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The lakes of Titan

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The surface of Saturn's haze-shrouded moon Titan has long been proposed to have oceans or lakes, on the basis of the stability of liquid methane at the surface[1,2]. Initial visible[3] and radar[4,5] imaging failed to find any evidence of an ocean, although abundant evidence was found that flowing liquids have existed on the surface[5,6]. Here we provide definitive evidence for the presence of lakes on the surface of Titan, obtained during the Cassini Radar flyby of Titan on 22 July 2006 (T_{16}). The radar imaging polewards of 70° north shows more than 75 circular to irregular radar-dark patches, in a region where liquid methane and ethane are expected to be abundant and stable on the surface[2,7]. The radar-dark patches are interpreted as lakes on the basis of their very low radar reflectivity and morphological similarities to lakes, including associated channels and location in topographic depressions. Some of the lakes do not completely fill the depressions in which they lie, and apparently dry depressions are present. We interpret this to indicate that lakes are present in a number of states, including partly dry and liquid-filled. These northern-hemisphere lakes constitute the strongest evidence yet that a condensable-liquid hydrological cycle is active in Titan's surface and atmosphere, in which the lakes are filled through rainfall and/or intersection with the subsurface 'liquid methane' table.

Liquid methane is a thermodynamically allowed phase anywhere on the surface of Titan today. However, at all except the highest latitudes, the methane relative humidity (amount of methane relative to the saturated value) is less than 100%, and so standing bodies of methane must evaporate into the atmosphere. There is no methane ocean in contact with the atmosphere[8], and the timescale for saturating the atmosphere by evaporation of methane from the surface (about 10^3 years (ref. 9)) is much longer than the seasonal cycle of just under 30 years. Hence methane precipitation near the poles should dominate the 'hydrology' of methane on Titan[10]. Thus, lakes will 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 such surface methane fluids with putative subterranean 'methanifers', analogous to terrestrial aquifers.

An additional factor in establishing and stabilizing the presence of lakes at high latitude is the preferential deposition of ethane in polar regions (see, for example, ref. 11). This in turn may be controlled by the availability of cloud condensation nuclei in the stratosphere enhanced by the sedimentation of heavier organics such as C_4N_2 (ref. 12) in the seasonal polar hood. This feature, imaged nearly a Titan year ago by Voyager in the north and now also seen to be present (see, for example, ref. 13), forms during polar winter. Observations and modelling suggest that high-latitude clouds poleward of 75° south are methane but include an ethane mist[9]. Ethane is fairly involatile at Titan surface conditions, and hence if present would form a permanent component to lakes. With the observations currently available, the condensed-phase surface methane-to-ethane ratio cannot be constrained. Even if the as yet unmeasured surface temperatures above 75° north latitude are 3–5 K below the equatorial 93.6 K (ref. 14), as suggested by Voyager observations[11], dissolved nitrogen in binary methane–nitrogen lakes will depress the freezing point sufficiently, and ternary methane–ethane–nitrogen lakes will have strongly depressed freezing points.

The Cassini Titan Radar Mapper[4,15] (K_u-band wavelength 2.17 cm) instrument had its sixth radar pass of Titan (T_{16}) on 22 July 2006 (UTC). The synthetic aperture radar (SAR) arc-shaped imaging swath extends from mid-northern latitudes to near the north pole and back, and is 6,130 km long with spatial resolutions of 300–1,200 m (Fig. 1, and Supplementary Fig. 1). Incidence angles across the swath vary from 15° to 35°. The portion of the swath that extended from about 70° to 83° north contained more than 75 radar dark patches, from 3 km to more than 70 km across.

The dark patches contrast with the surrounding terrain, which has a mottled appearance similar to that of other 'plains' regions on Titan[4,5,16]. The backscatter of some of the dark patches is extremely low. Several appear at the noise floor of the data (about -25 dB σ_0), with much lower reflectivity than previously imaged areas on Titan, including the radar-dark (about -13 dB σ_0) sand dunes observed near Titan's equator. For the darkest patch we have observed so far, the normalized radar cross-section (σ_0) value is less than about -26 dB and could be zero, because the measured signal is at the system noise level (Fig. 2). We are unable to ascertain that any signal at all has been reflected from this feature.

The radar backscatter of the dark patches at Cassini SAR imaging incidence angles is consistent with that expected from a very smooth surface of any kind (for example liquid, rock, ice or organics) or even simply a non-reflecting, absorbing surface (for example a low-density surface smoothly matched into a non-scattering absorber such as fluffy soot or dirty snow overlying a uniform and electrically absorbing substrate). Radiometric brightness temperatures are obtained along with the SAR swaths, although the spatial resolution is limited to the footprints of the respective radar beams (that is, more than

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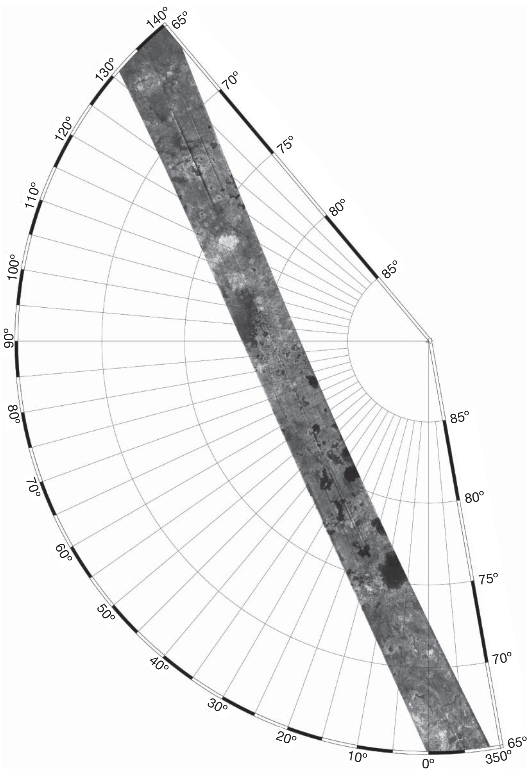

Figure 1 | Northern portion of the T_{16} swath. This portion of the T_{16} swath contains the dark patches interpreted as lakes. The image swath is shown in a polar projection; for scale, 1° of latitude is about 45 km. A high-resolution version of this image is given in Supplementary Information.

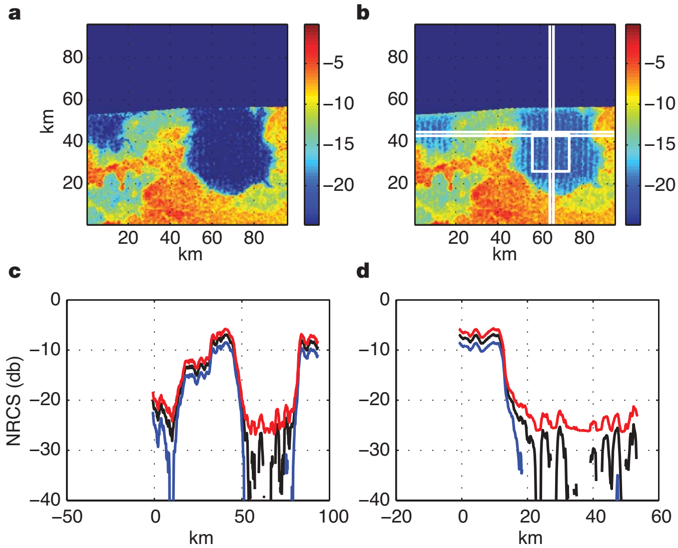

Figure 2 | Radar return from the darkest observed lake. **a**, Pseudo-colour image of observed normalized radar cross-section (NRCS) over lake at 80.5° north, 50° west. Corrections have been applied to remove known systematic biases in return resulting from thermal noise. NRCS measurement produced by thermal noise alone is referred to as the noise floor. Noise floor varies throughout the image due primarily to shape of antenna gain pattern. Dark blue region at top is outside radar observation. **b**, The same image without noise correction. White vertical and horizontal lines depict cuts used to produce **c** and **d**. To reduce the effect of random variance, we averaged NRCS over a 17 m × 17 km region (white rectangle). **c**, Horizontal cut through the noise-corrected NRCS image (black) with a 2σ lower bound (blue) and upper bound (red). In **c** and **d**, each point on the solid black curve is the average NRCS over a 3.6 km × 3.6 km area. Error bars include the effect of relative calibration errors due to spacecraft attitude knowledge, errors in noise subtraction process, and random variance. Cassini radar NRCS estimates have an unknown absolute bias estimated to be ±3 dB. Gaps in the NRCS curve and the lower bound curve are regions in which the values are zero or negative and thus cannot be represented in dB. **d**, Vertical cut through the noise-corrected NRCS image. There is a large contrast (15 dB) in NRCS across lake boundaries.

6 km). Nevertheless, several dark patches were observed that were resolved or partly resolved by at least one of the beams. The temperature contrast between these dark patches and the surrounding terrain is consistent with a flat surface of low dielectric constant in an ice terrain, where the emissivity of the ice is probably decreased somewhat by volume scattering. From microwave reflectivity and emissivity considerations, then, the dark patches are probably smooth surfaces of a low-dielectric material such as liquid methane.

At several of the dark patches, radar-dark sinuous features lead into the dark patch (Fig. 3a). These features resemble channels elsewhere on Titan interpreted to be fluvial in origin[4,5,17]. Two of the dark patches are connected by a narrow, radar-dark channel (Fig. 3b). However, even the dark patches with channels do not have extensive associated channel networks, suggesting that the channels are not the sole source of dark material infilling the patches.

Fifteen dark patches are in relatively steep-sided, rimmed, circular depressions, in contrast with other dark patches in this region that exhibit no such topography at this scale. These depressions seem to have existed in this form before being filled with dark material, and do not show clear evidence of erosion. The dark patches in depressions resemble terrestrial lakes confined within impact basins (for example Clearwater Lakes, Canada), volcanic calderas (for example Crater Lake, Oregon, USA) or karst dolines or sinkholes. The nested nature and limited size range of the depressions make an impact origin unlikely. A volcanic origin for the depressions is possible, given their morphology and our previous identification of cryovolcanic calderas on Titan[4,18]. Although liquid methane is thought to be unable to dissolve water ice[19], it is also possible that dissolution of a mixed organics and ice substrate has produced topographic depressions that can hold liquid.

Only two hypotheses are consistent with the radiometric and morphological characteristics of the dark patches: either we are observing liquid-filled lakes on Titan today, or depressions and channels formed in the past have now been infilled by a very low-density deposit that is darker than any observed elsewhere on Titan. The absence of any aeolian features in this area makes low-density, porous, unconsolidated sediments unlikely. This, combined with the morphologic characteristics of the dark patches, leads us to conclude that the dark patches are lakes containing liquid hydrocarbons.

Several types of characteristic margins or shorelines of the lakes are observed (Figs 1 and 3). As described above, some have steep margins and very distinct edges, suggesting confinement by a topographic rim. These lakes are more consistent with seepage or groundwater drainage lakes, with the lake intersecting the subsurface liquid-methane table. Other lakes have diffuse, more scalloped edges, with a gradual decrease in backscatter towards the centre of the lake. These lakes are more likely to have associated channels, and thus may be either drainage lakes or groundwater drainage lakes. Other lakes are more sinuous, or have sinuous extensions, similar in appearance to terrestrial flooded river valleys.

Several of the depressions seem to be filled with liquid, whereas others are only partly filled (Fig. 3c). These partly filled depressions may never have filled fully, or may have partly evaporated at some point in the past. Other features in the swath have margins similar to other lakes but a surface backscatter similar to the surrounding terrain (Fig. 3d). We interpret these to be possibly depressions that are now devoid of liquid. These lakes in possible varying states of fill suggest that the lakes in this region of Titan might be ephemeral, on some unknown timescale.

Although the lakes have generally very radar-dark surfaces, some have areas of increased radar brightness most commonly near their edges. The proximity to the edges suggests that the enhanced

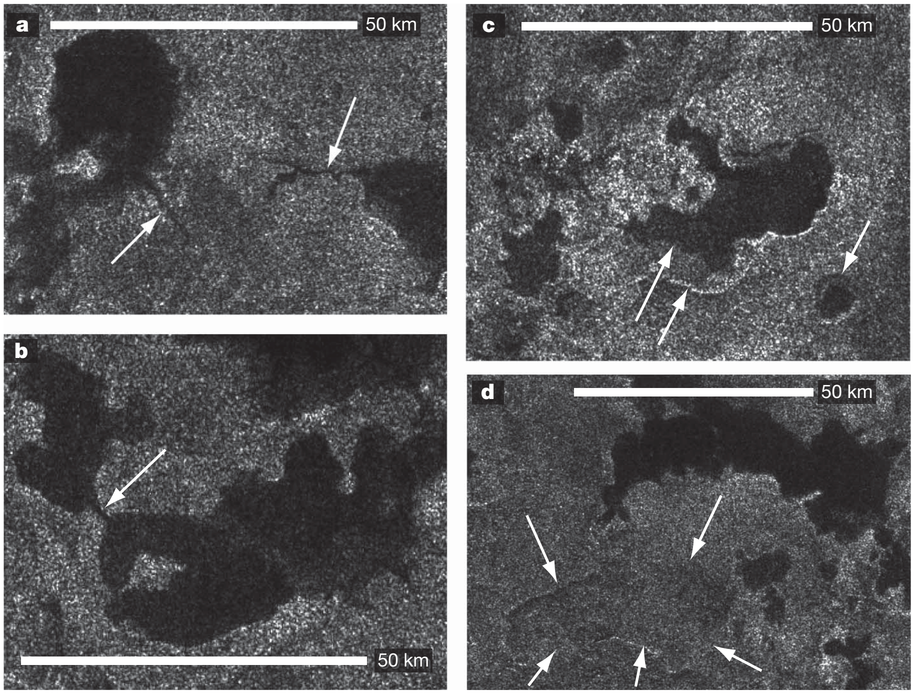

Figure 3 | Examples of lakes from the T_{16} swath. a, Sinuous radar-dark channels can be seen leading into two lakes. **b**, A pair of irregularly shaped lakes connected by a radar-dark channel. **c**, Radar-dark material in the lake to the left lies inside an apparent topographic edge (arrows), indicating that it might once have been at a higher level. The circular lake to the right seems to be a nested depression, with dark material filling the inner depression. **d**, A feature with a shape similar to lakes (arrows), but with backscatter similar to surrounding plains. On the basis of similarly shaped lakes and possibly partly filled features, we interpret this feature to be a dry lakebed.

brightness might be due to a reflection from the lake bottom, where it is sufficiently shallow that the bottom echo is not completely attenuated. K_u-band energy may penetrate many tens of metres through pure hydrocarbon liquids such as ethane or methane. Tidal winds at these high latitudes are predicted[20] to be less than $0.5\ \mathrm{m\,s^{-1}}$, an order of magnitude lower than that needed to form capillary waves in liquid hydrocarbons in wind-tunnel tests on Earth[21]. The higher air density on Titan may facilitate wave growth somewhat, and over long fetches small gravity waves may form (amplitude about 5 cm; wavelength much less than 1 m) that could potentially be detected by the radar. We note that it is also possible that bright patches near the lake edges could be small 'islets' protruding through the surface. Floating 'icebergs' are unlikely because most materials would not float in liquid hydrocarbons.

Our inference that the northern-hemisphere lakes discovered by Cassini radar are at least partly liquid methane is consistent with various other considerations. If such lakes cover at least 0.2–4% of Titan's surface (depending on the amount of relatively involatile but highly soluble ethane contained within them), they will buffer the atmospheric methane's relative humidity at its observed value[7], removing the requirement for a putative steady drizzle at the equator[22]. If the abundance of lakes seen in the T_{16} data are typical of their coverage poleward of about 70° in both hemispheres, then the fraction of Titan's surface covered by lakes is within this range. More recent polar radar data from Cassini support this assertion.

Titan's northern hemisphere lakes probably participate in a methanological cycle that has multiple timescales. As Titan's seasons progress over the 29-year cycle of Saturn's orbit around the Sun, lakes in the winter hemisphere should expand by steady methane precipitation while summer hemisphere lakes shrink or dry up entirely. More speculatively and possibly less frequently (about 10^3 years for any given location[9]), mid-latitude and equatorial regions could experience a progressive growth in methane humidity leading to much more violent methane thunderstorms[23], carving the erosional patterns seen in the Huygens probe images[6] and other radar swaths[24]. On timescales of tens of millions of years[25], atmospheric photochemistry decreases the total methane—atmospheric, lacustrine and methaniferic—available to the system, causing lakes at progressively higher latitudes to be dry all year round. The abrupt and striking transition southwards of about 70° north latitude from the very dark lakes to features similarly shaped but bearing no contrast with the surroundings might be a consequence of the progressive depletion of methane from the surface–atmosphere system. On unknown but possibly longer timescales, thermal evolution of Titan's interior may drive additional methane into the surface–atmosphere system[26] by means of cryovolcanic events, geysering or the impact-generated release of methane stored below the surface. This last postulated resupply of methane from the interior is most speculative and is not directly implied by the presence of the lakes, although possible volcanic constructs seen by radar[4] and the visible and near-infrared mapping spectrometer[27] hint at the long-term role of volcanism and outgassing.

Future radar observations will determine the origin of lake surface textures (for example winds or lake bottom effects) and will also constrain liquid dielectric properties, and possibly depth and shoreline characteristics through diversity in the viewing geometry. SAR imagery of the lakes near the end of a proposed extended mission, in 2009 or 2010, would provide a sufficient time base on which to detect seasonally driven changes in lake extent, predicted to occur[7] if the lakes are not connected to a much larger subsurface methanifer. Future missions to the surface will be required for a full understanding of the lakes of Titan, in particular how they formed, their detailed composition and their interaction with their shorelines.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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