Icarus 212 (2011) 957–959

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Note

Shoreline retreat at Titan's Ontario Lacus and Arrakis Planitia from Cassini Imaging Science Subsystem observations

E.P. Turtle [a,*], J.E. Perry [b], A.G. Hayes [c], A.S. McEwen [b]

[a] Johns Hopkins Univ. Applied Physics Lab., 11100 Johns Hopkins Rd., Laurel, MD 20723, United States
[b] Lunar and Planetary Lab., Univ. of Arizona, 1541 E. University Blvd., Tucson, AZ 85721, United States
[c] California Inst. of Technology, 1200 E. California Blvd., Pasadena, CA 91125, United States

ARTICLE INFO

Article history:
Received 22 April 2010
Revised 31 December 2010
Accepted 10 February 2011
Available online 15 February 2011

Keywords:
Titan
Meteorology
Satellites, Surfaces

ABSTRACT

Recent observations by Cassini's Imaging Science Subsystem reveal that part of the shoreline of Titan's Ontario Lacus has retreated by several kilometers and may indicate that the dark area that appeared at Arrakis Planitia (80°S, 120°W) in late 2004 has subsequently faded. These changes provide constraints on aspects of Titan's methane cycle, as well as on the properties of Titan's surface materials.

1. Introduction

Observations of Titan's south-polar regions acquired by Cassini's Imaging Science System (ISS) over several years (2004–2009) have revealed differences indicative of changes in the distribution of liquids on the surface. In images acquired of Ontario Lacus in March 2009, the shoreline appears to have retreated from its location in June 2005 by 9–11 km in the southwest (Fig. 1). A distant observation taken in February 2009 suggests that the large dark area that appeared between July 2004 and June 2005 (Turtle et al., 2009) may have subsequently faded (Fig. 2). To date, we have not detected differences in repeated ISS observations of the lakes and seas at high northern latitudes. The recent changes are interpreted to be the result of the evaporation and infiltration of surface liquids, essential components of Titan's methane cycle, and they provide insight into and allow us to put constraints on the amount of precipitation from a storm observed in October 2004 (Fig. 2; Schaller et al., 2006). The observations also demonstrate that the bed of Ontario Lacus is not dark at near-infrared wavelengths, an important piece of information regarding the poorly understood nature of Titan's surface materials.

2. Observation details

2.1. Ontario Lacus

ISS observed Ontario Lacus (∼70°S, ∼180°W) in July 2004 (designated T0), in June 2005 (Rev009), and in March 2009 (T51). Fig. 1 shows images from the last two of these; observational parameters are listed in Table 1. The 2009 observation was acquired during a targeted Titan flyby and, thus, at much closer range, so the exposure times were shortened significantly (by more than a factor of 4) to prevent smearing. Moreover, the wide-angle camera (WAC) was used and the images were summed over 4 × 4 squares of pixels to improve the signal-to-noise ratio; nevertheless, the signal-to-noise ratio of the T51 observation is lower than that of Rev009 (Fig. 1). (Scattering in Titan's atmosphere limits the scale of surface features that can be resolved to several hundred meters at best (Porco et al., 2004), depending on the surface contrast, even when the pixel scale is smaller. So summing when at close range does not degrade resolution significantly.)

All images of the surface were acquired using the narrowband CB3 filter centered at 938 nm. Surface contrast is enhanced by dividing out Titan's atmospheric haze using images taken at the same time through the narrowband MT1 filter (619 nm) for narrow-angle-camera (NAC) observations and the broadband red filter (647 nm) for WAC observations (Porco et al., 2004). (See also Turtle et al. (2009) Auxiliary Material for more detailed discussion of acquisition and processing of ISS images of Titan's surface.)

We mapped the shoreline in each observation by using a mean value between terrain on either side of the lake and the dark material in the lake's interior as a threshold value. (Complications due to atmospheric scattering currently preclude determination of absolute albedo values.) To assess potential effects of differences in surface contrast and illumination on the location determined for the shoreline we varied the threshold value. This analysis demonstrated that along the southern boundary the location is robust to a single pixel, giving us confidence that the differences along the southwestern shoreline reflect true changes (Fig. 1). There is much more uncertainty (few to several pixels) along the northern boundaries, especially on the western side, so we cannot interpret changes there with confidence. The ISS shoreline generally agrees with Cassini RADAR observations in June and July 2009 (Fig. 1c; also Hayes et al., 2010a), with the newer southwestern boundary appearing to be the better match. Any change in the boundary of Ontario Lacus between the T0 and Rev009 observations was below the resolution of the observations, or less than ∼5 km.

2.2. Arrakis Planitia

ISS observed Arrakis Planitia (∼80° S, ∼120° W) in July 2004 and June 2005, and the large new dark feature and nearby smaller ones in the 2005 observation were interpreted (Turtle et al., 2009) to be the result of ponding after a large storm observed in early October 2004 by Schaller et al. (2006) as well as ISS (Fig. 2). This region was observed again by ISS in February 2009 (Fig. 2). The phase angle was comparable in all three observations, although the emission angle was higher

* Corresponding author.
E-mail address: Elizabeth.Turtle@jhuapl.edu (E.P. Turtle).

0019-1035/$ - see front matter © 2011 Elsevier Inc. All rights reserved.
doi:10.1016/j.icarus.2011.02.005

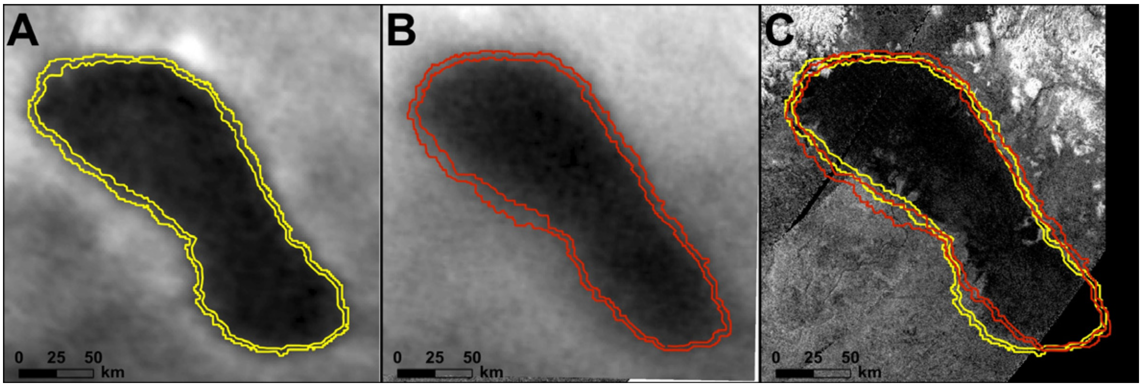

Fig. 1. Comparison of Cassini ISS observations of Ontario Lacus acquired in June 2005 (left) and March 2009 (middle), Rev009 and T51 in Table 1. SAR data of the same region from 22 June and 8 July 2009 (T57 and T58) is shown at right (see also Hayes et al., 2010a). The shoreline locations identified in the two ISS observations are indicated in yellow (Rev009) and red (T51); double lines illustrate the level of uncertainty ($\geqslant$1 pixel) determined by our threshold analysis (see text). North is up.

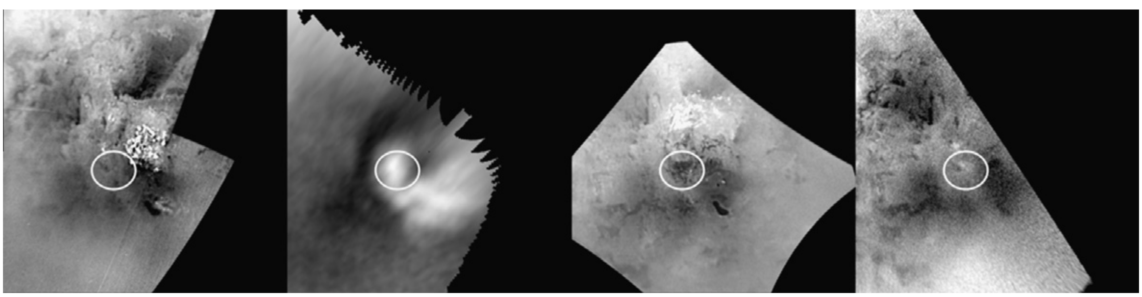

Fig. 2. Observations of Titan's south-polar region acquired (from left to right) on 3 July 2004 (designated T0 in Table 1), 6 October 2004 (Rev00A), 6 June 2005 (Rev009), and 6 February 2009 (Rev102), illustrating the storm and surface changes at Arrakis Planitia (circled). The South Pole is at the center of each frame.

Table 1
Details of ISS observations of Ontario Lacus and Arrakis Planitia.

Observation	Date	Phase angle @ Ontario Lacus (°)	Emission angle @ Ontario Lacus (°)	Incidence angle @ Ontario Lacus (°)	Phase angle @ Arrakis Planitia (°)	Emission angle @ Arrakis Planitia (°)	Incidence angle @ Arrakis Planitia (°)	Pixel scale (km)	Camera[a]	Range (10^3 km)	Figures
T0	3 July 2004	70	37	77	67	33	60	2.0–4.0	NAC	340	2
Rev00A	6 October 2004	64	61	70	64	61	60	32	NAC	5430	2
Rev009	6 June 2005	57	27	56	65	11	58	2.6	NAC	450	1 and 2
Rev102	6 February 2009	70	55	79	70	40	76	3.6	NAC	620	2
T51/Rev106	27 March 2009	74	32	74	N/A	N/A	N/A	2.3	WAC (summed 4 × 4 pixels)	9.4–10	1

[a] NAC = ISS narrow-angle camera; WAC = ISS wide-angle camera.

during the 2009 observation (Table 1). There may also be some diffuse brightening in the 2009 observation suggestive of nearby clouds, which could obscure the view of the surface; low-lying clouds or fog, as observed by Brown et al. (2009), could also be indicative of evaporation of liquid from the surface. Nonetheless, other neighboring dark features can be seen, including Ontario Lacus. So, the lack of evidence in the 2009 image for the large dark feature observed previously suggests that liquid may no longer be present on the surface in this area as a result of evaporation or infiltration into the subsurface over the intervening 44 months. This interpretation is consistent with the lack of liquid detected by RADAR in this area in December 2008 (T49).

3. Discussion

The observations reveal retreat of the shoreline of Ontario Lacus of up to 9–11 km along its southwestern margin, while the southern and southeastern margins appear unchanged at the resolution of these observations (Fig. 1). The variability of the changes along the shoreline is consistent with variability in the nature of the shore along the lake's perimeter documented by RADAR (Hayes et al., 2010b; Wall et al., 2010): the eastern shore is quite steep; the western shore much more gradual. Differences along the northern margins are at the level of sensitivity of the ISS data and may not reflect changes; the least well-defined margin is that along the northwest, also seen to be more gradual in the RADAR observations (Hayes et al., 2010b). The observed retreat represents a decrease in area of ~500 km^2 over almost 4 years. However, there is no information in the ISS data to constrain local topography, so the volume of liquid lost cannot be determined. (See Hayes et al., 2010a for a detailed assessment based on the RADAR data.)

On the other hand, we can use constraints on the duration of the feature at Arrakis Planitia to infer some aspects of the surface in this area and to derive estimates of the amount of liquid involved. First, if the dark area observed in June 2005 was flooded during the October 2004 cloud outburst, liquid must have persisted on the surface for at least 8 months. Thus, as Hayes et al. (2008) concluded for the northern lakes based on the lack of changes between repeat observations and vertical infiltration rates of at least 1 m/year derived from reasonable estimates for near-surface permeability, this timescale of several months strongly suggests either a shallow impermeable layer or that the local methane table lies close to the surface.

Secondly, adopting the ~1 m/year loss rate for combined evaporation and infiltration derived by Hayes et al. (2010a) based on south-polar RADAR observations from December 2007 through May 2009 (also, Graves et al., 2010), in order for the dark feature to persist for at least 8 months an average of ~70 cm of liquid must have covered the surface. If we instead assume that the liquid persisted until shortly before the area was observed by RADAR in December 2008, we derive an upper limit of 4.2 m. The area observed to be covered in June 2005 was ~34,000 km, which yields a range of volumes from 24 to 140 km^3 of liquid. The cloud system believed to be the source of the precipitation is estimated to have covered ~8% of the disk of Titan (Schaller et al., 2006); measurements of the cloud observed by ISS on 6 October 2004 yield an area of $\sim 1 \times 10^6$ km^2. Assuming a greatly oversimplified even distribution of precipitation over the entire storm system, 2.4–14 cm of rain would have been necessary to provide enough liquid to persist for 8–51 months. This calculation assumes that all liquid was collected via runoff in this basin alone and that evaporation was the only loss mechanism. It neglects loss due to infiltration or gain from a higher methane table. Therefore, it provides a lower limit on the amount of rain from the storm. As such, it is consistent with model-derived precipitation amounts, which can be several tens of centimeters (Tokano et al., 2001; Lorenz et al., 2006; Hueso and Sanchez-Lavega, 2006; Barth and Rafkin, 2007, 2010).

Finally, the fact that a change in the shoreline of Ontario Lacus is apparent to ISS has particular significance regarding the nature of the floor revealed. Low albedos are not unique to hydrocarbon liquids; at the wavelength of ISS surface observations (938 nm), not only are Titan's lakes and seas dark, but the equatorial expanses of dunes are also dark. So the fact that ISS can detect changes in the shoreline indicates that the floor that has been revealed is not dark at near-infrared wavelengths. It had been hypothesized that lakebeds would be covered with dark hydrocarbon material, but the ISS observation suggests either that any such materials were removed as the lake retreated, e.g. by wave action, or that sedimentary deposits covering the lakebed here consist of brighter material. VIMS data of material along the shoreline of Ontario Lacus have been interpreted as lake-bottom sediments that are somewhat lighter than the liquid in the near-IR, surrounded by bright material with low water–ice content. The latter is inconsistent with cleaning during lake retreat, but suggestive that bright organic condensates may be deposited within the lakes and exposed as the liquid level drops (Barnes et al., 2009).

Albedo alone does not discriminate the composition – sediments on Titan, whether light or dark are very likely to include hydrocarbons (e.g., Soderblom et al., 2007) – however, this observation demonstrates that, at least in some cases, ISS can distinguish between lakes and empty lakebeds. ISS observations of the South Pole in 2004 and 2005 revealed numerous dark features (Turtle et al., 2009), but liquid has only been identified in a few of these areas in more recent RADAR observations (e.g., Hayes et al., 2010a), although others did appear to be low-lying basins. Given that more than two years (28 months) elapsed between the ISS and the earliest RADAR observations, the data are ambiguous as to whether the differences are caused by a lack of correlation between near-IR albedo and radar backscatter values (e.g., in the case that ISS was detecting dark, but dry, lakebeds) or due to changes in the distribution of liquids on the surface in the interim. Observations that the exposed lakebed of Ontario Lacus is lighter in albedo supports the interpretation that ISS observed lakes that have subsequently evaporated, similar to Arrakis Planitia, in the years between the ISS and RADAR observations.

4. Conclusions

The changes observed in ISS observations of Titan's south polar lakes suggest that liquid deposited during late summer storms is being lost to evaporation and infiltration into the subsurface as southern fall progresses. Using loss rates derived from repeat south-polar observations by Cassini RADAR (Hayes et al., 2010a), we derived precipitation rates for the October 2004 storm of at least a few to several centimeters, consistent with model predictions. The ISS observations also demonstrate that ISS can distinguish between lakes and dry lakebeds. The stability of Titan's polar lakes and seas and how their distribution changes in response to weather and seasons provides important clues about Titan's methane cycle and atmospheric circulation. Repeated observations of Titan by ISS and RADAR will provide opportunities to document seasonal changes on the surface as well as in weather patterns.

Acknowledgments

We are deeply grateful to all who have worked to create and operate the Cassini–Huygens mission, thereby making possible the acquisition and analysis of its wealth of data. We also thank J. Soderblom and an anonymous reviewer for their careful assessments and suggestions for improving the manuscript. This work was supported by the Cassini–Huygens mission, which is a joint endeavor of NASA, ESA, and ASI and is managed by JPL/Caltech under a contract with NASA.

References

Barnes, J.W. et al., 2009. Shoreline features of Titan's Ontario Lacus from Cassini/VIMS observations. Icarus 201, 217–225.

Barth, E.L., Rafkin, S.C.R., 2007. TRAMS: A new dynamic cloud model for Titan's methane clouds. Geophys. Res. Lett. 34, L03203. doi:10.1029/2006GL028652.

Barth, E.L., Rafkin, S.C.R., 2010. Convective cloud heights as a diagnostic for methane environment on Titan. Icarus 206, 467–484.

Brown, M.E., Smith, A.L., Chen, C., Adamkovics, M., 2009. Discovery of fog at the South Pole of Titan. Astrophys. J. 706, L110–L113.

Graves, S., Schneider, T., Schaller, E.L., Brown, M.E., 2010. Causes of Titan's lake and cloud distributions and predictions of future changes. Bull. Am. Astron. Soc. 42. Abstract #36.23.

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

Hayes, A.G. et al., 2010a. Transient surface liquid in Titan's polar regions from Cassini. Icarus 211, 655–671. doi:10.1016/j.icarus.2010.08.017.

Hayes, A.G. et al., 2010b. Bathymetry and absorptivity of Titan's Ontario Lacus. J. Geophys. Res. 115. doi:10.1029/2009JE003557.

Hueso, R., Sanchez-Lavega, A., 2006. Methane storms on Saturn's moon Titan. Nature 442, 428–431. doi:10.1038/nature04933.

Lorenz, R.D., Griffith, C.A., Lunine, J.I., McKay, C.P., Renno, N.O., 2006. Convective plumes and the scarcity of Titan's clouds. Geophys. Res. Lett. 32, L01201. doi:10.1029/2004GL021415.

Porco, C.C. et al., 2004. Cassini imaging science: Instrument characteristics and anticipated scientific investigations at Saturn. Space Sci. Rev. 115, 363–497.

Schaller, E., Brown, M., Roe, H., Bouchez, A., 2006. A large cloud outburst at Titan's South Pole. Icarus 182, 224–229.

Soderblom, L.A. et al., 2007. Correlations between Cassini VIMS spectra and RADAR SAR images: Implications for Titan's surface composition and the character of the Huygens Probe Landing Site. Planet. Space Sci. 55, 2025–2036.

Tokano, T., Molina-Cuberos, G., Lammer, H., Stumptner, W., 2001. Modelling of thunderclouds and lightning generation on Titan. Planet. Space Sci. 49, 539–560.

Turtle, E.P., Perry, J.E., McEwen, A.S., Del Genio, A.D., Barbara, J., West, R.A., Dawson, D.D., Porco, C.C., 2009. Cassini imaging of Titan's high-latitude lakes, clouds, and south-polar surface changes. Geophys. Res. Lett. 36, L02204. doi:10.1029/2008GL036186.

Wall, S. et al., 2010. Active shoreline of Ontario Lacus, Titan: A morphological study of the lake and its surroundings. Geophys. Res. Lett. 37, L05202. doi:10.1029/2009GL041821.