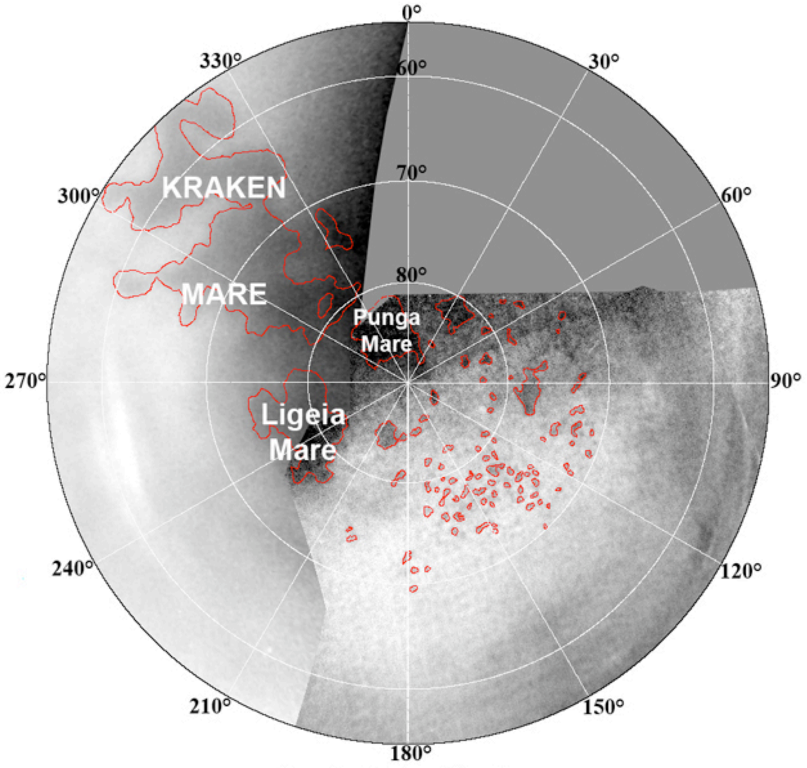
Titan Lake Probe



North Polar Region

A White Paper

J. H. Waite, Jr.,* T. Brockwell, D.T. Young, W.S. Lewis
Southwest Research Institute, San Antonio, Texas 78228-0510, USA

C.P. McKay
NASA Ames Research Center Moffett Field, California 94035-1000, USA

Francois Raulin
LISA-UMR CNRS 7583, Universités Paris, F-94000 Créteil, France

G. Schubert
Earth and Space Sciences Deparment, UCLA, Los Angeles, California 90095-1567, USA

15 September 2009

*To whom inquiries should be directed (tel.: 210.522.2034; e-mail: hwaite@swri.edu)

Titan Lake Probe

The NASA/ESA Titan Saturn System Mission (TSSM), an Outer Planets Flagship Mission envisioned for launch between 2023 and 2025 [*Coustenis et al.*, 2009], comprises an orbiter and two in-situ probes that would be deployed from it: 1) a montgolfière instrumented to image and map Titan's surface from low altitude and to sample the gases and aerosols in Titan's troposphere; and 2) a lake lander that would measure the composition of Kraken Mare, Titan's largest lake. This White Paper describes the concept for a Titan Lake Probe, which could be implemented either as an element of a TSSM-type mission or as a stand-alone New Frontiers mission. The Lake Probe could be configured either as a boat or as a submersible, with the latter configuration increasing the scope of the investigation and significantly enhancing the science return.

Introduction

Data acquired by the Voyagers in the Saturn system gave rise to speculation in the 1980s that Titan might have oceans of liquid hydrocarbons that would serve to replenish the methane irreversibly destroyed in the atmosphere by photolysis (see the review by *Lunine* [1993]). Based on Voyager 1 radio occultation data and photochemical modeling, *Lunine et al.* [1983] proposed, for example, that Titan would have a global ethane-methane ocean, one to several kilometers deep, with a layer of solid acetylene "plus a small amount of organic debris" at the bottom. The properties of the putative ocean were studied by *Dubouloz et al.* [1989], who calculated the mixing ratios of the main constituents for two surface temperatures, 92.5 K (ethane-dominated ocean) and 101 K (methane-dominated ocean), and calculated solubilities for a number of minor constituents. The possibilities for pre-biotic organic chemistry in Titan's ocean were explored by *Raulin* [1987] and *Raulin et al.* [1989].

It is now known that Titan does not have a global ocean. However, observations with the Cassini Radar Mapper have revealed a large number of lakes in Titan's northern hemisphere [*Stofan et al.*, 2007], while data from the Visual and Infrared Mapping Spectrometer (VIMS) provide strong evidence for the presence of ethane in Ontario Lacus, a large (40,000 km^2) lake in the southern hemisphere [*Brown et al.*, 2008]. The presence of propane, butane, and other alkanes is also suggested, and it is assumed that liquid methane and nitrogen are present as well. Based on Synthetic Aperture Radar imaging, three types of lakes have been observed, those that are completely liquid-filled, empty basins, and shallow lakes that represent a transitional evolutionary stage between liquid-filled and empty [*Hayes et al.*, 2008]. Over 655 potential lakes, ranging in area from <10 km^2 to 400,000 km^2 (Kraken Mare) and displaying a variety of morphologies, have been identified; the majority of them are liquid-filled. It is estimated that Titan's lakes range in depth from 10 to 300 meters and may contain as much as 300,000 km^3 of liquid hydrocarbons [*Lorenz et al.*, 2008a].

Although only ethane has been identified with some degree of confidence as a constituent in Titan's lakes [*Brown et al.*, 2007], it is highly probable, based on the composition of Titan's atmosphere and the pressure and temperature measured at the surface[1], that the lakes consist of a mixture of ethane, methane, and nitrogen, with ethane being the dominant constituent [*Lunine et al.*, 1983; *Mitri et al.*, 2007]. In addition to these bulk constituents, the lakes are expected to

---

[1] The surface at Titan's north (south) pole is 90.5±0.8 K (91.7±0.7 K) compared with an equatorial temperature of 93.7± 0.6 K [*Jennings et al.*, 2009]. *Mitri et al.* [2007] calculate a melting point temperature of 88.16 K for the ethane/methane/nitrogen mixture that they postulate in their study.

contain, as minor constituents, hydrocarbons and nitriles that have precipitated out of the atmosphere and are present as solutes in higher concentrations than in the atmosphere [*Raulin*, 2008a]. In addition, refractory organics (tholins) will also precipitate—or be washed from the surface—into the lakes. Saturated minor constituents will condense and settle to the bottom of the lake; however, seasonal convective overturning is expected to maintain some of the lighter sediments in suspension throughout the lake [*Tokano*, 2005]. Titan's lakes may also contain the noble gases xenon, krypton, and argon-38, which were not detected in the atmosphere by the Huygens Gas Chromatograph Mass Spectrometer (GCMS) [*Niemann et al.*, 2005]. The missing noble gases may have been trapped in Titan's haze particles and removed from the atmosphere as the aerosols settle onto the surface [*Jacovi & Bar-Nun*, 2008], in which case they should be present in the lakes.

Scientific Objectives

The scientific objectives of a Titan Lake Probe mission are 1) to understand the formation and evolution of Titan and its atmosphere through measurement of the composition of the target lake (e.g., Kraken Mare), with particular emphasis on the isotopic composition of dissolved minor species and on dissolved noble gases; 2) to study the lake-atmosphere interaction in order to determine the role of Titan's lakes in the methane cycle; 3) to investigate the target lake as a laboratory for both pre-biotic organic chemistry in both water (or ammonia-enriched water) solutions and non-water solvents; and 4) to determine if Titan has an interior ocean by measuring tidal changes in the level of the lake over the course of Titan's sixteen-day orbit.

Objective 1: Lake Composition. As noted above and illustrated in **Table 1**, the mixing ratios of minor constituents (hydrocarbons, nitriles, noble gases) dissolved in the ethane-methane fluid of Titan's lakes are expected to be higher than in the atmosphere, enabling spectrometric measurements of significantly higher sensitivity than were achievable with the Huygens GCMS or the Cassini INMS. Measurements of the dissolved species will provide information needed to better constrain models of the formation and evolution of Titan and its atmosphere.

Ratios of the stable isotopes of hydrogen, carbon, and nitrogen provide valuable clues to the origin of Titan's volatiles. For example, determination of the D/H ratio in H_2 in Titan will help resolve the question whether Titan's methane is primordial or the product of serpentinization. *Mousis et al.* [2009] argue that the D/H ratio in Titan's water should be close to that measured in the plume of Enceladus (~3 x10^{-4}) [*Waite et al.*, 2009] because both satellites are expected to have formed in the same region of the outer solar nebula. If serpentinization is responsible for the production of CH_4, the D/H ratio in CH_4 measured by CIRS (1.32 x 10^{-4}, *Bézard et al.* [2007]) implies a D/H ratio in Titan's primordial water significantly lower than that expected on the basis of the value at Enceladus. Measurement of a D/H ratio in Titan's water ice consistent with that at Enceladus would be strong evidence in favor of the primordial origin of Titan's CH_4.

Mandt et al. [2009] have shown that the nitrogen and carbon isotopes in N_2 and CH_4 and their photochemical derivatives (HCN, C_2H_2, etc.) can be used to trace the evolution of Titan's atmosphere over geological time. For example, N_2 has a $^{14}N/^{15}N$ of 160, which is much less than the$^{14}N/^{15}N$ ratio in terrestrial N_2 (272). The difference between the Titanian and terrestrial value has been interpreted as evidence for a large loss of N_2 over geological time. However, Mandt et al's modeling suggests (1) that this fractionation cannot be achieved by preferential loss of the light isotope of nitrogen through escape (as in the case of Mars) and (2) that the original nitrogen that formed Titan had a nitrogen isotopic ratio much more closely represented by C/N measurements in comets. On the other hand, photochemistry on Titan appears to have led to an

HCN ratio in Titan's atmosphere less than half that of N_2 (~65), which suggests that important photochemical fractionation has occurred. In addition, the carbon isotopes of CH_4 relative to heavier hydrocarbons show elevated heavy isotope signatures that may also be due to photochemistry. As these results indicate, to characterize the evolution of Titan's atmosphere, it is necessary to determine the origin and evolution of the nitrogen isotopes, in the NH_3 source as well as in present-day N_2 and the derived nitriles and amines formed through photochemistry; in in the case of the evolutionary history of Titan's methane, the $^{12}C/^{13}C$ ratio must be accurately determined in methane and its photochemical derivatives. All of the important chemical species will be concentrated in the lakes. Detailed and accurate (1 per mil) isotopic measurements of hydrogen, carbon, and nitrogen isotopes of these materials will go a long way towards understanding how the measured ratios relate to the volatile evolution of Titan.

Table 1 Concentration of lake solutes (from Raulin et al. 2009)

Species	ppm if not %
Ethane	65%
Propane	2%
Butane	4000
2-Methylpropane	4000
Pentane	400
2-Methylbutane	400
Dimethylpropane	400
Hexane	40
2-Methylpentane	40
2,2-Dimethylbutane	40
2,3-Dimethylbutane	40
3-Methylhexane	4
Ethene	4%
Propene	50
2-Methylpropene	5
1-Butene	5
2-Butene	5
1,3-Butadiene	5
Benzene	5
Ethyne	400
Propyne	30
1-Butyne	400
1,3-Butadiyne	0.5
Allene	100
Methanenitrile	3
Ethanenitrile	30
Ethanedinitrile	0.6
Propanenitrile	50
Butanenitrile	1
2-Methylpropanenitrile	1
2-Methylbutanenitrile	1
Propenenitrile	10
2-Butenenitrile	1
2-Methylpropenenitrile	1
2-Butenenitrile	1
Propynenitrile	3
2-Butynenitrile	2
Pyrimidine	2
Adenine	0.01
Carbon dioxide	10
Carbon monoxide	4
Water	$2x10^{-7}$
Ammonia	5

Objective 2: Titan's hydrological** (**methane) cycle. Like Earth, Titan has a vigorous hydrological cycle, including rain, drizzle, a variety of clouds, lakes, streams, and possibly even subsurface flow. As noted above, Titan's lakes are located in the polar regions, where the temperatures are a few degrees lower than at the equator. The vast equatorial regions of Titan appear to be a desert. From the equator poleward to 50º in both hemispheres, there are no apparent bodies of liquid. Instead there are huge linear sand dunes of organic material. Yet orbital data indicate empty stream beds and lakebeds in the equatorial desert; and at the Huygens landing site at least, the surface was moist with liquid hydrocarbons.

Cycling of surface liquids on Titan may driven by physical effects on a range of timescales. The shortest timescale could be seasonal with summer and winter variations. Alternatively the cycles may be driven by changes in the obliquity of Titan's axis and the eccentricity of Saturn's orbit. Finally, on the long timescale, changes in the amount of methane due to photochemical destruction on 100 Myr timescale may determine the extent of liquid bodies on Titan. The Cassini observations began when Titan was just past summer solstice (Ls=300º) and have continued through northern spring equinox (Ls=0º). Interestingly, throughout this time (1/6 of a Titan year), the lakes on the surface of Titan have shown only small changes, if any.

Despite superficial similarities, the global hydrological cycle on Titan is profoundly different from that on Earth. In addition, the physical properties of bodies composed of liquid methane and ethane are different from those composed of water. On both Titan and Earth, lakes in the high latitudes are near their freezing point. However, because of water's unusual density properties near its freezing point, it is likely that the thermal structure of polar lakes on Titan is quite different from the thermal structure of polar lakes on Earth. In terrestrial polar lakes, the bottom waters are often at the density maximum of 4º C, with colder, less dense water at the surface (0º C) in contact with a floating ice cover. This thermal stratification often results in chemical stratification as well, most significantly with respect to dissolved oxygen. In lakes on Titan, temperature and density are more simply related and stratification would imply colder bottom temperatures than surface temperatures. Any solar or geothermal heating would tend therefore to mix lakes. In contrast with Earth, lakes on Titan have two volatile components with significantly different volatilities. A mixture of methane and ethane may preferentially evaporate methane, changing the density of surface fluids. Denser, ethane-enriched, surface layers would sink in a methane lake further enhancing mixing.

To understand the role of the lakes in the methane cycle of Titan, it is necessary to measure the thermodynamic state of the atmosphere above the lake including the relative humidity of methane and ethane, the static stability, the wind vector, the height of the boundary layer and other parameters relevant to modeling the evaporation from the lake.

To characterize the structure of polar lakes on Titan, it is necessary to measure the temperature profile in the upper layers (many meters) of the lake. It would also be important to determine if there was a composition change in the upper layers with respect to methane and ethane mixing ratios.

Objective 3: Pre-biotic organic chemistry. The relative deficiency of Titan's atmosphere in oxygen gives rise to the question whether prebiotic organic chemistry at Titan (1) is terrestrial in nature, occurring in cryovolcanic ammonia-water flows or in melt pools resulting from impacts, or (2) represents an altogether different chemistry, "where ammonia substitutes for water, and N-chemical groups substitute for O-chemical groups" [*Raulin and Owen*, 2002, p.383; *Raulin*, 2008b]. With its hydrocarbon lakes and ammonia-water cryomagma, Titan affords a unique laboratory for the investigation of alternative—"weird"—biochemical processes involving non-water polar solvents (ammonia) or nonpolar solvents (hydrocarbons) [cf. *NRC*, 2007].

The possibility of prebiotic organic chemistry in transient exposures of liquid water was proposed by *Thompson and Sagan* [1992]. Recent studies have demonstrated that both impact melts [*O'Brien et al.*, 2005] and cryovolcanic flows [*Neish et al.*, 2006] can remain unfrozen for centuries or longer, providing a medium in which tholins, hydrocarbons, and nitriles deposited on the surface of Titan can react with water or an ammonia-water solution. The aqueous chemistry occurring in such a medium is expected to produce a host of complex oxygenated and N-bearing organic compounds [*O'Brien et al.*, 2005; *Neish et al.*, 2009], including amino acids, which can be produced in substantial amounts by the hydrolysis of tholins [*Khare et al.*, 1986], as well as amino acids, purines, and pyrimidines from the hydrolysis of the oligomers of HCN [*Ferris et al.*, 1978]. The resulting compounds will wash, along with frozen water droplets and hydrocarbon-covered water-ice "pebbles" [*Tomasko et al.*, 2005], from Titan's surface into the lakes, where they can be measured with high sensitivity.

An additional site for prebiotic chemistry would be provided by porous connections to an ammonia-enriched water ocean hypothesized to lie beneath Titan's ice crust. The chemistry would be enabled (1) by the ability of methane/ethane solvents in the lake above the interface to provide a rich chemical environment for evolution of bipolymers that would otherwise be impossible to obtain if water were the predominant solvent, (2) by the ability of the ammonia-water mixture to supply trace minerals or trace compounds such as phosphor or arsenic, and (3) by the rich heteroatomic nature of the seed organics formed by dissociation of nitrogen and methane in the upper atmosphere of Titan.

Objective 4: Interior Science. Models of Titan's formation and internal structure predict that Titan has an ammonia-enriched ocean beneath a thick ice crust [e.g., *Lunine and Stevenson*, 1987; *Sohl et al.*, 2003], and recent observations of Titan's rotational period have been interpreted as evidence for the presence of an internal water ocean decoupled from Titan's rock core [*Lorenz et al.*, 2008b]. An additional science objective for the Titan Lake Probe is to confirm the existence of the predicted interior ocean. Like any lander on Titan, a Titan Lake Probe would have the capability of making observations that would constrain our knowledge of the moon's interior. Admittedly, although the relevant measurements by the Probe for interior science would be more difficult to interpret than corresponding measurements by a fixed lander, it should be possible to account for the Lake Probe's motions induced by winds or currents in the lake or other motions of the lake surface. In order to understand Titan's origin, evolution, and present state, we need answers to the following questions: What is the extent of differentiation of Titan's interior? Does Titan have a metallic core? What is the physical state, solid or liquid, of a possible metallic core in Titan? Does Titan have a subsurface global water ocean under its ice shell? What is the thickness of the ice shell and how does the ice thickness vary with location?

Cassini has provided some data that partially address these questions, e.g., determination of the moon's lowest-order gravitational coefficients by the radio science experiment and measurement of the rotation of the surface by the radar. However, additional measurements are needed to definitively answer these questions. A Lake Probe could be instrumented to determine its vertical displacement due to tides, thereby constraining the possibility that Titan might have an internal water ocean. With a magnetometer, the Probe might be able to detect induced time-varying electrical currents, thereby contributing to the identification of an internal ocean. A pressure sensor could give information on modes of oscillation of the coupled atmosphere/solid body. Accurate tracking of the Probe would provide crucial information for interpreting the other measurements and isolating currents within the lake. These are just examples of the measurements that could be made by a Lake Probe. Clearly they need more careful study to assess their potential to probe Titan's interior.

Implementation

Both the Titan Explorer (TE) and the Titan Saturn System Mission (TSSM) studies have demonstrated that it is possible to place a landing ellipse in the center of Kraken Mare or another one of Titan's large lakes from a range of trajectories including Saturn flyby, Saturn orbital or Titan orbital. Suggested mission concepts have included boats (TSSM) and submersible lake probes [*Brockwell and Waite*, 2008]. Both concepts allow first order characterization of the lake composition and provide information about the lake-atmosphere interaction. These studies agree that a well-equipped chemical analysis system that includes noble gas, organics, and CHON isotopic determination are the first measurement priority and that a meteorological package that measures the relative humidity of methane and ethane, the static stability, the wind vector, the height of the boundary layer and other parameters relevant to modeling the evaporation from the lake, is a necessary secondary payload.

The use of the submersible enables additional studies: 1) determination of the lake's vertical structure (temperature and pressure), 2) determination of changes in lake composition and chemistry as a function of depth, 3) measurement of the lake tides from a fixed platform at the bottom of the lake, which in conjunction with 1 will allow determination of the Titan lake tides with an accuracy of ~10 cm, and 4) characterization of the lake sediment composition. These additional objectives require the payload to be augmented by a lake temperature and pressure sensor, as well as an upward looking sonar.

There are no major technical drivers that must be overcome to make a lake probe possible. A submersible can be designed to accommodate the uncertainty in the density of the lake (methane/ethane ratio) and alternative concepts that include a floater and a sinker are also possible. The use of a floater can facilitate communications by housing the antenna and communication subsystem. Communications can be difficult for a flyby mission and may require direct to Earth or a delayed, well-timed flyby from the carrier spacecraft. If the lake probe is part of an architecture that includes a Saturn or Titan orbiter the communications options are greatly improved (see the TE and TSSM study reports).

Thermal design is an important concern. Radioisotope Heating Units (RHUs) and or Radioisotope Thermionic Generators (RTGs) if used must be cooled to space during cruise. Maintaining an operable temperature in the lakes may be accomplished by using a vacuum pressure vessel to minimize heat losses in the 94 K environment. Compositional sampling can be facilitated by the use of membranes, which are routinely used to sample the Earth's oceans volatile composition.

References

Bézard, B. et al. Detection of $^{13}CH_3D$ on Titan, *Icarus* **191**, 397-400 (2007).

Brockwell, T. & Waite, J.H., Jr. *Concept for a Titan Submersible*, SwRI White Paper (2008).

Brown, R.H. et al. The identification of liquid ethane in Titan's Ontario Lacus, *Nature* **454**, 607-610 (2008).

Coustenis, A. et al. Earth-based support for the Titan Saturn System Mission, *Earth Moon Planet* **105**, 135-142 (2009).

Dubouloz, N., Raulin, F., Lellouch, E., Gautier, D. Titan's hypothesized ocean properties: The influence of surface temperature and atmospheric composition uncertainties, *Icarus* **82**, 81-96 (1989).

Ferris, J.P. et al. HCN: A plausible source of purines, pyrimidines and amino acids on the primitive Earth, *J. Mol. Evol.* **11**, 293-311 (1978).

Hayes, A. et al. Hydrocarbon lakes on Titan: Distribution and interaction with porous regolith, *Geophys. Res. Lett.* **35**, L09204, doi: 10.1029/2008GL033409 (2008).

Jacovi, R. & Bar-Nun, A. Removal of Titan's noble gases by their trapping in its haze, *Icarus* **196**, 302-304 (2008).

Jennings, D.E. et al. Titan's surface brightness temperatures, *Astrophys. J. Lett.* **691**, L103-L105 (2009).

Khare, B.N. et al. Amino acids derived from Titan tholins, *Icarus* **68**, 176-184 (1986).

Lorenz, R.D. et al. Titan's inventory of organic surface materials, *Geophys. Res. Lett.* **35**, L02206, doi: 10.1029/2007GL032118 (2008a).

Lorenz, R.D. et al. Titan's rotation reveals an internal ocean and changing zonal winds, *Science* **319** 1649-1651 (2008b).

Lunine, J.I. Does Titan have an ocean? Review of current understanding of Titan's surface, *Rev. Geophys.* **31**, 133-150 (1993).

Lunine, J.I. & Stevenson, D.J. Clathrate and ammonia hydrates at high pressure: application to the origin of methane on Titan, *Icarus* **70**, 61-77 (1987).

Lunine, J.I., Stevenson, D.J., Yung, Y.L. Ethane ocean on Titan, *Science* **222**, 1229-1230 (1983).

Mandt, K. et al. Isotopic evolution of the major constituents of Titan's atmosphere based on Cassini data, *Planet. Space Sci.*, in press (2009).

Mitri, G. et al. Hydrocarbon lakes on Titan, *Icarus* **186**, 385-394 (2007).

Mousis, O. et al., A primordial origin for the atmospheric methane of Saturn's moon Titan, *Icarus*, accepted (2009).

Neish, C.D., Lorenz, R.D., O'Brien, D.P. The potential for prebiotic chemistry in the possible cryovolcanic dome Ganesa Macula on Titan, *Int. J. Astrobiol.* **5**, 57-65 (2006).

Neish, C.D., Somogyi, A. Lunine, J.I., Smith, M.A. Low temperature hydrolysis of laboratory tholins in ammonia-water solutions: Implications for prebiotic chemistry on Titan, *Icarus* **201**, 412-421 (2009).

Niemann, H.B. et al. The abundances of constituents of Titan's atmosphere from the GCMS instrument on the Huygens probe, *Nature* **438**, 779-784 (2005).

NRC *The Limits of Organic Life in Planetary Systems*, The National Academies Press, Washington D.C. (2007).

O'Brien, D.P., Lorenz, R.D., Lunine, J.I. Numerical calculations of the longevity of impact oases on Titan, *Icarus* **173**, 243-253 (2005).

Raulin, F. Organic chemistry in the oceans of Titan, *Adv. Space Res.* **7**, 71-81 (1987).

Raulin, F. Organic lakes on Titan, *Nature* **454** 587-588 (2008a).

Raulin, F. Astrobiology and habitability of Titan, *Space Sci. Rev.* **135**, 37-48 (2008b)

Raulin, F. & Owen, T. Organic chemistry and exobiology on Titan, *Space Sci. Rev.* **104**, 377-395 (2002).

Raulin, F., Dubouloz, N., Frère, C. Prebiotic-like organic syntheses in extraterrestrial environments: The case of Titan, *Adv. Space Res*. **9**, 35-47 (1989).

Raulin, F. et al. Titan's Astrobiology, in: *Titan from Cassini-Huygens*, eds. R.H. Brown et al., Springer Science + Business Media BV (2009)

Sohl, F. et al. Interior structure modesl and tidal Love numbers of Titan, *J. Geophys. Res.* **108**, CiteID 5130 (2003).

Stofan, E.R. et al. The lakes of Titan, *Nature* **445**, 61-64 (2007).

Thompson, W.R. & Sagan, C. Organic chemistry on Titan: surface interactions, in: *Symposium on Titan*, 167-176, ESA SEE N92-32348 23-91 (1992).

Tokano, T. Thermal structure of putative hydrocarbon lakes on Titan, *Adv. Space Res.* **36**, 286-294 (2005).

Tomasko, M.G. et al. Rain, winds and haze during the Huygens probe's descent to Titan's surface, *Nature* **438**, 765-778 (2005).

Turtle, E.P. et al. Cassini imaging of Titan's high-latitude lakes, clouds, and south-polar surface changes, *Geophys. Res Lett.* **36**, L02204, doi: 10.1029/2008GL036186 (2009).

Waite. J.H., Jr. et al. Liquid water on Enceladus from observations of ammonia and ^{40}Ar in the plume, *Nature* **460**, 487-490 (2009).

Cover. Cassini Imaging Science Subsystem map of Titan's northern hemisphere showing Kraken Mare, Ligeia Mare, and Punga Mare, along with a number of other putative lakes. Coastlines are outlined in red (from *Turtle et al.*, 2009).