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Photometric changes on Saturn's Titan: Evidence for active cryovolcanism

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[1] We report infrared spectrophotometric variability on the surface of Saturn's moon Titan detected in images returned by the Visual and Infrared Mapping Spectrometer (VIMS) onboard the Cassini Saturn Orbiter. The changes were observed at 7°S, 138°W and occurred between October 27, 2005 and January 15, 2006. After that date the surface was unchanged until the most recent observation, March 18, 2006. We previously reported spectrophotometric variability at another location (26°S, 78°W). Cassini Synthetic Aperture RADAR (SAR) images find that the surface morphology at both locations is consistent with surface flows possibly resulting from cryovolcanic activity (Wall et al., companion paper, this issue). The VIMS-reported time variability and SAR morphology results suggest that Titan currently exhibits intermittent surface changes consistent with present ongoing surface processes. We suggest that these processes involve material from Titan's interior being extruded or effused and deposited on the surface, as might be expected from cryovolcanism. **Citation:** Nelson, R. M., et al. (2009), Photometric changes on Saturn's Titan: Evidence for active cryovolcanism, *Geophys. Res. Lett.*, *36*, L04202, doi:10.1029/2008GL036206.

1. Introduction

[2] Instruments on the Cassini Saturn Orbiter have observed the surface of Titan since the spacecraft entered Saturn orbit in mid 2004. One of these instruments, the Visual and Infrared Mapping Spectrometer (VIMS), has, over time, repeatedly imaged surface units on Titan at eight wavelength bandpasses within the $0.93 < \lambda < 4.95$ μm range, where Titan's atmosphere is relatively transparent. We have previously reported that a region near 26°S, 78°W (hereafter called "region 1") exhibits spectral, and therefore compositional, variability consistent with surface activity [*Nelson et al.*, 2005a, 2005b, 2005c, 2006, 2008]. *Barnes et al.* [2005] reported this region to be anomalously bright in the infrared but did not note its variable nature. Here we report photometric changes at another region on Titan at 10°S, 140°W, hereafter referred to as "region 2". As with region 1, the changes observed at region 2 were found in color ratios of VIMS images taken since Cassini began its orbital tour of the Saturnian system in 2004. It is the second area observed by VIMS on Titan's surface that exhibits photometric variability.

[3] In a companion paper (Wall et al. this issue) RADAR (SAR) high spatial resolution images of Titan's surface are shown for both region 1 and 2. These authors report that these regions have morphologies consistent with cryovolcanic flows. Cryovolcanism has long been conjectured on Titan [e.g., *Lunine and Stevenson*, 1987; *Lorenz*, 1996] and several structures interpreted as cryovolcanic have been previously identified on Titan [*Lopes et al.*, 2007; *Barnes et al.*, 2006; *Sotin et al.*, 2005]. This is the first report of photometric variability associated with regions with cryovolcanic morphology. This morphology, combined with the VIMS report of variability suggests that Titan's surface is currently active. Previous reports of variability were

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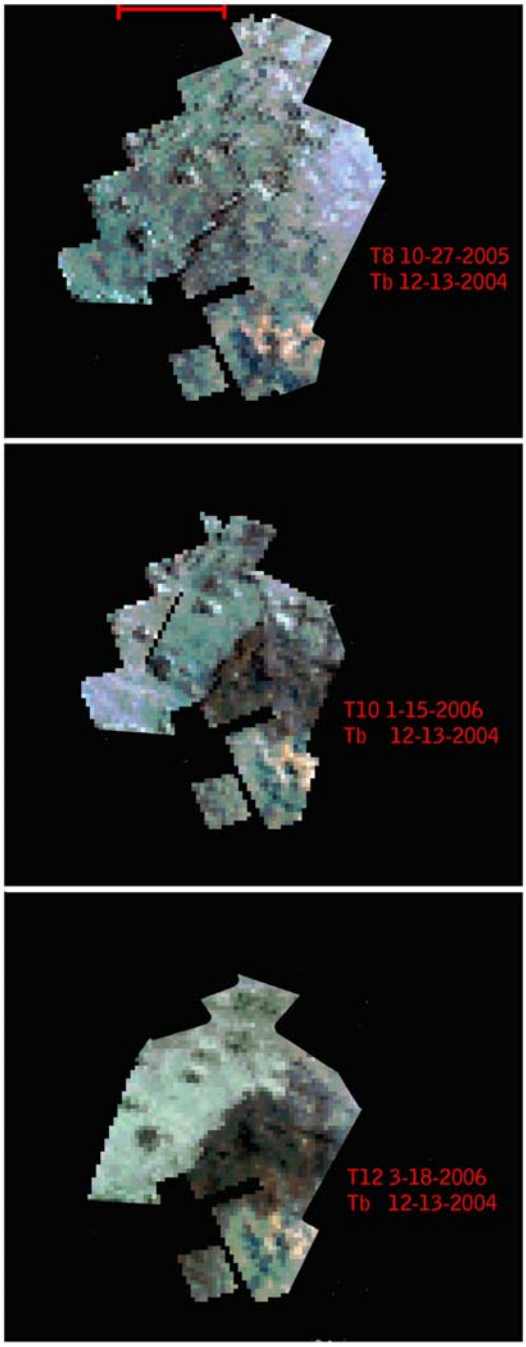

Figure 1. (top) The ratio of the VIMS Lommel-Seeliger corrected composite image taken at T8 flyby (Oct27/2005) to that of the composite image of the Tb (Dec13/2004) flyby. In each color image R = 2.78 μm, G = 2.01 μm, and B = 1.59 μm). These three colors were selected because the evidence of color change suggests a spectral, and therefore a compositional change. The images are in a sinusoidal projection with central longitude at 140° W and central latitude at 0° with North up. The scale bar is 500 Km. (middle) Same as Figure 1 (top) except the T10 (Jan15/2006) flyby composite is divided by the Tb flyby composite. (bottom) Same as Figure 1 (top) except for the T12 flyby (Mar18, 2006). The region to right of center in the image changed significantly sometime in the period between Oct 27, 2005 and Jan15, 2006. The change remained the same or may have increased between Jan15, 2006 and Mar 18, 2006.

associated with the formation of clouds [*Griffith et al.*, 2005].

2. Observations

[4] Region 2 was observed by VIMS on four occasions (13 Dec 2004, 27 Oct 2005, 15 Jan 2006, 18 Mar 2006; designated as Tb, T8, T10 and T12 respectively). The VICAR image processing software at the Jet Propulsion Laboratory was used to project the spectral-imaging cubes acquired by VIMS. For each epoch the calibrated VIMS image cubes were combined into mosaics of the region using techniques described by *Nelson et al.* [2005a, 2005b, 2005c, 2006, 2008]. The ISIS image processing software of the United States Geological Survey Flagstaff Office was used to support the photometric analysis.

[5] The change in region 2 is best demonstrated in color ratio images shown in Figure 1. The region is observed to darken with time relative to the surrounding terrain. Here we have taken calibrated VIMS images at three epochs (T8, T10, and T12) and divided them by cosi/(cosi+cose) to make a first-order correction for differing angles of incidence i and emergence e. These Lommel-Seeliger corrected images were then divided by the earliest cube in the time sequence (Tb). All cubes were first projected to a common sinusoidal perspective centered at 140°W at a resolution of 25 km/pixel. Color images were constructed from the image cubes at three bandpasses (R = 2.78 μm, G = 2.01 μm, B = 1.59 μm) as shown in Figure 1.

[6] From 13 Dec 2004 to 27 Oct 2005 (Figure 1 (top), T8/Tb) very little change is seen in the area right of center. However between 27 Oct 2005 and 15 Jan 2006 a dramatic darkening occurred (Figure 1 (middle), T10/Tb). A subsequent image taken at 18 Mar 2006 indicated that the change persisted and may have become more pronounced (Figure 1 (bottom), T12/Tb).

[7] The changes were first seen in simple epoch-to-epoch comparisons of the images at an effective wavelength of 2.0178 μm. As a consequence we conducted a spectrophotometric analysis. We measured the reflectance (I/F) of 26 points on Titan's surface at various angles of incidence (i), emission (e) and phase (θ) for each apparition; thus, four I/F measurements were obtained for each point at a distinct set of i, e, θ. The location of these 26 points is shown in Figure 2.

[8] In general, the reflectance of a surface unit as measured in an image of a spherical object varies as:

$$\mathrm{I/F}(\mathrm{i},\mathrm{e},\theta) = \mathrm{LS}(\mathrm{i},\mathrm{e}) \cdot \mathrm{f}(\mathrm{i},\mathrm{e},\theta),$$

where LS(i,e) = cos(i)/(cos(i)+cos(e)) is the Lommel Seeliger function, and f(i,e,θ) represents the single scattering phase function combined with the contribution of multiple scattering [*Hapke*, 1993, equation (8.35a); *Chandrasekhar*, 1960, equation (76)]. Over the range of phase angles subtended by these observations, f(i,e,θ) generally increases as i,e, and θ decrease. Thus, for each of the 26 points under study we divided I/F by LS to produce a Lommel Seeliger corrected reflectance, or reduced reflectance, which is proportional to f(i,e,θ).

[9] For 14 of the 26 points in Figure 2, f(i,e,θ) increased as expected as i, e, and θ decreased. For the purpose of this

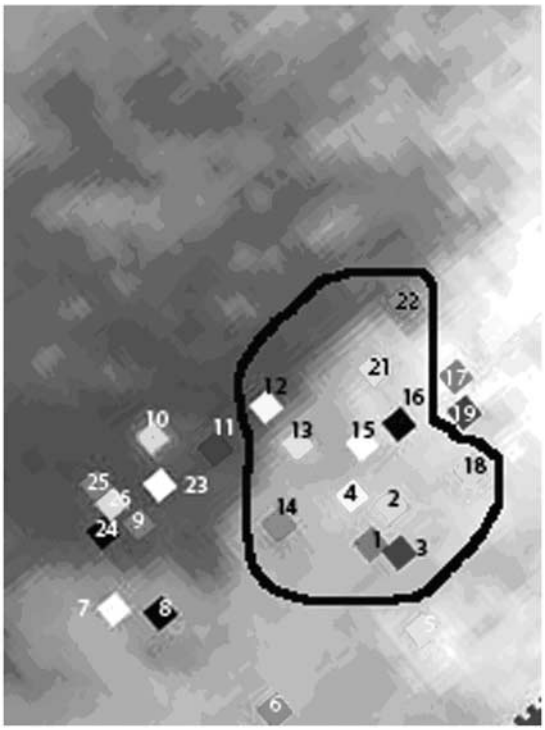

Figure 2. Location of 26 points in Titan's surface where I/F was measured for this photometric study. The 14 points that with white numbers associated exhibit ''normal photometric behavior'. The 12 points with black numbers associated exhibit ''unexpected photometric behavior.' The location of the approximate center of the unusual photometric behavior (point 15) is 7°S, 138°W. The black line shows the approximate border of region where the points exhibit anomalous activity.

discussion we call this ''expected photometric behavior'. A typical example of this expected photometric behavior for one of these points (point #7) is shown in Figure 3 (top). However, for 12 of the 26 points under investigation the change in reduced reflectance did not exhibit normal (i.e. expected) photometric behavior. In these instances, the reduced reflectance decreased between T8 and T10 when i, e, and θ decreased. A typical example of this 'unexpected photometric behavior' is shown in Figure 3 (bottom) for point #1. This behavior is not predicted by photometric theory and is not observed in laboratory investigations of the angular scattering properties of particulate materials simulating planetary regoliths (including condensables such as ammonia, water, and hydrocarbons typically associated with Titan's surface) regardless of grain size.

[10] Significantly, the 12 points that exhibit this unexpected photometric behavior are located near each other on Titan's surface centered at ~7 S, 138 W. The 14 points that exhibit expected photometric behavior (identified by black typeface in Figure 2) surround the 12 points that exhibit unexpected photometric behavior (shown in white typeface in the figure). We argue below that the most reasonable interpretation of these results is that the surface changed between the differing epochs at the locations defined by the points that exhibit unexpected photometric behavior: it was more reflective in 2004 than it was in 2005.

3. Discussion

[11] Changes in the appearance of any particular point on Titan's surface might be due to transitory atmospheric processes such as tropospheric clouds. Such clouds exhibit photometric behavior that is detectable using VIMS (or v-near IR instruments) image ratioing techniques [*Griffith et al.*, 2005]. We performed such an analysis on region 1 and found that the observed change could not be explained by the region being elevated as might be expected were it a cloud. The activity is on or close to the surface. [*Nelson et al.*, 2008]. We have repeated this analysis for region 2 and find that, similarly, region 2 also does not exhibit photometric properties consistent with clouds. The changes observed on both regions are due to processes at or very near the surface. In the case of region 2 the surface unit that changed did not vary with time as it did in region 1. Instead, it changed once between the second and third observations and maintained its brightness in measurements acquired before and after this change. There remains the possibility that the effect is caused by a cloud near the ground (a local fog) or that a precipitation event deposited a condensate or washed an existing surface deposit away. However, region 2 changed between October 27, 2006 and January 15 2006. Once it changed it did not change back to its initial state. If it were a fog we would expect it to change in spatial dimension with time due to wind activity. We did not see this. Furthermore, both region 1 and region 2 are at relatively low latitude. Titan's tropospheric clouds and associated lakes are concentrated near the poles. Therefore, we consider a ground fog to be unlikely. We also cannot rule out entirely the possibility that this effect is related to a single event aeolian deposition such as a sandstorm. If so, then dune like deposits would be expected at this location. The companion paper by Wall et al finds no evidence of dune like morphology in the far higher resolution RADAR data. Instead they suggest the morphology at region 2 is cryovolcanic. This suggests that surface activity such as cryovolcanism is the most likely interpretation.

[12] To further address the cause of this change we consider Cassini Synthetic Aperture RADAR (SAR) and radiometer observations of Titan. Cassini RADAR was able to observe the region 2 environs on one flyby (T13-30Apr2006). This region, in western Xanadu, shows interfingered, lobate RADAR dark and RADAR bright structures that were interpreted as being consistent with the morphology expected from cryovolcanic flows. SAR also observed region 1 on the T44 flyby. Region 1 has drainage patterns and apparent lobate flow features. The well-matched correspondence of the VIMS boundary and the SAR image showing the flow features is shown in the companion paper by Wall et al.

[13] In the case of region 1 the size of the photometrically bright region changed from ~70,000 km^2 to 140,000 km^2 as it increased in reflectance [*Nelson et al.*, 2008]. In case 2, the size of the region that changed was estimated to be 120,000 km^2. The size did not increase but the region changed in brightness over the timescale of the current

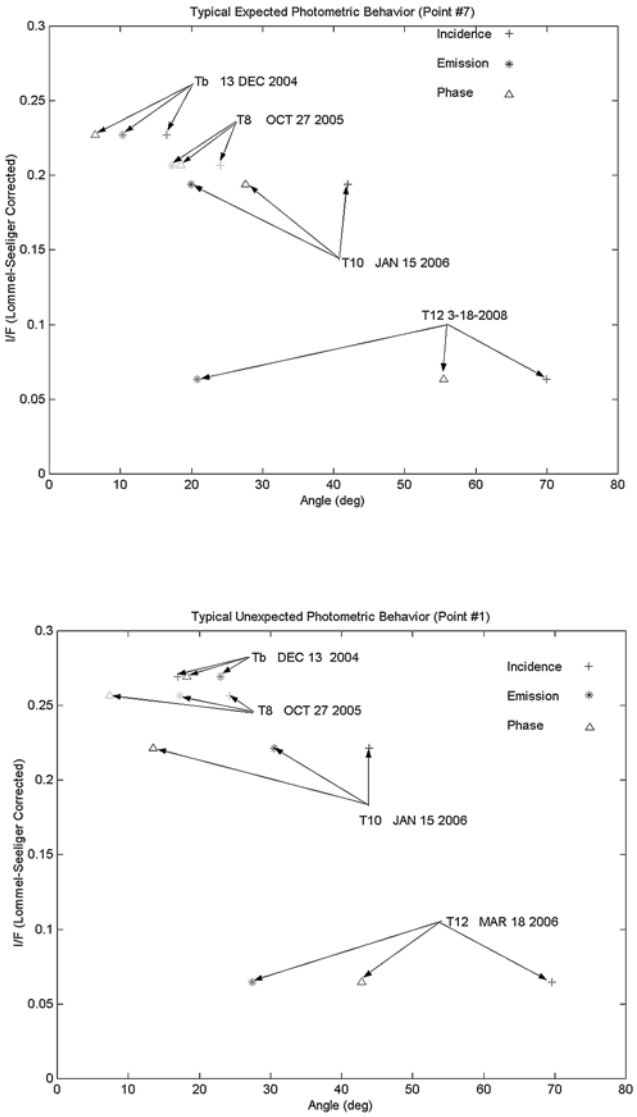

Figure 3. Photometric behavior of points on Titan's surface. (top) Expected photometric behavior of a point on a planetary surface. Here, as the aggregate of i, e, and θ decrease, Lommel Seeliger corrected (I/F) increases. This is typically what is seen on planetary surfaces that are not changing with time. This behavior is seen in 14 of the 26 photometric points measured on Titan's surface. (bottom) Unexpected photometric behavior. Here, as the aggregate of i, e, and θ decrease, The Lomell Seeliger corrected I/F decreases when Tb is compared to T8. This is not seen on unchanging planetary surfaces and is not seen the photometric response of undisturbed samples emulating planetary regoliths as measure.

observations. This suggests that region 1 is a repeating process and region 2 was a singular event.

4. Conclusion

[14] The VIMS instrument has found two locations on Titan that exhibit pronounced reflectance changes over time suggesting a change in composition and/or texture. In both cases, the area of reflectance variability is large, larger than Io's Loki volcano or the Big Island of Hawaii. Observations by another Cassini orbiter instrument, the RADAR using SAR mode, find that the morphology of the terrain in both locations is consistent with what would be expected from cryovolcanic activity, though other origins cannot be completely discounted. If the area is currently or recently cryovolcanically active, the spectrophotometrical changes we have observed could be due to degassing, such as from fumarolic vents or a hydrothermal system, even if the flows are not currently being emplaced.

[15] Pre-Cassini, Titan was thought of as a pre-biotic earth that was frozen in time. Cassini VIMS observations now suggest that Titan is a snapshot of a episodically changing or evolving object with a dynamic surface.

[16] **Acknowledgment.** This work done at JPL, California Institute of Technology, under contract with NASA.

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