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Oceanography on Saturn's Moon, Titan

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***Abstract*—Saturn's frigid moon Titan was long suspected to have seas of liquid methane and ethane : the existence and extent of these seas has been determined by the Cassini spacecraft, and sea state, depth and the physical properties of the liquid are being learned. Titan's meteorology leads to concentration of liquid in the polar regions : two major northern seas, Kraken and Ligeia, and one shallow lake in the south, Ontario Lacus, are particularly well-studied to date. Titan serves as a new laboratory for physical oceanography, with familiar processes occurring under very alien conditions.**

***Keywords*—physical oceanography; liquid hydrocarbons; Titan**

I. Introduction

Oceanography is no longer just an Earth Science. Saturn's moon Titan [1,2], whose equatorial deserts were visited by the Huygens probe in 2005, has been found to have lakes and seas of liquid hydrocarbons, predominantly in its polar regions. Titan is 5150km in diameter (larger than the planet Mercury) and has a thick 1.5 bar nitrogen atmosphere. Titan's temperatures (94K at the surface) allow methane and ethane to exist as a liquid.

Mapping by the NASA/ESA/ASI Cassini spacecraft, which is in Saturn orbit but makes close passes of Titan every few weeks, revealed [3]in 2006 hundreds of lakes around Titan's north pole. Later, three bodies of liquid large enough to merit designation as 'seas' were identified. One major south polar lake is known, and a few transient areas of liquid have been spotted at low latitudes. The northern seas especially are prime targets for future exploration, not only as reservoirs of organic material of astrobiological interest, but as laboratories for air:sea exchange and other oceanographic processes.

In this paper I review current knowledge of Titan's seas, and consider their future exploration.

II. Titan

Titan is a unique satellite in the solar system in that it has a dense atmosphere, mostly of molecular nitrogen, with a surface pressure of 1.5 bar. This atmosphere endows Titan with many of the processes and phenomena more familiar on terrestrial planets than on the icy moons of the outer solar system. At Saturn's distance from the sun (10 AU), the surface temperature on Titan is 94K, as a result of the competing greenhouse effects (due principally to methane and nitrogen) which warms Titan by 22K compared to an airless body of similar reflectivity, and the antigreenhouse effect which lowers the temperature by about 10K. This antigreenhouse effect is due to sunlight absorption by the organic haze which renders Titan's atmosphere an obscuring orange-brown. Methane, which is present at about 1.7% in the stratosphere, rising to ~5% near the surface, is a condensable greenhouse gas, just like water vapor on Earth. Similarly, methane forms clouds, hail and rain : the latter phenomenon carves river valleys on Titan's surface, although most such valleys are presently dry. The weak sunlight that drives Titan's hydrological cycle results in rain being a rare occurrence (on average only a few cm per year, concentrated in high latitude summer) - a given location on Titan may see rain only every few centuries, but as a massive downpour depositing tens of cm or even meters of rain in a few hours. In some respects, Titan is to Earth's hydrological cycle what Venus is to its greenhouse effect - a terrestrial phenomenon taken to a dramatic extreme.

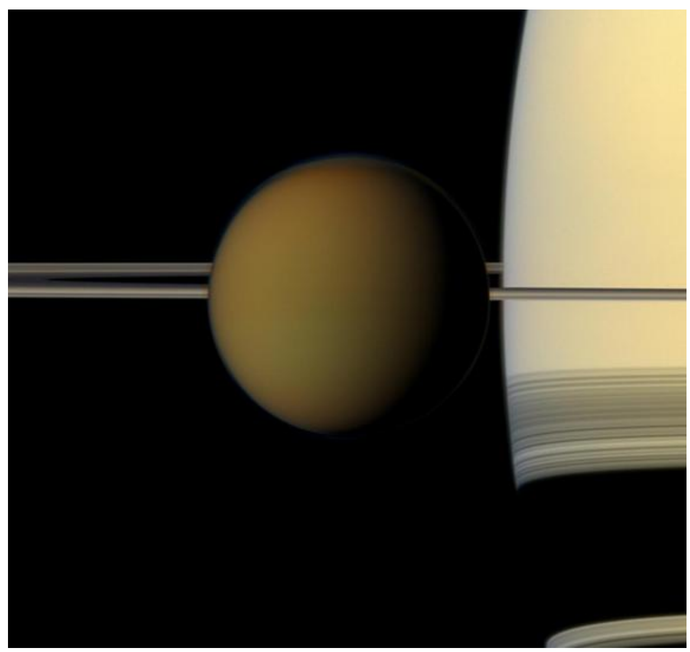

Fig. 1. Titan, next to its parent planet. Note the filigree shadows of the rings cast onto Saturn. Titan is perceptably darker/redder than Saturn, and darkening near Titan's north polar region can be seen here.

Titan has a tilt of 26 degrees relative to it and Saturn's heliocentric orbit so its climate has significant seasonal forcing. It takes 29.5 years to go around the sun, so the average season is 7.5 Earth years long (spring equinox was in 2009; northern midsummer will be in 2017). The orbit is appreciably eccentric, so the seasons are of slightly unequal length.

Titan's bedrock is believed to be water ice, with an apparently significant veneer of organic materials (formed from the breakdown of methane by sunlight - the process that forms the haze) such that water ice is only exposed in a few locations. Mountain belts exist, as well as the rugged region named Xanadu on the leading side of Titan (which is tidally locked to Saturn), identified in Hubble images [1] as bright in near-infrared light (which can penetrate the haze). The topographic range on Titan is modest, with the highest peaks and lowest depressions spanning only about 2-3km of elevation. Relatively few impact craters are present, as erosive and depositional processes (and perhaps cryovolcanism) renew the surface. Midlatitude regions are rather bland overally, while the equatorial half of the world (between +/-30^{o} latitude) has vast seas of dark organic sand dunes. More of Titan's surface is covered with dunes than any other (known) world. It was in a slightly damp cobbled streambed at 10^{o} S, about 30km south of some dunes, that the Huygens probe landed after a 2.5hr parachute descent in January 2005.

Thus Titan has been transformed in the decade since Cassini's arrival, from an intriguing and mysterious astronomical object, into a world with many features and processes that are both familiar and exotic. Perhaps most striking of these are the lakes and seas that have been found, predominantly in Titan's polar regions.

III. TITAN'S SEAS

Although hydrocarbon seas were long speculated [4] to exist on Titan, bodies of standing liquid were only confirmed (in northern winter darkness) by radar observations [3] in 2006, some two years after Cassini arrived in the Saturnian system. Hundreds of radar-dark [5] lakes, typically 20km across, were discovered at about 70^{o}N (figure 2). By international convention, lakes on Titan are named after lakes on Earth, a policy that will hopefully not lead to confusion. Later, a 300-400km body, Ligeia Mare, was observed in radar images [6], as well as parts of two other seas, Punga Mare (close to the north pole) and Kraken Mare, which may extend over almost 1000km but has a narrow sprawling shape indicated in near-infrared images [7,8] and has not yet been fully mapped by radar. Only one major lake, Ontario Lacus, is present in the south : this feature was detected in near-infrared images soon after Cassini's arrival [8], but could not be distinguished in these data from the dark sand seas that dominate the equator [1].

In fact, largely because the southern hemisphere illumination 2004-2010 allowed near-infrared remote sensing on Cassini to be brought to bear, Ontario Lacus is the most-studied body of liquid on Titan. This 250x70km body (about the size of Lake Ontario, hence its name) was determined by near-infrared spectroscopy [9] to contain liquid ethane (liquid methane could not be confirmed : the thick methane- and haze-laden atmosphere makes composition determination challenging.)

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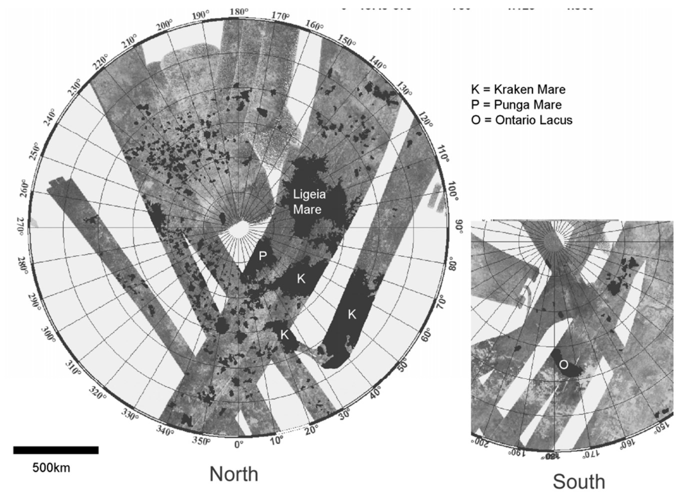

Fig. 2. A map of Titan's northern polar regions - light gray areas are not yet imaged by radar. The low radar reflectivity of the seas and lakes is apparent, as is the somewhat complex outline of the PLK seas (Punga, Ligeia and Kraken Mare). A partial map of the south (at the same scale) shows only modest liquid deposits by comparison.

Further analysis [10] of the near-IR data suggests that Ontario Lacus may in fact be muddy, and a bright margin is suggestive of a 'bathtub ring' of evaporite deposits [11]. Of course, these are not salts familiar as solutes in terrestrial waters, but some organic analog where differential solubility in an evaporating basin has been preferentially deposited at the shrinking margins. In fact, a comparison between an optically-measured outline and the margins in a radar image some years later [12] suggest that Ontario may have shrunk in extent, due to seasonal evaporation. Such an observable (several km) shoreline retreat is due to the very shallow slopes (measured by radar altimetry) around - and perhaps in - Ontario, of about 1m per km [13]. Radar imaging shows bright interior margins of Ontario, suggesting that microwaves can penetrate several meters down to the lake bed [14]. Much of Ligiea is at most a few meters deep : in many ways it seems analogous to desert playa lakes such as Racetrack Playa in Death Valley [13], the Great Salt Lake, Lake Eyre or the Etosha Pan.

Near-IR data suggested Ontario be smooth [9], and in fact a close examination of radar altimetry echo characteristics [15] requires that Ontario be exceptionally flat and smooth - in fact with rms roughness of 3mm or less. We will return to the question of waves on Titan seas later.

The preponderance of seas in the northern hemisphere is thought to be the result of the astronomical configuration of Titan's seasons in the current epoch [16], which has the result that the northern summer is less intense but longer in duration than that in the south. This results in a longer 'rainy season' in the north, such that methane and ethane accumulate there. This seasonal configuration lasts several tens of thousands of years, much like the Croll-Milankovich cycles that play a part in the Earth's ice ages and the Martian polar layered terrain. This picture of a drying south and accumulating north is consistent with the ria coastlines of PLK (e.g. figure 3) which suggest valleys being flooded by rising sea levels, and with the kidney-shaped outline, shallow (and possibly declining) depth of Ontario Lacus in the south.

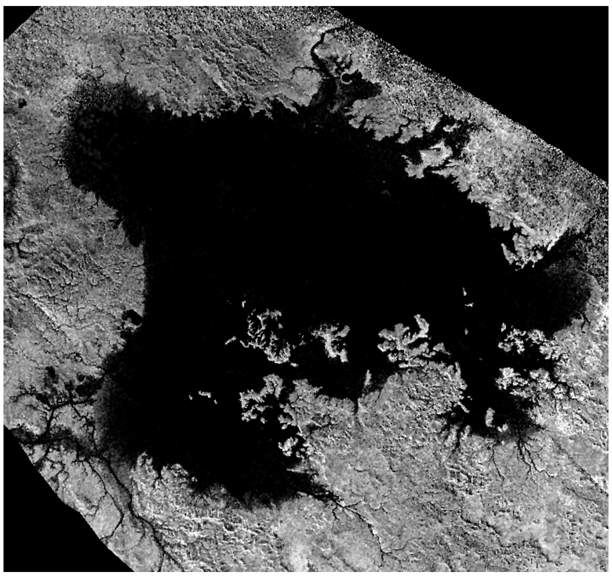

Fig. 3. Ligeia Mare, imaged by the Cassini RADAR mapper. The mosaic (from images acquired in 2007) is 500km across. The calm sea surface appears pitch-black except near some edges where some bottom reflection may be detected. The shoreline betrays a complex geologic history, with drowned valleys indicating a recent sea level rise. The rectilinear arrangement of river channels at bottom left suggests some tectonic control on hydrology.

Studies of the morphology around Ligeia Mare in the north suggest that some of the river networks [17] draining into it may have tectonic controls. The steep terrain and flooded valleys are consistent with relatively recent sea level rise (which could be an increase in the volume of the sea, or lowering of the terrain due to tectonic deformation. The islands on the south side of Ligeia Mare resemble the mountains and islands of the Musandam Peninsula in Oman/U.A.E, where the terrain is diving beneath the Eurasian plate at a few cm/year.

Near-IR mapping appears to indicate evaporite deposits around some northern lakes and lake basins [18], suggesting that even if the northern terrain is accumulating liquid in the present epoch, there may have been drier episodes in the past. This supports the notion of periodic astronomically-forced climate change on Titan.

One of the most striking observations in the near-IR is of the sun glinting off the surface of the lakes [19]. In fact this told us little that wasn't already evident from the low radar reflectivity, that the roughness of the lakes must be exceptionally low, but is a very iconic observation. In fact neither the lake (appropriately, Jingpo Lacus named after the 'Mirror Lake' in China) are spatially-resolved by the near-IR image which was taken at some distance, but with the lake outline known from Radar imaging, the shoreline acted as a shaped mask [20] to interrogate the spatial structure of the glint pattern, establishing some quantitative constraints on reflectivity and roughness. Because the glancing reflection occurred at a fairly low sun elevation (as it must, given the polar distribution of the seas) the atmospheric scattering and attenuation is significant and only the 5-micron atmospheric window (between methane absorption bands) allowed the glint to be seen : at the 0.94, 1.08, 1.28, 1.6 and 2 micron windows, the contrast was too low [21].

Fig. 4. Ligeia Mare, imaged by the Cassini RADAR mapper. The mosaic (from images acquired in 2007) is 500km across. The calm sea surface appears pitch-black except near some edges where some bottom reflection may be detected. The shoreline betrays a complex geologic history, with drowned valleys indicating a recent sea level rise. The rectilinear arrangement of river channels at bottom left suggests some tectonic control on hydrology.

Microwave radiometry of the seas [22], acquired by the radar receiver in between imaging or altimetry pulses, suggests a fairly high emissivity of the seas, requiring a low dielectric constant material of 2 or less. This is consistent with liquid hydrocarbons [3,5,23]. So far most information in the north is from radar, but as we move into northern summer, the optical remote sensing will improve.

IV. Titan Oceanography

The notion of extraterrestrial seas [24], especially filled with exotic liquid hydrocarbons, is of course of great popular appeal, and will likely be of paedagogical utility in oceanography and physical science education. In fact, the liquid methane and ethane that dominate the sea composition are handled routinely on Earth, at the temperatures encountered on Titan, by the liquefied natural gas (LNG) industry. Now that Titan's seas are being documented in progressively more detail, it is likely that extensive study of physical processes in Titan's seas may be stimulated, but in fact a considerable body of work already exists on some basic processes.

A. . Composition

Rainfall on Titan is predominantly methane with dissolved nitrogen, and perhaps a tiny amount of ethane. However, while methane and nitrogen are relatively volatile, ethane is not. Thus to be in thermodynamic equilibrium with the atmosphere (where the methane relative humidity is only about 50%), the seas likely might be expected to be dominated by ethane [4,25]. However, thermodynamic equilibrium may or may not be applicable in every instance, since the polar regions see strong seasonal forcing.

The density of ethane is about 2/3 that of water, and the viscosity at 94K is rather similar, depending on temperature. Methane is a little less dense and rather less viscous [26]. Many dissolved constituents (higher hydrocarbons, nitriles) may also be present and would increase the density, viscosity and dielectric constant.

Unlike water, hydrocarbons have solids that are generally denser than the liquid, and thus no 'icebergs' are expected. Conceivably porous material could float [27,28], and in thermodynamic conditions perhaps encountered in Titan's cooler past [29], certain ices are fractionally less dense than the liquid.

B. Structure

Liquid hydrocarbons, unlike water, have a monotonic temperature/density relationship. It is conceivable [30] that compositional layering may occur in seas and lakes (indeed, such layering can occur in liquefied natural gas tanks on Earth). If a uniform composition is assumed, surface heating in summer should lead to a fairly stable stratification, although models show that in the fall, the cooling surface layers may become dense enough to cause overturning. More work needs to be done in modeling possible wind-driven circulation, and to understand whether solar heating in summer is enough to overcome the competing effect of freshening winds and evaporative cooling.

C. Tides

Tides are the result of the radial variation of gravitational acceleration from the perturbing body, but how they are manifested depends significantly on planetary rotation. Whereas Earth's ocean tides essentially result from the earth rotating 'underneath' two sets of tidal bulges resulting from the moon and sun, on Titan solar tides are negligible, but the powerful gravity of Saturn leads to a ~100m bulge in equipotential height on Titan [31,32,33] at the sub- and anti-saturnward points (like our Moon, Titan is gravitationally locked to its primary, pointing the same fact towards it - nominally the 0 longitude point at the equator). However, Titan's orbit around Saturn is appreciably eccentric (e=0.029) so the tidal acceleration varies by ~3e~9%, so if there were a global ocean the tidal range would be ~9m, twice every Titan day of 15.945 Earth days. The tidal forcing period is large enough that even relatively shallow basins have natural periods that are too short [33] to be resonant with the forcing - there is no equivalent on Titan of the Bay of Fundy!

At the present epoch at least, Titan's seas are of quite limited geographical extent, so the tidal amplitude is not nearly so large as this. The static and dynamic terms of the potential are dependent on location, and so each sea must be considered separately. Tokano [34]adapted the Bergen Ocean Model to Titan conditions and computed a tidal range of ~0.4m for Ontario Lacus, and some ~5m for the sprawling Kraken Mare. Corresponding results for Ligeia Mare are shown in figure 5.

Recently, gravity measurements [35] by the Cassini spacecraft have quantified the mass redistribution as Titan responds to the changing potential around its orbit : the relatively low Love number measured implies a weak crust and a liquid interior. Thus (like Europa and other large icy satellites) Titan may have a 'habitable' interior ocean of liquid water. But this also means that Titan's crust deforms to the same shape that surface liquids would strive to attain, and thus the difference between the crustal (land) surface and the equipotential surface of the hydrocarbon sea is substantially reduced, probably to a factor of ~5 smaller than the tidal amplitudes above.

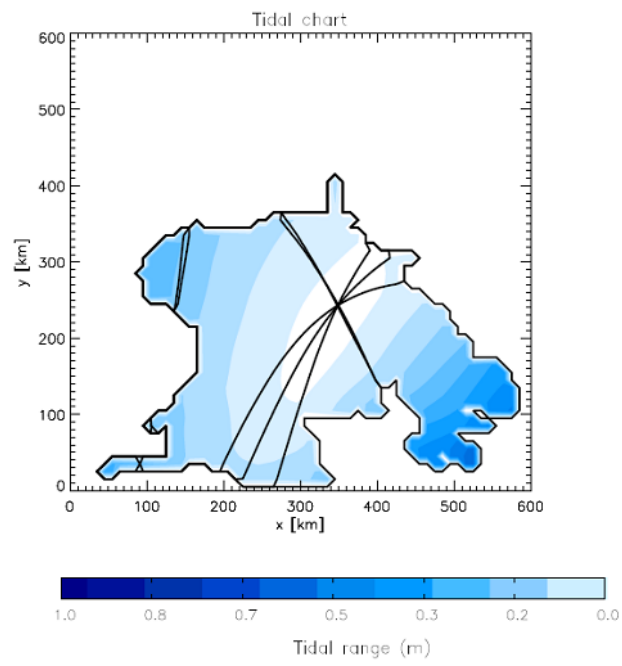

Fig. 5. Amphidromic lines and tidal amplitudes (max-min) on Ligeia Mare

The magnitude of tidal currents depends on the assumed depth of the seas. Assuming a central depth of 300m for Ligeia Mare, currents in that sea [36] were estimated at up to ~1cm/s -

because of the crustal weakness, this estimate should likely be reduced to ~0.2cm/s.

It has been suggested from recent observations [7] that Kraken Mare and Ligeia Mare may be hydraulically connected by a network of narrow surface channels. If this is the case, the tidal dynamics in this network could be most interesting, and could lead to substantial tidal dissipation and erosion.

Tidal dissipation, in Titan's interior and in its atmosphere as well as in surface seas, should act to dissipate energy and circularize the orbit around Saturn . Why it does not appear to have done so is a puzzle that has confronted Titan science since the 1980s and remains so.

D. Waves

The possibility of waves on Titan's seas was recognized during the formulation of the Cassini mission [37,38], and the Huygens probe was equipped with tilt sensors to measure any motion on waves should the probe survive splashdown on a liquid surface (since the surface was completely unknown, surface operations were not guaranteed). In Titan's low gravity, propagation of a wave of given wavelength is rather slow compared with Earth. Similarly, a wave of a given energy would be higher in amplitude, and so the fact that waves of a given height could be generated by lower winds on Titan was noted. However, other factors may be important too - the possible role of atmospheric density [39] in wave formation and growth was explored in some wind tunnel experiments before Cassini's arrival.

The remarkable flatness of Titan's seas posed a puzzle. Why, in Titan's low gravity and thick atmosphere, should the seas not have waves if the hydrocarbon liquids behave somewhat like water? One possibility is that winds are too light (yet it is evidently strong enough sometimes to form sand dunes); the other is that the seas may contain enough dissolved material to increase the viscosity enough to damp waves [26].

Although waves have yet to be observed, the question of wave height is of interest for shoreline erosion effects, and in particular for the design of vehicles that might float on the surface of the seas : the development of one such vehicle design (see next section) motivated particular attention to wave generation.

The wave threshold has been quantified recently by Hayes [40], who adapted various models for terrestrial capillary-gravity wave generation to Titan conditions. That work found that the threshold wind speed for wave generation should be ~0.4 m/s for methane-rich (low viscosity) seas, or ~0.6m/s for ethane-rich seas (viscosity similar to water). Such speeds have likely not been encountered during the Cassini mission, in either hemisphere [26,40], although in coming years as we move towards northern summer solstice, the probability that winds over Kraken or Ligeia may freshen enough to generate observable waves will increase (Hayes et al consider Bragg scattering of the Cassini Ku-band (2cm) radar energy, as well as the geometric reflectivity of a ripple-corrugated surface - compared with water on Earth, liquid hydrocarbons are intrinsically nonreflective). Note that these are Global Circulation Model (GCM) predictions of winds resulting from the large-scale atmospheric motions - local winds around methane rainstorms could be higher.

Once capillaries form, they can grow, and become progressively larger gravity waves (because of the low surface tension of liquid hydrocarbons, the wavelength at which gravity dominates on Titan is actually similar to that on Earth). Wave-wave interaction and other dissipative processes can limit wave growth, but the principal effect controlling wave height in a given wind is that a growing wave will run faster, such that the relative speed of the wind over it (and thus the energy flux into it) will decline, so growth becomes self-limiting.

Lorenz [41] found that this fully-developed state should be reached after a fetch of the order of 20km, so that many lakes may be growing seas, but the PLK seas should have a fully-developed wave spectrum across most of their extent. The fully-developed significant wave height SWH should be of the order of ~0.2U2/g, or ~20cm for a 1m/s wind. The GCM predictions are of maximum ~2m/s, giving 80cm wave height. Of course, as on Earth, the SWH is merely a statistical indication of wave height, and the Rayleigh distribution should be used to consider how often given 'rogue' waves might be encountered.

E. Air-Sea Exchange

Since the relative humidity of methane on Titan is only ~50%, a body of pure methane cannot persist indefinitely on Titan's surface since it is not in thermodynamic equilibrium [4,29]. The evaporation rate has been estimated, using terrestrial empirical transfer coefficients by Mitri et al. [42], and rates of ~1m/year may be expected, although this is strongly dependent on wind speed. The evaporation rate is composition-dependent, in that the saturation vapor pressure of ethane is very low, so ethane acts to suppress the partial pressure of methane above mixed-composition seas (much as syrup will evaporate in a kitchen much more slowly than water).

In fact transient surface darkening has been observed at low latitudes on Titan [43] in association with methane clouds, followed by brightening, suggesting that shallow flooding occurred, followed by evaporation - the hydrological cycle is clearly active today.

Air-sea exchange processes on Titan would be most interesting to study - the threshold windspeeds for effects such as whitecapping and spray formation (likely very important factors in exchange on Earth) may be quite different from those for water on our planet.

F. Sediment Transport

The terminal velocity of ice or organic particles in hydrocarbon liquids on Titan is rather low [44], owing to the modest density contrast, and to the low gravity. Thus the fluid currents required to move sediments are quite small. On the other hand, liquid of a given depth flowing along a given slope will have a lower speed than on Earth [45], so the net effect is of similar sediment mobility. Thus sedimentary structures such as sandbars and beaches might be expected on Titan [46]. There is some evidence of these depositional processes in action in Titan's lakes and seas, notably in Ontario Lacus [47].

V. Future Exploration of Titan's Seas

Titan's landscape, atmosphere and climate system has many parallels with Earth, with the added interest of the astrobiological implications of Titan's prebiotic chemistry and rich inventory of organics. Thus Titan remains an important target for future exploration. The Cassini mission, in the Saturn system since 2004, continues to operate well and makes several Titan encounters per year. A wide range of concepts has been advanced for future exploration of Titan, e.g. [48] including hot air balloons, airplanes, orbiters, helicopters and even hovercraft, exploiting Titan's low gravity and thick, cold atmosphere. In fact, given that liquids were expected based on what was known circa 1990, the Huygens probe was designed to float (although no other engineering requirements were levied on surface survival beyond making sure battery energy and communications geometry would permit at least 3 minutes of operation [49]. After Titan's seas were discovered, a Titan Saturn System Mission (TSSM) concept featured an orbiter, a hot air balloon, and a 'lake lander'. This expensive 'Flagship' mission was quickly shelved, however.

More recently, Titan's seas were the focus of a more modest mission recently evaluated by NASA, the Titan Mare Explorer (TiME), which would feature a capsule delivered by parachute to Ligeia [50]. This vehicle, to have been launched in 2016 to arrive in 2023: this late northern summer arrival date would permit the Earth to be visible from Ligeia's high northern latitude, allowing a direct-to-Earth data transmission, without requiring an expensive orbital relay. The winds in this season were evaluated to be modest [51] leading to small waves [41]. The capsule would operate over three months (6 Titan days) measuring the liquid composition and turbidity, studying sea-surface conditions and air-sea exchange processes with cameras and meteorological instruments, and exploring the seabed with a depth sounder [52]. During that time, it was expected [36] to drift several km per day, perhaps reaching the shoreline.

Further exciting proposals to study Titan and its seas can be expected, and in the meantime ongoing Cassini observations will doubtless reveal new surprises about Titan's alien seas.

Acknowledgments

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