Crater lakes on Titan: rings, horseshoes and bullseyes

Ralph D. Lorenz

Unit for Space Sciences, University of Kent, Canterbury, Kent CT2 7NR, U.K.

Received for publication 3 December 1993

Abstract. Recent observations indicate that Titan has a predominantly icy surface, although photochemical models suggest that substantial amounts of liquid hydrocarbons may exist near or on the surface: the most plausible model of Titan's surface therefore is an icy one, with lakes or small seas of hydrocarbons (principally ethane), many in impact craters. Medium-sized craters will have central peaks, while large craters may undergo viscous relaxation, their centres doming upwards, to push the liquids into an annulus, thereby forming a ring lake. Additionally, craters with central pits may form "bullseye" lakes. The large tidal effects of Saturn on such lakes will affect their shape, distorting rings into horseshoes, and may also cause erosive migration.

Introduction: the surface of Titan

The nature of Titan's surface is largely unknown (Lunine, 1993; Lorenz, 1993), due to the optically opaque haze in its thick atmosphere, but by analogy with other outer planet satellites, it should be predominantly composed of ice. The high observed abundance (a few percent) of methane (which should have been depleted photolytically within ~10^6 years), and the proximity of the surface conditions to its triple point, suggested that reservoirs of liquid methane could exist on the surface (Eshleman et al., 1983; Flasar, 1983). Further, photochemical models (Yang et al., 1984) predicted that over the age of the Solar System (4.5 Gyaers), a global ocean of some 600 m depth of ethane (also a liquid at Titan surface conditions) should have been produced by methane photolysis: a global ethane–methane–nitrogen ocean (Lunine et al., 1983), of depth 0.7-10 km, depending on the methane content (Dubouloz et al., 1989) was a favoured model of Titan's surface. However, observations by radar (Muhleman et al., 1990, 1992), microwave radiometry (Grossman and Muhleman, 1992), and measurements of albedo in atmospheric "windows" in the near-infrared (Griffith et al., 1991; Lemmon et al., 1993; Noll and Knacke, 1993; Griffith, 1993) are incompatible with a pure hydrocarbon surface, and indicate that the surface is composed predominately of "dirty ice", although lakes and seas of hydrocarbons are possible. A recent photochemical model (Lara et al., 1994), with improved treatment of transport and condensation processes and updated reaction coefficients, gives excellent agreement with observations of atmospheric composition, and suggests that the ethane production is of the order of 100-400 m. This ethane inventory is rather easier to reconcile with observations (Stevenson, 1992; Lunine, 1993), since much of it may be stored in the 0.3-8 km thick ice regolith (Lara et al., 1994) near the surface. However, since the ethane is deposited (by sedimentation or rainout) from above, it may accumulate in impact craters or basins on the surface. The observational data are perfectly compatible with the existence of such lakes.

Formation and evolution of crater lakes

If Titan's surface is old (4 Gyaers), then interpolating between Hyperion and Rhea (the satellites adjacent to Titan) suggests that there should be about 100-200 craters of diameter 20 km or greater in every 10^6 km^2 of surface (Plescia and Boyce, 1985; Neukum, 1985), or about 10,000 over Titan's entire surface. Most of these will have been generated in the initial heavy bombardment following the formation of the Saturnian system. The "steady-state" production rate of >20 km craters is 4 x 10^-15 km^2 year^-1 (Thompson and Sagan, 1992).

Observed crater densities may be much lower if resurfacing has occurred recently on Titan, although the crater density may be rather higher than indicated above, since Titan may have suffered an intense bombardment episode following the fragmentation of Hyperion (Lorenz, 1993; Lara et al., 1994; Farinella et al., 1990; McKinnon, 1990).
Studies of crater morphology on Ganymede and other icy satellites suggests some differences from craters on the terrestrial planets (Schenk, 1989, 1993). Assuming crater morphology on Titan is similar to that on Callisto and Ganymede, small craters (less than 5–10 km diameter) will have simple, bowl-shapes. Above about 10 km, central peaks tend to be prominent, while above about 40 km diameter, craters tend to have a central pit, sometimes occupied by a small dome. Note that impactors that would generate craters smaller than 200 m diameter will be screened out by atmospheric shielding (Thompson and Sagan, 1992).

Photochemical models suggest that ethane will be deposited in a crater at the rate of about 1 m depth every 20 Myears; depending on the atmospheric conditions at the surface (about which there is still some ambiguity), atmospheric methane may dissolve in the ethane to form an equilibrium mixture up to 16 times deeper (Dubouloz et al., 1989). In the same interval, about 1.5 m of water-ice impact ejecta (deposited on average at a rate of about $8 \times 10^{-6}$ g cm$^{-2}$ year$^{-1}$ (Thompson and Sagan, 1992), and about 0.25 m of (solid) photochemical aerosol will have been deposited in the lake. Due to viscous relaxation (Parmentier and Head, 1981), the centre of a crater 100 km in diameter, however, will have domed upwards on this timescale, such that the liquid will be forced into an annulus. If the crater has a central pit, some liquid will probably accumulate here, so a “bullseye” appearance will result (centre liquid, then ice, then a liquid annulus, then the crater rim; if a central dome exists in the pit, then the sequence may be ice, liquid, ice, liquid, ice, although such a configuration would probably be short-lived).

The relaxation timescale cited above applies for ice rheology at the 120 K surface temperature of the Galilean satellites: for water ice at Titan’s 94 K surface temperature, the timescale will be orders of magnitude longer. However, ices on Titan may incorporate a significant fraction of ammonia and other volatiles, which tend to reduce viscosity. Thus, using Galilean relaxation rates is perhaps as good an estimate as any. Since, in any case, the liquid deposition rate (bearing in mind the current uncertainty in the methane/ethane mix that can be in equilibrium with the atmosphere) is also poorly constrained with present data, the timescale for doming of the crater may be small or large compared with its filling time. Thus, if doming is fast (see Fig. 1), the ring lake configuration will be common, while if doming is slow compared with liquid deposition, craters will tend to fill completely forming simple circular lakes (with a slightly shallow region in the centre).

Note that lake appearance will be modified by subsequent impact events: a large, old crater may have several smaller craters superimposed on it. By studying the crater morphology, it may be possible to determine whether the impact sites of these smaller craters were deeply submerged or not when the impact occurred, giving an indication of the liquid depth history of the larger crater.

The appearance of large crater lakes may also be modified because Saturn induces a strong near-stationary tide in fluids on Titan (Sagan and Dermott, 1982; Lorenz, 1992), yielding a tangential acceleration $f = \frac{3}{2}GM_5r \sin \phi$, where $G$ is the gravitational constant, $M_5$ the mass of Saturn, $r$ is the Saturn–Titan distance and $R$, Titan’s radius. $\phi$ is the Titanocentric angle between the sub-Saturn point and the point under consideration. This acceleration tilts the local vertical by an angle $\delta = f/y$, where $y$ is the local gravitational acceleration ($1.35 \text{ m s}^{-2}$). This angle varies with location and time between zero and a maximum of about $6 \times 10^{-5}$ rad (for $\phi = 45$). This may be compared with the $10^{-6}$ tilt due to tides. Thus, for a 100 km diameter lake, the difference in level between shores is up to 6 m, comparable with the depth after an age of 6–300 Myears, so that the low-tide region may “dry up” completely—causing the lake to be horseshoe shaped. Lakes in smaller craters, which relax much more slowly (Parmentier and Head, 1981) are likely to remain circular, although should they fill up, are more likely to burst their banks at the “high-tide” end.

**Tide dynamics in crater lakes**

Because the orbit of Titan is non-circular (eccentricity 0.029), the Titanocentric angular rate of Titan varies with orbital position, while the angular velocity of Titan about its own axis is constant. Thus, there is an oscillation of the Titanocentric longitude of the sub-Saturn point of amplitude $\sim 3^\circ$, corresponding to about $\pm 130$ km along...
erosion (Sagan and Dermott, 1982) of $3\varepsilon = 9\%$ in the magnitude of the tide (Sagan and Dermott, 1982).

These variations in tidal strength and direction, coupled with Coriolis forces, may lead to strong currents, causing erosion (Sagan and Dermott, 1982; Lunine and Stevenson, 1985) at the edge of the lake nearest the sub- or anti-Saturnward points [even though water-ice is relatively insoluble in cryogens (Rest et al., 1990)]. A significant pathway for erosion may be by abrasion due to suspended particles (Lunine, 1990) although this is difficult to quantify. The solubility of solid organic compounds is low enough (Raulin, 1987) that these will appear as suspended particles rather than dissolve in the lakes. If Titan rotates non-synchronously (Muhleman et al., 1992)—not unlikely since the orbit is non-circular (Greenberg and Wiedenschilling, 1984; see also Sears et al., 1993) with a period of $15.911$ days (its orbit period is $15.945$ days)—then there is superimposed on the oscillation in the longitude of the sub-Saturn point a secular drift (0.05 day$^{-1}$), which will “smear out” lakeside erosion to become antipoleward all over Titan.

The above arguments apply for a perfectly spherical “billiard ball” Titan. However, it is likely that Titan’s crust may have responded to the tidal potential induced by Saturn: if this is the case, and Titan rotates synchronously, tidal effects in lakes will be quite small. If Titan rotates non-synchronously, then the crust will respond to the tidal potential (a rotating prolate spheroid averaged over the crust relaxation timescale, thus an oblate spheroid) and the tidal effects will manifest themselves according to the difference between the instantaneous tidal potential (a prolate spheroid with the long axis pointing toward Saturn, to which liquids will quickly respond to attain equilibrium) and the crustal shape. In general, this may mean that high (but more modest than suggested above) tides may occur on the edges of lakes closest to and furthest from the sub-Saturn point, although on the equator, the tide will be unidirectional and horseshoe lakes may indeed appear.

Especially since the tides on Titan are relatively large in any case, it is worthwhile examining whether resonant tides are likely on Titan. A good terrestrial example is the Bay of Fundy in Nova Scotia where the natural period of oscillation is half that of the semidiurnal tide, leading to large tidal amplitude and strong tidal currents (Bearman, 1989). The speed of a shallow ocean wave, where depth is much smaller than wavelength, is $aD/\nu$ or $1.2\cdot 1.6$ m s$^{-1}$ for a depth of 1-100 m on Titan. For seas of diameter 100 km (the displacement of the tidal bulge due to eccentricity) the resonant period is $2\times 10^{3}/1.2\approx 1.7\times 10^{6}$ s, much shorter than the orbital period of $5.4\times 10^{5}$ s, so resonant tides are unlikely to occur, even in improbably wide, shallow seas.

Even without resonant effects, however, the tidal amplitude is significant. In terrestrial seas, for those regions (“tidal flats”) where wave effects are minimal and mass transport is dominated by tidal action, gradients are comparatively shallow (Bearman, 1989), of order 0.001. Thus the intertidal distance of a 100 km diameter lake may be up to 100 km $\times (6\times 10^{-5})\times 0.09/0.001 \approx 540$ m.

Conclusions

We will only be confident about our understanding of Titan’s surface after the arrival of the ESA Huygens probe, which will descend through Titan’s atmosphere in late 2004/early 2005. Its camera will give high-resolution images of the area around the landing site [probably about 20 N, 200 E for mission planning reasons (Ott, 1992)], complemented by more extensive radar, visual and infrared mapping from orbit. The arguments I have presented here suggest that we may find small circular lakes, and larger ring-, bullseye- or horseshoe-shaped lakes, with tides of high amplitude (around the Huygens landing site, the tides may be “high” on the SW margin of lakes: see Fig. 2). Study of the lake morphology, and any cratering in lakes, may give indications as to the softness of Titan’s crust.

It may be noted that the dynamics of tidal currents, and the consequent erosive processes, are likely to be complex and will be an interesting topic of further study. Further work is also required in quantifying the likely response of Titan’s crust as a whole to tidal effects.

Acknowledgements. The author acknowledges the support of a postgraduate research grant from the U.K. Science and Engineering Research Council. Jonathan Lunine made a helpful review of the paper and Mark Lemmon made useful comments. Productive discussions with William Sears are also acknowledged.

References


