariably a brown unit that spectroscopically appears to contain less water ice than other units on Titan, and various organic materials would be consistent with the data. Dunes were resolved in high-resolution VIMS data (T20) in Fensal (Barnes et al. 2008). These observations show clear interdune areas, implying that at those locations the interdunes are completely free of sand.

Finally, the presence of dunes in the T8 swath, which also imaged the Huygens landing site, was in fact instrumental in coregistering the 2-cm radar image with the near-infrared DISR image (e.g., Lunine et al. 2008). These different data did not always correlate well, especially at the small scale, but the dunes (seen only in the distance as horizontal dark streaks in the DISR side-looking images) were dark in both datasets.

Sand Composition, Size, and Amount

There are no direct measurements of the size of particles making the dunes, although their radar-darkness suggests particles much less than centimeter-scale. The optimum particle size for saltation in Titan’s atmosphere, assuming interparticle cohesion similar to terrestrial materials, is about 250 microns in diameter (“sand” geologically is a particle-size classification, not a compositional one). The likely means for creating such material is by breakdown of coarser materials such as impact ejecta or fluvial sediments, or by agglomerating finer material such as the atmospheric haze.

At present, the latter origin appears to be favored: The optically dark appearance of the material, and its spectral characteristics, support an organic composition, suggesting that the sand formed from haze particles. Conversion of <1-micron haze particles into 250-micron sand grains could occur by sintering over long timescales, or perhaps more likely, it may involve cycles of wetting and drying in Titan’s lakes. The latter scenario would require that the sand move from the lakes at the poles to the equatorial regions where the dunes are found.

In an initial estimate, the volume in observed river channels was thought to be insufficient to account for the volume of sand needed to construct the dunes. Because more heavily eroded areas have since been found, this calculation may need to be revisited. The observed impact crater distribution, which was originally thought to be a likely source for sand-sized material (believed to be the dominant sand source on Venus), is unable to provide the required volume, unless some other process has broken down larger ejecta.

Noting that about 20% of Titan appears covered in dunes, and using radarclinometric, radiometric, and similarity arguments to estimate the average depth, Lorenz et al. (2008b) have estimated the total sand volume to be between 200,000 and 800,000 km³ of material. This estimate corresponds to a thickness of several meters over the whole planet. It is interesting that this amount of material is a factor of several larger than the observed inventory of lake liquid.
Implications for Meteorology

The dunes provide an important set of constraints on Titan’s meteorology. First, their distribution, confined to the tropics, defines the latitudes equatorward of 30° N and S as having, at least sometimes, the conditions required for dune formation (available and transportable, i.e., dry, sediment, and winds strong enough to move the material).

Models even before the dune discovery (e.g., Rannou et al. 2006) suggested that low latitudes on Titan should eventually dry out unless resupplied by a surface methane source. Mitchell (2008) has explored this question further and estimated some 1–2 m of liquid methane per year could be removed from low latitudes. He found that the latitudinal extent of the dry region depends on the total methane inventory, with between 7 and 20 m agreeing best with observations. This number is much larger than what is present in the lakes if their typical depth is only tens of meters.

Second, the predominance of the longitudinal (linear) dune form requires a modestly changing (typically bidirectional) wind regime (e.g., Lancaster 1995). Sources of such a variation include seasonal change (the usual reason for this wind regime on Earth) and possibly the gravitational tide in the atmosphere.

Finally, the dune orientation pattern represents an important diagnostic on the tropospheric winds, for which there are few clouds to act as tracers. Although the dunes almost exclusively indicate eastward sand transport, there are regional deviations of up to 45° (see Figure 8, notably around the 2500-km continental-scale feature Xanadu).

Tokano (2008) has explored the winds in a global circulation model (GCM) and found that surface winds should not infrequently exceed the saltation threshold of 0.5–1 m s⁻¹, and furthermore that bidirectional winds are encountered over the course of a Titan year, owing to a seasonal change in the hemisphere-to-hemisphere Hadley circulation. However, this model (and simple consideration of the overall planetary angular momentum balance) predicts that the near-surface winds at low latitudes are predominantly easterlies (i.e., blowing westward), in contradiction to the appearance of the dunes. Some fundamentals of Titan’s circulation are not understood, perhaps related to the distribution of topography on Titan. New topographic data, and perhaps monitoring of Titan’s rotation, may provide a resolution.

5. OVERALL SCHEME OF THE METHANE CYCLE

The elements of the methane cycle on Titan that are known, or strongly suspected, to be present in the surface and atmosphere are shown in Figure 9. There are two major distinctions between Titan and the Earth in respect to their hydrological cycles. First, in place of a single liquid, water, on the Earth, Titan’s hydrological cycle is strongly suspected to involve both methane and ethane, on the basis of the detection of both at the Huygens landing site (Niemann et al. 2005), and the known conversion of methane predominantly to ethane in Titan’s stratosphere. The second is the absence of a global ocean on Titan, in place of which are the dunes.

We address first the impact of the two-component ethane-methane fluid system, the vapor pressure contrast of which was already introduced in Section 1. This difference, along with the nearly ideal solubility of ethane and methane with respect to each other, will act to couple different timescales associated with the movement of methane and ethane in Titan’s hydrological system, and possibly to amplify hemispherical differences in methane abundance. Any differences associated with topography, subsurface crustal liquids, or obliquity/eccentricity variations (E. Schaller, personal communication, 2007; see also Lorenz 2008) that may lead to an asymmetry in the
abundance of ethane in the southern versus northern hemispheres will potentially lead to an amplified difference in the amount of methane available for seasonal transport because of the vapor pressure reduction of methane solubilized in ethane. A liquid solution of 50% ethane and 50% methane has half the methane vapor pressure of the pure liquid methane (we leave aside here the effect of the nitrogen).

A second effect associated with the presence of a two-component, ideal-solution hydrological working fluid is reduction of the freezing point. Depending upon the relative abundances of methane and ethane in the lakes or putative subsurface crustal liquids, or both, a significant portion of the liquid will remain unfrozen well below the pure melting point of 90 K and 91 K, respectively, for the methane and ethane. The impact of both these effects, the vapor pressure and the melting point, on the behavior of the methane hydrological cycle has yet to be considered quantitatively for present-day Titan, though pre-Cassini models of the evolution of Titan’s surface and atmosphere did consider it (McKay et al. 1993).

The absence of a massive methane or methane-ethane ocean at present implies a sharp departure from the way Titan’s climate behaves relative to that of the Earth today. It might, however, serve as a useful analog for the behavior of Earth’s hydrosphere during the late main sequence of the Sun’s life when the latter’s luminosity is sufficient to elevate our planet’s tropopause temperature, leading to rapid stratospheric photolysis of water and escape of hydrogen (Kasting et al. 1988). More generally, it represents a system with an active hydrologic cycle different in important respects from that of the Earth, far more active than that of Mars or Venus, and hence worthy of further study.
6. REMAINING QUESTIONS

Density of Fluvial Features

The lack of spatial resolution of a global scale better than 350 m (500 m in most places) represents a severe hindrance to understanding the origin of the broad fluvial valleys that are seen in the radar data, and their relationship to the much finer scale, dense dendritic feature observed close-up by the Huygens probe. Without this information, it is impossible to quantify the total amount of fluid that is or has moved through fluvial erosive systems, and to understand the origins of these fluvial systems in various geological contexts on Titan.

A fascinating feature of many transport networks (from river channels, to vascular or bronchial networks in animals, and root and branch networks in plants) is that they exhibit fractal self-similarity. However, there is a scale below which fluvial channels tend to show a break in their character that depends on the regolith properties (its erodability and the ease with which liquid can percolate into the ground rather than flowing across it). Studies of terrestrial fluvial channels and shorelines suggest that the break in fractal behavior is below the resolution of the Cassini radar images. The fractal dimensionality of several lake coastlines studied in radar images is comparable to that of terrestrial coastlines that are rough and intricate, such as those of Ireland (Sharma & Byrne 2008). A similar study over larger spatial scales would be useful to try to identify a terrestrial-like break in slope. Unfortunately, DISR imagery of the Huygens landing site does not overlap in spatial resolution with Cassini radar imagery over the site, because haze obscured DISR images until the Huygens probe was below about 20-km altitude where the image scale was below what could be usefully discerned from the radar data.

Possibility of Plumbing/Alkanofers with Lakes

Radiometric data from the Cassini radar suggests that the crust of Titan, which is presumably water ice, might have substantial porosity (Paganelli et al. 2008). This, coupled with the absence of the hundred of meters equivalent depth of ethane expected from methane photolysis over the age of the solar system (Lunine et al. 1983), raises the question of whether large amounts of ethane or methane, or both, might be stored in Titan’s crust. The appearance and configuration of the smaller lakes in particular hints at the possibility of a hydraulic connection between them—the alkanoferic (methane-ethane) equivalent of aquifers.

The question of hydraulic connection between lakes has been raised by Hayes et al. (2008), who considered how the lake levels might change as a function of season with and without a connection to a substantial underground plumbing system. Results depend on the lake size, as well as crustal permeability, but potentially, observations over a time span of much of a Saturn year—decades—could detect the stabilization of small lakes by a crustal methane table. The effect of a mixed ethane-methane crustal plumbing system has yet to be investigated.

Source of Methane and Sink of Ethane

Another unresolved question is the ultimate source of the methane and the disposition of the ethane. If methane has been photolyzed without major interruptions over the age of the solar system, hundreds of meters equivalent depth of ethane should have been produced during this time. Disposal of the ethane during volcanic (Mousis & Schmitt 2008) and impact events might explain its relative absence on the surface. Alternatively, it is possible that much less ethane actually
survives to the surface from the stratosphere than is predicted by photochemical models (Atreya et al. 2006), because its vapor pressure is high enough that condensation into aerosols in the lower atmosphere is avoided, or it is incorporated somehow into other organic aerosols (Hunten 2006), or both. In either case, the surface ought still to be buried under hundreds of meters of solid or solid + liquid debris globally averaged, and the dune fields covering 20% of the surface do not appear to be either extensive enough or deep enough to account for all this material. Alternatively, material may have been pushed into the subsurface crust, or deeper, as noted above for the ethane.

Methane itself might have been manufactured in the deep interior by reaction of carbon dioxide, water, and rock (Atreya et al. 2006) or brought into Titan and stored in the deep interior from the beginning, expelled during discrete events in Titan's history (Tobie et al. 2006) or continuously (Fortes et al. 2007). Depending on the extent and timing of methane's outgassing, a global ocean of methane along with ethane could have existed in Titan's past, gradually being converted to ethane with a reduction in volume and eventually being lost to subsurface crustal (or deeper) storage. Alternatively, the amount of surface methane may never have been sufficient for global coverage, confined instead at most to low points such as the floors of craters and other closed basins.

The presence of an ocean sufficient to submerge topography would have had a primary effect on the evolution of Titan's climate, crustal geology, and surface chemistry. Specific predictions are difficult, although the extent and small free eccentricity of Titan's orbit might be hard to reconcile with tidal dissipation in such an ocean during its late, shallow stages (Sagan & Dermott 1982). A complete mapping of the distribution, extent and ages of fluvial features would be helpful in this regard, but is surely ambitious. If large craters such as Menrva are ancient, then they should reflect erosional processes associated with the presence and eventual decline of such an ocean, including the deposition of hydrocarbon and nitrile sediments in the crater floor.

7. FUTURE OBSERVATIONS

The Cassini orbiter continues to operate around Saturn at this time of writing, with the prospect of mapping the surface beyond the roughly 35% presently seen at resolutions better than a kilometer, and long-baseline observations over years that could see seasonal changes in lake deposits, or allow near-infrared spectra of the lakes at high Sun angles, or both. But Cassini will remain limited in spatial resolution, particularly in its near-infrared capability.

To comprehensively understand the fluvial and aeolian transports on Titan, and to constrain subsurface reservoirs, a global and homogenous topography dataset is needed, like that generated by the Mars Orbiting Laser Altimeter (MOLA) at that planet. Although Cassini will provide some piecemeal topographic profiles, they are not systematically distributed and cover only a small fraction of Titan. A future mission to orbit Titan would, as one of its key goals, provide radar altimetry and sounding over a large fraction of Titan's surface. Complementary to this would be a much higher sensitivity infrared mapping camera and spectrometer, operating just beyond 5 microns to get 50-m surface resolution and see diagnostic features of surface hydrocarbons between 5- and 6-micron wavelength. In situ capabilities such as landers or floaters on the lakes, or a balloon to cover large amounts of territory at 10-km cruising altitude, are essential complements to the orbiter (Lorenz et al. 2005).

Such a mission is currently under study by the U.S. and European space agencies, with an uncertain launch date pending phasing with other potential outer solar system targets. Meanwhile, methane continues to run across Titan, and glisten in the still lakes of its high northern latitudes brightening under a weak spring sun.
SUMMARY POINTS

1. Titan has a methane cycle analogous to the Earth’s water hydrological cycle.
2. Extensive areas of fluvial erosion are seen across Titan’s surface.
3. The Huygens landing site is near a hilly area cut by dendritic features.
4. Methane and probably ethane were present in liquid form under the Huygens lander.
5. Lakes exist at high northern and, to a lesser extent, southern latitudes.
6. Most of these lakes and the larger “seas” appear to be filled with ethane and methane.
7. Dunes cover 20% of the surface and are composed of particles of (or coated with) organic solids.
8. Titan’s hydrologic cycle is distinctive in lacking a global liquid ocean and in having two chemically soluble liquid components with very different vapor pressures.

DISCLOSURE STATEMENT

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Errata

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