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The Lakes and Seas of Titan

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The study of Titan, Saturn's largest satellite, is a major goal of the Cassini-Huygens mission. This joint project between NASA, the European Space Agency, and the Italian Space Agency consists of a Saturn orbiter (Cassini) and a Titan probe (Huygens). Since the mission's arrival at Saturn in July 2004, one of its most spectacular discoveries has been the finding of the first extraterrestrial nonmagmatic standing bodies of liquid: Titan's hydrocarbon lakes and seas. In July 2006, the first synthetic aperture radar (SAR) images of Titan's north polar region obtained by the Cassini spacecraft showed dozens of lakes above latitudes of 70° [Stofan *et al.*, 2007]. Subsequent SAR images obtained by Cassini have covered approximately 68% of Titan's north polar region at latitudes above 60 degrees. These images show more than 400 radar-dark areas that we interpret as being liquid lakes (shown in dark blue in Figure 1), including a few that are so large that they rightfully may be called seas. We discuss here the evidence for liquids on Titan, the distribution and morphology of lakes, and recent data that indicate the presence of lakes in the south polar regions.

Radar backscatter is affected by three factors: (1) local topography (if a surface is angled toward the instrument, it will generally appear brighter); (2) surface roughness, at or near the wavelength of the radar instrument (2.2-centimeter Ku band); and (3) surface dielectric constant (the dielectric constant is the relative permittivity of a dielectric, and it directly affects how much radar is reflected back at the spacecraft). The extremely low radar backscatter from most of Titan's lakes indicates both that these areas have a low dielectric constant and that they are very smooth at the 2.2-centimeter wavelength. Studies of the lakes' morphology, distribution, and associated channels, together with the low radar reflectivity and correspondingly high emissivity, all

support the hypothesis that the lakes currently contain liquid hydrocarbons [Stofan *et al.*, 2007], most likely containing a mixture of methane and ethane, and probably also dissolved nitrogen [Mitri *et al.*, 2007].

The existence of liquid hydrocarbons on Titan's surface had been predicted, based on thermodynamic models of the stability of liquid hydrocarbons at the low surface

temperatures of Titan and on the observations of methane in the atmosphere, which is destroyed by sunlight and therefore must be replenished [Lunine *et al.*, 1983]. Observations by the Huygens probe to Titan, as well as SAR images at low latitudes, had shown ample evidence for processes involving liquids, including fluvial networks, rounded pebbles at the Huygens landing site, and evaporating liquids. Finding bodies of liquids remained elusive, though the Cassini imaging system observed a dark fea-

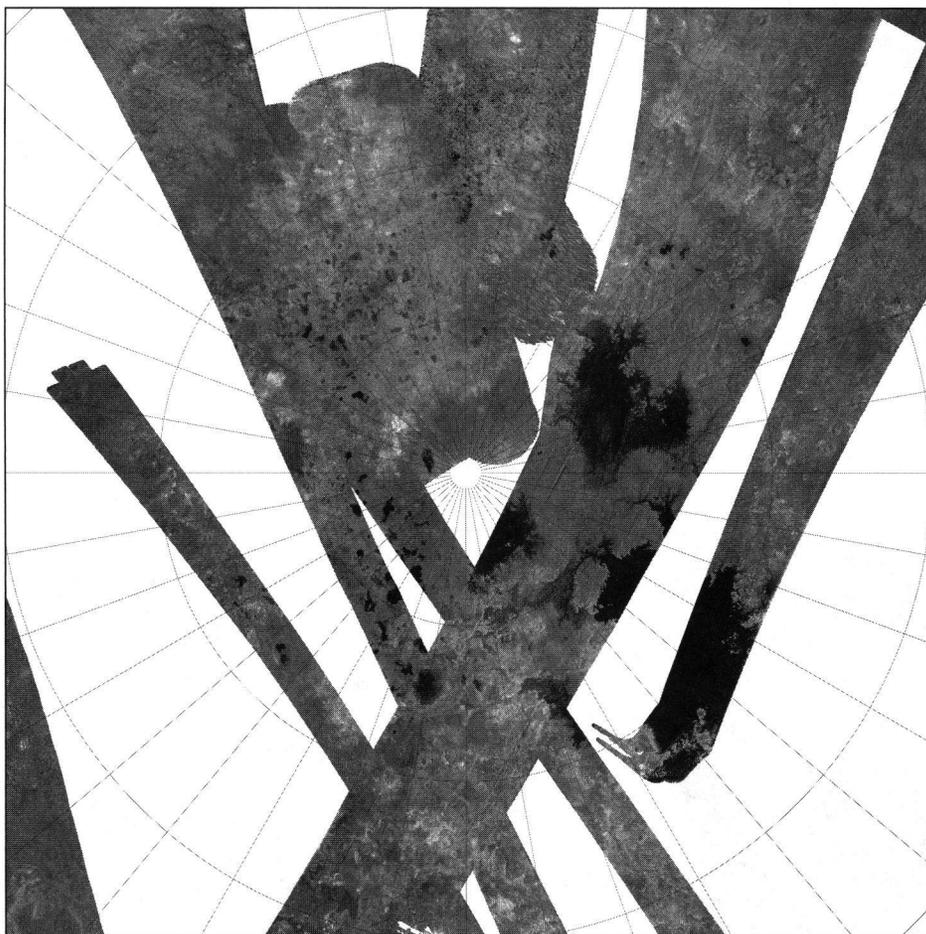


Fig. 1. This colorized synthetic aperture radar (SAR) image obtained by Cassini is a composite made from seven Titan flybys. The image shows that Titan's north polar region is pitted with giant hydrocarbon lakes and seas (shown in dark areas) and that at least one of them (upper right) is larger than Lake Superior, the largest freshwater lake on Earth. Approximately 68% of Titan's north polar region, above 60° latitude, has been mapped by Cassini's radar instrument (used in SAR mode). About 14% of the mapped region is covered by lakes and seas, which are interpreted to be liquid. The 0°–180° longitude line intersects the image from top (180°) to bottom (0°). Latitude circles are in 10° intervals. The image is about 2700 kilometers wide. The image is available at <http://photojournal.jpl.nasa.gov/catalog/PIA10008>. Original color image appears at the back of this volume.

By R. M. C. LOPES, K. L. MITCHELL, S. D. WALL, G. MITRI, M. JANSSEN, S. OSTRO, R. L. KIRK, A. G. HAYES, E. R. STOFAN, J. I. LUNINE, R. D. LORENZ, C. WOOD, J. RADEBAUGH, P. PAILLOU, H. ZEBKER, AND F. PAGANELLI

ture near Titan's south pole, named Ontario Lacus, that was interpreted as a lake [Turtle *et al.*, 2007].

The presence of liquid methane and ethane at high latitudes also was predicted, based on the relative humidity of methane (amount of methane relative to the saturated value) in Titan's dense atmosphere. Except at the highest latitudes, the relative humidity of methane is under 100%, and it is below 50% at low latitudes, which would cause any standing liquids to evaporate. Methane precipitation near the poles is thought to dominate the "hydrological" cycle of Titan [Rannou *et al.*, 2006], with methane playing a role similar to that of water on Earth. Lakes containing liquid methane should be stable from the poles down to a latitude determined by the abundance of methane in the surface-atmosphere system and by the possible intersection of surface fluids with putative subterranean "methanifers," analogous to terrestrial aquifers [Stofan *et al.*, 2007]. Mitri *et al.* [2007] proposed that the observed humidity of the atmosphere could result from a global liquid coverage of as little as 0.2–2% of Titan's area, which is consistent with the radar-dark areas shown in Figure 1.

The Case for Liquids

The evidence that these radar-dark lakes are liquids can be summarized as follows. First, their morphology and relationship with fluvial features give strong evidence that the lakes are, or recently were, filled with liquids. Second, the anomalously low radar backscatter (at times, the lowest the radar can see) implies that these areas are extremely smooth at the scale of 2.2 centimeters and, further, that very little or no energy is backscattered from the lake volume itself. Third, the presence of liquids at the polar regions is consistent with atmospheric and climatological models. Fourth, the lakes' radiometric brightnesses, higher by several degrees than the surrounding terrain, are consistent with the high emissivity expected for a smooth surface with the low dielectric constant (1.7–1.9) of liquid ethane-methane solutions. However, it can be argued that the liquids hypothesis has yet to be tested conclusively.

Since it is currently winter in Titan's northern polar regions, there is not enough reflected sunlight for optical and near-infrared instruments on Cassini to observe these regions. A season on Titan lasts nearly 7.5 years, one quarter of a Saturn orbit period, which is 29.5 Earth years long. It will be midsummer at the north polar regions in 2017, but in only a few more years, there may be enough sunlight at high northern latitudes for Cassini's near-infrared spectrometer to obtain observations that will confirm the evidence provided by SAR images.

While the Cassini mission was initially scheduled to last only until mid-2008, an additional 2 years of mission life are cur-

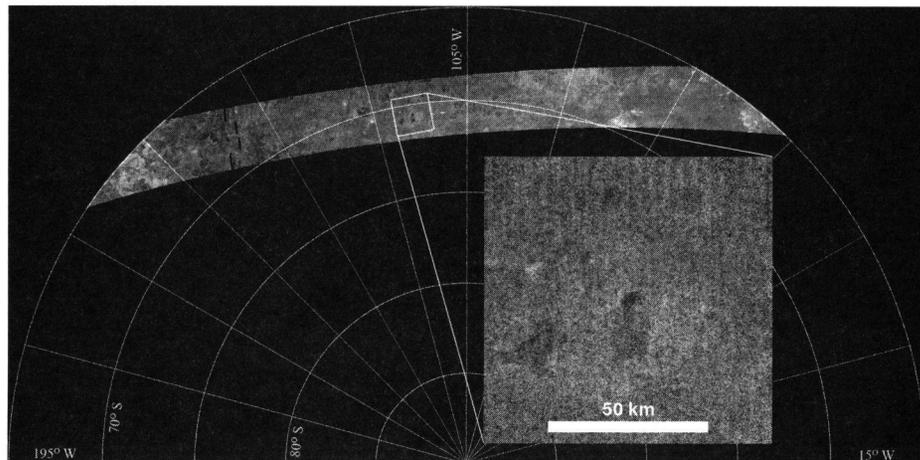


Fig. 2. Synthetic aperture radar images from the southernmost region of Titan, returned from a 2 October 2007 Cassini flyby, show the presence of lakes in the southern hemisphere. Shown here is a portion of the image swath and an inset with details in false color. Titan's south pole is at bottom center. A few small dark patches—interpreted as liquid-hydrocarbon-filled lakes—stand out, at about 70°S. The image swath is 2250 kilometers long and has average spatial resolution of 1.4 kilometers. The inset is 90 × 90 kilometers, centered at 70.5°S and 113.9°W. The image is available at <http://photojournal.jpl.nasa.gov/catalog/PIA10018>. Original color image appears at the back of this volume.

rently planned. Increased longevity of the mission not only provides the opportunity to observe seasonal changes but also permits repeated coverage of the north polar regions using SAR, and consequent study of possible changes in liquid levels. Such changes would provide the strongest evidence for liquids.

Some overlapping coverage has already been obtained, and one of the lakes showed significant brightening. However, this may or may not be due to change in the level of liquid, as the brightening may be due to different viewing geometries between flybys. If the lakes are not filled with liquid hydrocarbons, an alternative possibility to explain the low-dielectric-constant material is that there is a layer of low-density solid hydrocarbons. We consider the simplest and most likely explanation to be that the polar lakes are filled with liquid hydrocarbons.

Morphology and Sizes

There is considerable variation in the morphology of lake depressions and also in their radar backscatter. Shapes range from circular to canyon-like. Some lakes are within steep-sided depressions (opposite-look stereo parallax measurements show some depressions to be several hundred meters deep), while others appear to have shallow or poorly defined margins but are surrounded by topographically high areas of the order of 1000 meters over distances of 50–100 kilometers. Lakes in steep-sided depressions appear morphologically similar to volcanic crater lakes, glacial lakes, or massive, karstic dolines (sinkholes). Other lakes, including the largest, have morphologies consistent with flooded drained basins (e.g., Lake Powell in Utah and Arizona). The origin of lake depressions is uncertain, but current hypotheses

include volcanic craters and karst-like depressions. Some of the depressions are completely filled with radar-dark material, others are partially filled, and some apparently are empty.

The lakes vary greatly in size, from the limit of SAR resolution (which varies from 300 meters to >1 kilometer) to over 100,000 square kilometers (for comparison, North America's Lake Superior is 82,000 square kilometers). The largest Titan lake observed in its entirety covers a greater fraction of Titan (0.12%) than the most extensive terrestrial inland sea, the Black Sea, does of the Earth (0.085%). We therefore refer to the largest of the radar-dark features as seas. The International Astronomical Union has recently approved the use of the term "mare" for the seas of Titan. Mare is a term previously only used for the Earth's Moon (to denote large expanses of volcanic deposits). Smaller lakes on Titan are designated "lacus" and are named after lakes on Earth similar in shape. To date, 12 lakes on Titan have been named; a figure with lake names can be seen on the planetary nomenclature Web site at http://planetarynames.wr.usgs.gov/images/NP_lakes_low_noboundaries.pdf.

Global Distribution

While much of the northern hemisphere has been imaged with SAR, only 20% of Titan's total area has been imaged so far. Are lakes and seas present in Titan's south polar regions? Other than the optical feature named Ontario Lacus, the first indication of the presence of lakes in the southern polar regions came from SAR data acquired on 2 October 2007. Three radar-dark lakes, with backscatter similar to those in the north polar regions, were detected where the radar swath reached its highest

southern latitude, at about 70° (Figure 2). Other features in these data include broad, steep-sided depressions adjoined to sinuous depressions interpreted to be empty topographic basins or drained lakes fed by channels. Similarities in features between northern and southern polar regions imply that the climatic conditions might be similar, despite the difference in seasons. Such morphological similarities also make a volcanic origin for the majority of lake depressions less likely, unless one can argue that volcanism can be concentrated at the polar regions.

Future Cassini flybys targeting high southern latitudes using radar will show whether the distribution of lakes and seas near Titan's south pole is comparable to that observed at the north polar regions. If this is the case, the reservoir of hydrocarbons at Titan may be much larger than implied by current data. Lorenz *et al.* [2007] estimated Titan's total inventory of methane/ethane lakes, all found in the polar regions, to be of the order of 30–300,000 cubic kilometers, containing hundreds of times more liquid hydrocarbons than the entire known gas and oil reserves on Earth.

The existence of lakes and seas on another world opens up new avenues of scientific inquiry for limnologists and oceanographers: The physics of waves, tides, stratification,

and sedimentation is the same as on Earth, but the dynamical parameters such as gravity and rotation rate, and fluid properties such as density and viscosity (summarized by Lorenz *et al.* [2003]) are different. Titan is therefore a laboratory in which these very different circumstances can be used to test our understanding of Earth's lacustrine and marine processes.

Acknowledgments

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NEWS

In Brief

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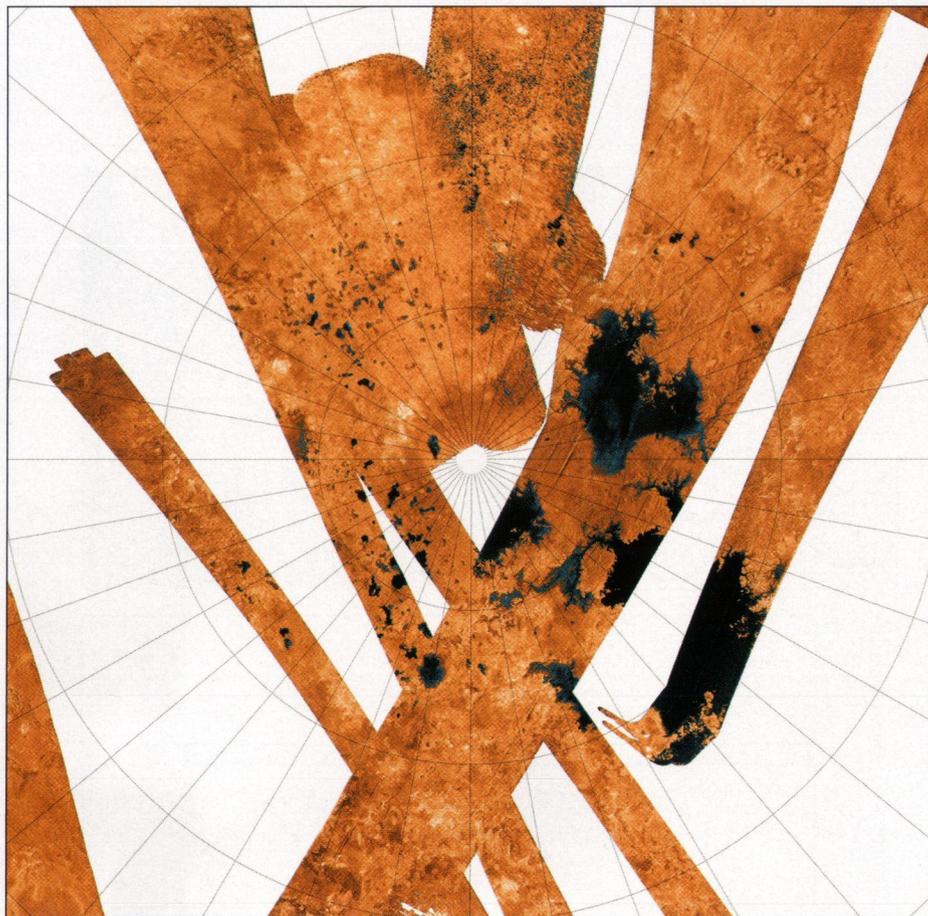
NASA mission to measure Moon's gravity NASA has selected a new mission to measure the Moon's gravity field in unprecedented detail, according to the agency's associate administrator for science, Alan Stern. The Gravity Recovery and Interior Laboratory (GRAIL), which is part of NASA's Discovery Program series of scientist-led, solar system exploration missions, is scheduled to launch in 2011 following the agency's 2008 launch of the Lunar Reconnaissance Orbiter. Scientists plan to use gravity field information from GRAIL's two spacecraft to X-ray the Moon from crust to

core to reveal subsurface structures and, indirectly, the Moon's thermal history. A camera aboard each spacecraft will allow the public to see observations from the satellites. GRAIL "offers to bring innovative Earth studies techniques to the Moon as a precursor to their possible later use at Mars and other planets," Stern said. For more information, visit the Web site: <http://discovery.nasa.gov/>.

Atlantic seasonal hurricane forecast Two hurricane forecasters are predicting that 2008 will be an above-average Atlantic basin tropical cyclone season with an above-average probability of a major hurricane making landfall in the United States. During 2008, there could be about seven hurricanes (the annual average is 5.9) and

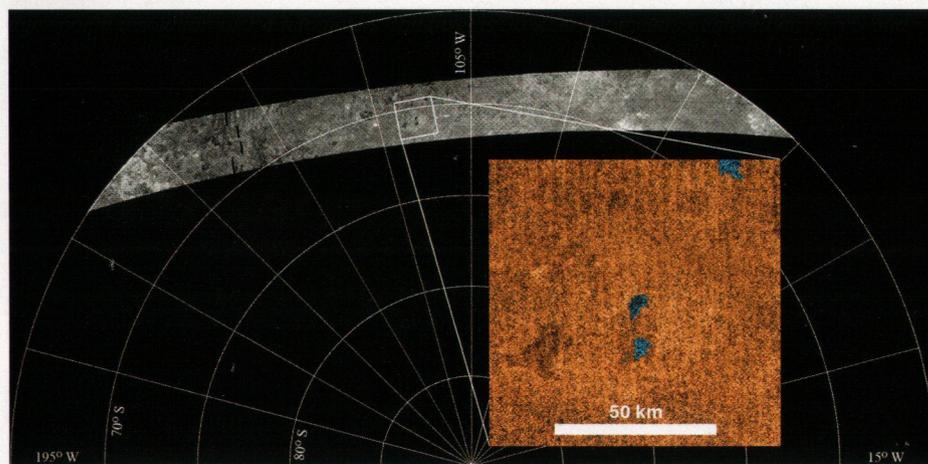
13 named storms (the average is 9.6), according to a 7 December report by Philip Klotzbach, research scientist at Colorado State University in Fort Collins, and William Gray, university professor emeritus of atmospheric sciences. The forecasters indicate that they believe the Atlantic basin is in an active hurricane cycle that is associated with a strong thermohaline circulation and an active phase of the Atlantic Multidecadal Oscillation. The report notes that, "real-time operational early December forecasts have not shown forecast skill over climatology during this 16-year period [1992–2007]. This has occurred despite the fact that the skill over the hindcast period... showed appreciable skill." For more information, visit the Web site: <http://hurricane.atmos.colostate.edu/Forecasts/2007/dec2007/dec2007.pdf>.

—RANDY SHOWSTACK, Staff Writer



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