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On Titan's Xanadu region

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ABSTRACT

A large, circular marking ~1800 km across is seen in near-infrared images of Titan. The feature is centered at 10°S, 120°W on Titan, encompasses much of Titan's western Xanadu region, and has an off-center, quasi-circular, inner margin about 700 km across, with lobate outer margins extending 200–500 km from the inner margin. On the feature's southern flank is Tui Regio, an area that has very high reflectivity at 5 μm, and is hypothesized to exhibit geologically recent cryovolcanic flows (Barnes, J.W. et al. [2006]. Geophys. Res. Lett. 33), similar to flows seen in Hotei Regio, a cryovolcanic area whose morphology may be controlled by pre-existing, crustal fractures resulting from an ancient impact (Soderblom, L.A. et al. [2009]. Icarus, 204). The spectral reflectivity of the large, circular feature is quite different than that of its surroundings, making it compositionally distinct, and radar measurements of its topography, brightness temperature and volume scattering also suggest that the feature is quite distinct from its surroundings. These and several other lines of evidence, in addition to the feature's morphology, suggest that it may occupy the site of an ancient impact.

1. Introduction

Saturn's satellite Titan has a thick atmospheric haze that very strongly scatters visible light (Smith et al., 1981; Tomasko et al., 2005) and makes studies of its surface difficult. Atmospheric scattering is much less effective in the infrared, but intense methane absorptions in Titan's spectrum allow surface observations only in atmospheric windows (Griffith et al., 2003). Several observational studies of Titan have been hampered by low spatial resolution (Adamkovics et al., 2004; Roe et al., 2004; Smith et al., 1996), but one of the first surface features recognized from the ground was the high-albedo area formally named Xanadu (Smith et al., 1996). Because Xanadu is so prominent on Titan, it is the subject of intense study and speculation. Here we report new data and analyses that bear on Xanadu's geologic characteristics.

2. Observations

The data were obtained using the Cassini Visual and Infrared Mapping Spectrometer (VIMS) (Brown et al., 2004). VIMS is an imaging spectrometer operating in the wavelength region 0.35–5.2 μm, having 352 channels, a 0.5-mrad pixel, and a maximum spatial format of 64 × 64 pixels. During all of the flybys of Titan up to the T12 flyby, including the Ta and Tb flybys (Wolf and Smith, 1995), VIMS' best coverage of Titan's Xanadu region occurred during the T12 flyby. The observations occurred at an average distance of ~30,000 km (~15 km/pixel) and an average phase angle of ~70°.

To provide context, in Fig. 1 is an orthographic projection of data obtained during the Ta through T12 flybys (between 2004 July and 2006 March; for specific dates the reader is referred to Barnes et al. (2009)), using false color (see Fig. 1). The quasi-circular, albedo feature seen near the center of Titan's disk in this projection, which we shall call here the Xanadu Circular Feature (XCF), is the subject of this paper and is centered at approximately 10°S and 120°W, near Titan's apex of orbital motion at 0°S and 90°W.

In Fig. 2 is an enlarged image of the XCF employing data from the T12 flyby. On the outer, southern margin of the XCF is Tui Regio. This area has flow-like features and is among the brightest on Titan at 5-μm wavelengths (Barnes et al., 2006, 2005). We will argue below that it is significant that the southern boundary of Tui Regio roughly coincides with the southern margin of the XCF. In addition to Tui Regio being on its southern flank, the XCF has several other significant characteristics that we will argue later in this paper evidence control by an ancient impact scar.

First, it is centered very near Titan's apex of orbital motion, its outer margin is roughly 1800 km across, and most prominently lobate to the northwest where it is bounded by dark, brown material, probably by intrusion of the widespread dune material seen in Titan's low-latitudes (Lorenz et al., 2006; Soderblom et al., 2007). Despite being lobate in detail, the margin of the XCF is quite circular on average (Fig. 2). Also, the XCF seems to partially bridge Titan's

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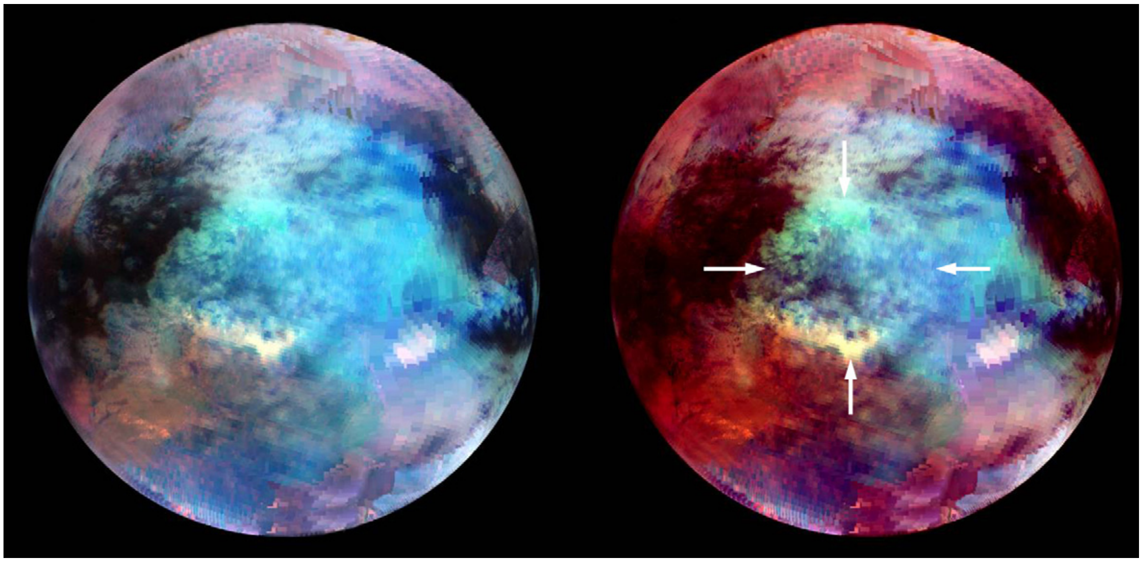

Fig. 1. An orthographic projection of all the VIMS data taken before Cassini's T13 flyby of Titan. The image on the left is false color constructed using 1.6 μm as the blue channel, 2.0 μm as the green channel and 4.8–5.1 μm as the red channel. The Xanadu Circular Feature (XCF) is seen near center of disk and is roughly centered at 10°S, 120°W. The image on the right is heavily stretched to bring out detail on the XCF. Its outer margin is denoted by the 4 white arrows.

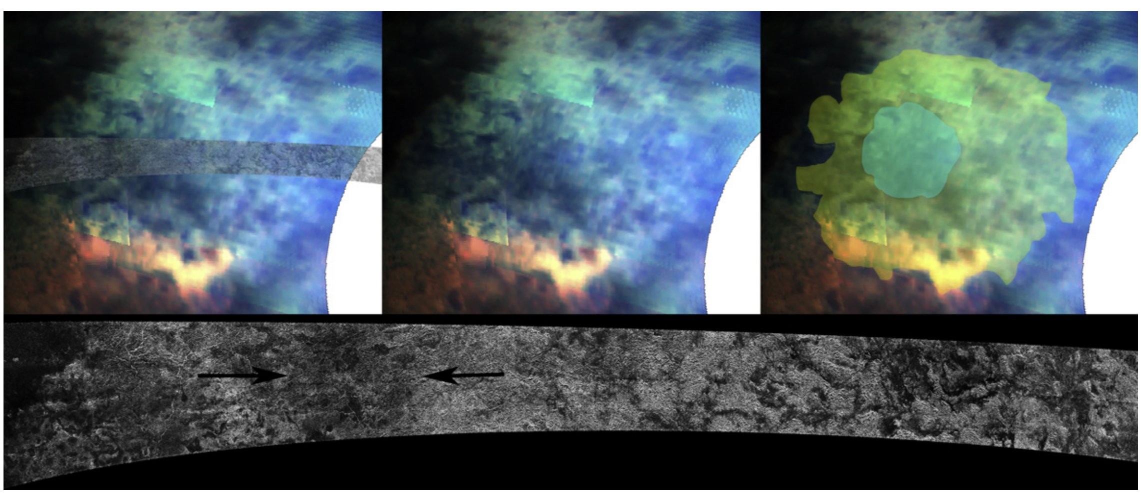

Fig. 2. A composite image of data obtained during the T12 flyby of Titan employing the same false-color scheme of Fig. 1. The left panel is the VIMS data that is also shown in the bottom panel overlain with the relevant portion of the T13 radar data (Elachi et al., 2004). The center panel is the left panel without the overlay. The right panel is the center panel annotated to show the margins of the XCF. Note the circular feature slightly to the west of center in the lower panel indicated by the black arrows. Slightly to the west of it is another apparent, smaller and possibly circular feature that may have been overprinted by the larger feature.

Dark Equatorial Belt, where Xanadu itself comprises the largest single break in the belt.

Second, the XCF has a quasi-circular, inner boundary, ~700 km across that circumscribes its interior, and is very slightly lobate in places. This region is mostly circular and it is offset by about 150 km to the northwest of the center of the outer margin (Fig. 2, right).

Third, the zone between the inner and outer margins is very mottled, suggesting topographical and/or albedo variations 1–10 km in scale, including sinuous markings reminiscent of channels seen in other VIMS data (Barnes et al., 2007) as well as Cassini RADAR data (Elachi et al., 2006; Stofan et al., 2006).

Fourth, as seen in Fig. 3, the XCF is a spectrally distinct compositional unit, similar in reflectivity to Tui Regio, and Xanadu itself is spectrally distinct from the rest of Titan's equatorial regions. While we are unable to say anything definitive regarding the specific chemistry of the units without absorption lines, the observed spectrum is, however, consistent with a mixture of ices and/or hydrocarbons and nitriles (Barnes et al., 2005; McCord et al., 2006; Soderblom et al., 2007).

Fifth, there exist extensive Cassini Synthetic Aperture Radar (SAR) data for Xanadu, including a RADAR pass of the XCF obtained on Cassini's T13 flyby of Titan. That image is superimposed upon the VIMS image from T12 in the left panel of Fig. 2, as well as shown in higher resolution in the bottom panel of Fig. 2. Inspection of the T13 SAR image shows important correlations between surface roughness and the inner and outer margins of the XCF. First, from west to east along the T13 radar swath, the region between the inner and outer margins of the XCF looks relatively rougher (i.e., radar brighter) than the region inside the inner margin, although it is clear that the center of the region inside the inner margin is also quite rough; east of the inner margin eastward to the outer margin, the

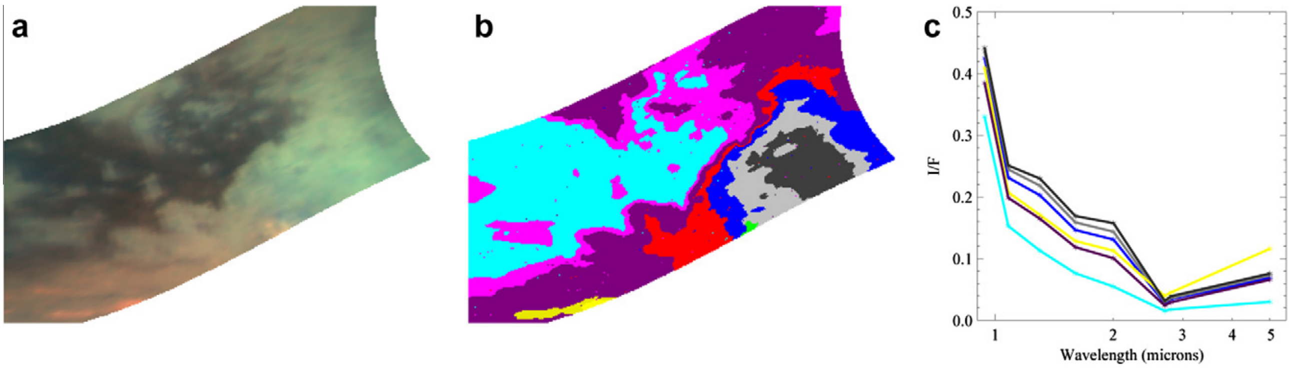

Fig. 3. A spectral composite. A hierarchical cluster analysis was used to assign each pixel to a spectral unit. The algorithm works by looking at the distance between each individual pixel in an eight-dimensional space determined by the VIMS-measured I/F in the 0.93-μm, 1.08-μm, 1.28-μm, 1.6-μm, 2-μm, 2.7-μm, 2.8-μm and 5-μm spectral windows. The two pixels with the shortest distance between them are merged into a single "unit" comprised of those two pixels, and whose spectrum is assigned to be the average of the pixels it contains. We then iterate by looking at the new distances between the units and each pixel, continuing to merge the two closest until all of the pixels are in one unit. The unit map is derived from exploring the resulting tree by hand, breaking up the cube into a number of units appropriate to the situation. To illustrate the spread in spectral characteristics, the right panel depicts the spectral reflectivity of six of the nine distinct compositional units in the Xanadu region identified from hierarchical cluster analysis. The spectra of the remaining 3 units are insufficiently different from that of their neighbors that their inclusion in the plot does not justify their additional clutter. The center panel shows the location of these units using color coding and the left panel is the false-color VIMS image used to generate the cluster map. The portion of Xanadu depicted here is the northwestern edge where dark material seems to be encroaching from the west (see also Fig. 2, upper left quadrant).

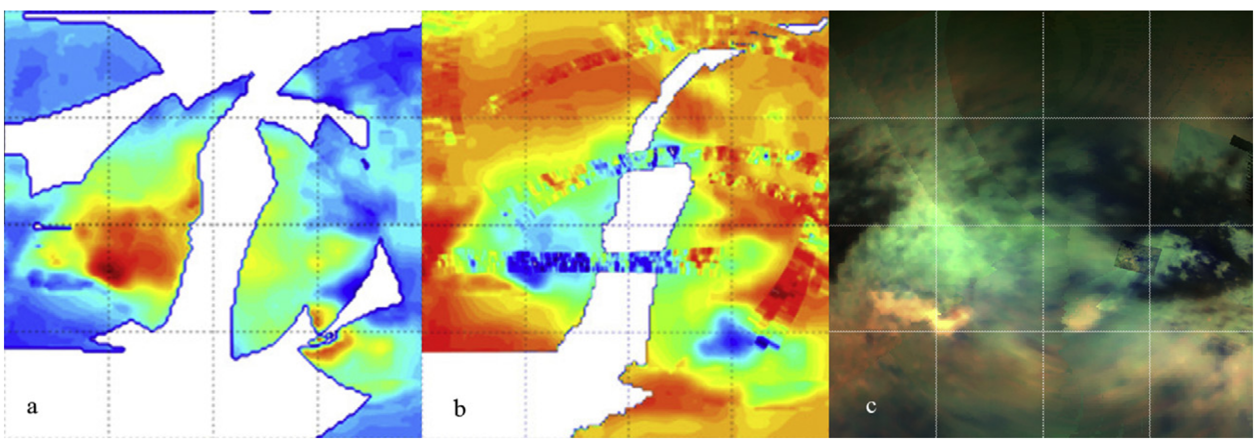

Fig. 4. Radar scatterometry and brightness temperatures in the region of the Xanadu Circular Feature. In panel (a) are data adapted from Janssen et al. (2009) showing the relative amount of volume scattering of an incident radar beam derived from measurements of back-scattered radar. Panel (b) depicts the radar brightness temperatures derived from passive emission at 2.2 cm wavelength, also adapted from Janssen et al. (2009). For comparison, in panel (c) is a subset of the VIMS data shown in Fig. 1. All three panels are cylindrical, equidistant projections centered on 90°W longitude and 0° latitude (the apex of Titan's orbital motion), with each division representing 30° in each direction. It is quite clear that the XCF is a region of anomalously high volume scattering and low brightness temperature at 2.2 cm wavelength, with the highest volume scattering and some of the lowest brightness temperatures in the region centered on the XCF and nearly coincident with what we identify as the inner margin of the XCF.

terrain again becomes rough. Second, there seems to be no sharp topographic boundary marking the transition to the inner margin.

Cassini RADAR scatterometry and radiometry observations also show important correlations with the XCF. In Fig. 4 it can be seen that Xanadu in general has a low radar brightness temperature relative to its surroundings, with the regions of lowest temperature nearly centered on, and similar in size to, the XCF (Paganelli et al., 2007; Zebker et al., 2009a, 2008). The temperatures near the center of the XCF are comparable to those of Menrva and Sinlap, two known impact features (Elachi et al., 2006; Paganelli et al., 2007; Stofan et al., 2006). As Fig. 4 also shows, polarimetry at 2.2-cm wavelength shows a region in Xanadu roughly the same size as, and nearly centered on the XCF that has the highest volumetric scattering coefficient of any region on Titan measured to date, consistent with the presence of heavily fractured ice in the XCF's near-surface layers (Janssen et al., 2009). In addition, altimetry measurements show that most of Xanadu is systematically lower than other regions in Titan's Dark Equatorial Belt, with one of its two lowest regions similar in size to, and located near the center of the XCF (Zebker et al., 2009b).

Finally, Tui Regio, which lies on the southern boundary of the XCF, is thought to be a cryovolcanic feature (Barnes et al., 2006). Recently the hypothesis has been advanced that Hotei Regio is a large, cryovolcanic region (Wall et al., 2009), whose morphology may be controlled by ancient, impact-generated, pre-existing fractures in Titan's crust (Soderblom et al., 2009; Wall et al., 2009). If the XCF is indeed an ancient impact feature, then the presence of cryovolcanic morphology in Tui Regio on the southern boundary of the XCF (Barnes et al., 2006) may have a similar explanation as does the cryovolcanism in Hotei Regio (Soderblom et al., 2009) in that geologically recent cryovolcanic eruptions may have reused ancient structural scars left by the impact.

3. Discussion and conclusions

All the lines of evidence exposited above are consistent with the idea that the XCF is an ancient impact feature: its circularity and large size, its presence near Titan's apex of motion, the relative sizes of its inner and outer margins, its low topographic relief, its low radar brightness temperature and high volumetric radar scattering coefficient, and the presence of cryovolcanic morphology in Tui Regio on its southern, outer boundary. We thus advance and discuss the hypothesis that the XCF is an ancient impact structure, the appearance of which in the infrared is suggestive of a palimpsest, which, in turn, allows several inferences.

First, the lobate outer margin of the XCF suggests that it is a fluidized ejecta deposit, and not a tectonic ring structure. Thus, the XCF differs from large, lunar basins that are surrounded by a few, widely spaced, inward-facing fault scarps (Melosh, 1989). It also differs from the Valhalla-type multi-ring structures on Callisto, Ganymede or Europa, which are surrounded by systems of closely spaced, tectonic graben (Schenk et al., 2004). In both cases the ejecta blanket lies well within the outer margin of the structure. The XCF more closely resembles Caloris crater on Mercury, which lacks an external ring system and whose ejecta extend about one crater diameter from the rim of the inner basin. The XCF and Gilgamesh basin on Ganymede are also similar, although the XCF does not appear to have the inward-facing scarp that encircles Gilgamesh. The lobate character of XCF's outer margin could result from interaction of ejecta with Titan's atmosphere, similar to craters on Venus that also have lobate ejecta patterns (Herrick et al., 1997). The off-center location of the smooth area in the XCF crater within its apparent ejecta blanket suggests an oblique impact (Schultz, 1992), with the projectile arriving from the northwest and impacting at an angle between 40° and 50°.

It is also possible that the lobate nature of the western and northwestern edges of the XCF is caused by erosion. Nevertheless, because there is a mild topographic low roughly centered on the XCF (Zebker et al., 2009b), and because the channel networks on Xanadu indicate mostly eastward and southward fluid flow (Lorenz et al., 2008), we think it is unlikely that the lobate shape of the western and northwestern boundaries of the XCF was produced by erosion.

Assuming Pi scaling of the final, 700-km-diameter crater, an impact angle 45°, and an impact velocity of 12 km/s of ice onto ice, we estimate that to produce a crater of the size and morphology of the XCF requires the impact on Titan of a $\sim$60-km-diameter object (Melosh, 1989; Melosh and McKinnon, 1978). This also requires Titan to have a thick, ice lithosphere – one too strong to slide laterally into the transient cavity (McKinnon and Melosh, 1980). Thus, the XCF implies that Titan had a very thick crust and perhaps even lacked a subsurface ocean (at a depth $<\sim$700 km) at the time of the impact. This simple conclusion, although based on a poorly-resolved structure, is supported by images of other large impact basins on Titan, such as 440-km-diameter Menrva (Stofan et al., 2006) which is morphologically similar to peak-ring basins on planets with thick lithospheres, and has radar backscatter characteristics very similar to those of the XCF (Paganelli et al., 2007).

We do not know the nature of Titan's crust/mantle interface, but its overall density of about 1.88 g/cc (Jacobson, 2004; Jacobson et al., 2006) indicates that the ice crust must be underlain by denser material. Impact basins on the terrestrial planets have low centers because the impact excavated and thinned their low-density crusts so that isostatic relaxation left them lying below their surroundings. It certainly seems conceivable (although there are presently no data to support this) that most of Titan's surface is underlain by dirty, and thus more dense ice, and that the formation of the XCF thinned a purer, less-dense, ice upper crust so that isostatic relaxation left a slightly depressed basin. If this is the case, the depression of the center of the XCF actually reveals information about the crustal thickness and density there. Of course, using this to argue for an impact origin is circular, but the fact that the center is low at long wavelengths cannot be used to argue against an impact origin.

If the XCF crater is indeed isostatically relaxed, it should have relatively straight radial features, presumably grabens, in its central regions, indicating a warping upward of the crater floor after freezing of impact-melted material, accompanied by discontinuous, concentric features linking the radials, similar to the radial-plus-concentric pattern of graben in Caloris on Mercury or Humboldt on the Moon. The existence of such features within the XCF would be the "smoking gun" in the case for the XCF's being a large impact feature.

A rough patch near the center of the inner circular region does not fit with a crater interpretation. Seen in the SAR image, this area may be part of the ejecta blanket of a 200-km-diameter crater superposed to the west of the center of the XCF (see Fig. 2). The center of this second crater clearly exhibits a radial-plus-concentric fracture pattern similar to that in the lunar crater Humboldt. Assuming that both the XCF and this feature are indeed craters, the existence of such large impact features on this area of Titan argues that the underlying surface is very old, despite superficial modification by Titan's active fluvial and aeolian cycles.

On balance, the evidence argues that the XCF is a very old, relaxed impact crater, whose appearance in infrared images of Titan is suggestive of a palimpsest. If the XCF is a large, ancient impact feature, there ought to be more such features on Titan, but, aside from Menrva, they have yet to be recognized, probably because so many processes on Titan seem to be working to erase evidence of their existence. Thus, further investigation of this hypothesis using existing and future data is important.

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