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Material transport map of Titan: The fate of dunes

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ABSTRACT

Using SAR data from Cassini's RADAR instrument, we examined the orientations of three terrain units on Titan, bright lineated plains, streak-like plains, and linear dunes. From the overall integrated pattern of their orientation, we were able to determine Titan's global material transport vectors. The analysis indicates that, in both the northern and southern hemispheres, materials from 0 to 35 deg latitude are transported poleward to a belt centred at roughly 35 deg. Materials from 60 to 35 deg latitude are transported equatorward to the belt at roughly 35 deg. Comparison with the global topographical gradient (Lorenz, R. D. et al. [2013]. Icarus 225, 367–377) suggests that fluvial transport is not the dominant process for material transport on Titan, or that it is at least overprinted with another transport mechanism. Our results are consistent with aeolian transport being the dominant mechanism in the equatorial and mid-latitude zones.

The zone at 35 deg is thus the ultimate sink for materials from the equator to low polar latitudes; materials making up the equatorial dunes will be transported to the latitude 35-deg belts. Only plains units are observed at latitudes of ~35 deg; dunes and materials with the spectral characteristics of dunes are not observed at these latitudes. This observation suggests that either dune materials are converted or modified into plains units or that the margins of dunes are transport limited.

1. Introduction

Saturn's moon Titan has been called the Earth of the outer Solar System. Beneath its thick, hazy atmosphere, Titan has been revealed by the Cassini spacecraft instruments to be a rich world with a geologically complex surface that has been modified by impact cratering, fluvial and aeolian erosion, deposition, tectonism, and possibly cryovolcanism (Lopes et al., 2010). Many of the surface materials are derived from high altitude photochemistry of methane and nitrogen, which causes a cascade of reactions that ultimately delivers organic materials to Titan's surface (Lavvas et al., 2008; Krasnopolsky, 2009). On Titan's surface, channels and fluvial valley networks have been identified both by Cassini, as well as by the Huygens descent probe (Barnes et al., 2007b; Jaumann et al., 2008; Langhans et al., 2012; Burr et al., 2013). Cassini spacecraft instruments, including both the Imaging Science Subsystem (ISS) and Visual and Infrared Mapping Spectrometer (VIMS) instruments, have observed storms and transient surface albedo changes resulting from precipitation (Turtle et al., 2009, 2011; Barnes et al., 2013; Solomonidou et al., 2016) which shows that Titan, like Earth, possesses an active hydrological cycle. Unlike Earth, the precipitating fluid on Titan is a mixture of light hydrocarbon molecules, such as methane and possibly ethane, as well as nitrogen (Lorenz, 2000; Graves et al., 2008). The hydrocarbon fluids interacting with Titan's surface materials drive surface processes such as fluvial erosion and possibly dissolution (Lorenz and Lunine, 1996; Burr et al., 2006; Mitchell et al., 2008; Jaumann et al., 2008; Malaska et al., 2011). In addition, Titan possesses a thick, nitrogen-dominated atmosphere that allows aeolian processes to occur, evidenced by extensive dunes in Titan's equatorial region (Lorenz et al., 2006; Radebaugh et al., 2008; Rodriguez et al., 2014). The different materials, temperatures, and gravity fields provide a stark contrast between the working conditions for geological processes that occur on Titan and Earth (Soderblom et al., 2007; Lorenz et al., 2008; Clark et al., 2010; Lopes et al., 2010).

The sources and sinks of the equatorial dune sand materials are unclear, but organic materials derived from Titan organic

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photochemistry are one possible source. The ultimate fate of the dune materials as well as other materials on Titan's surface is not known. Complicating any analysis on Titan is the omnipresent photochemical haze as well as methane in Titan's atmosphere. The haze limits the transmission of short wavelengths in the visible region, while the methane absorbs longer wavelengths well into the infrared, save for a few spectral windows. Moreover, scattering properties of Titan's atmosphere and hazes require development of sophisticated radiative transfer codes for spectral processing (McCord et al., 2006; Hayne et al., 2014; Solomonidou et al., 2014). Microwave radiation, at much longer wavelengths, easily penetrates the atmosphere and interacts with the surface to provide higher resolution data free from atmospheric interference.

Cassini carries a multimode Ku-band (13.78 GHz, $\lambda = 2.17$ cm) radar instrument, RADAR (Elachi et al., 2005a) that operates in four operating modes – synthetic aperture radar (SAR), altimetry, scatterometry, and radiometry. An overview of initial Titan results for all four modes is given by Elachi et al. (2005b, 2006). On Titan, the candidate surface materials (water ice, water–ammonia ice and other ice mixtures, hydrocarbons, tholins, see Soderblom et al. (2007)) are different from the rocky surfaces more commonly imaged with radars. Radar backscatter variations in SAR images can be interpreted in terms of variations of slope angle or faces orthogonal to the beam, surface roughness, incident angle of the beam, dielectric constant of the material, volume scattering, structural properties, and subsurface layering (such as varying dielectric constant). A change of any one of these properties could give a different radar backscatter. For example, a rough surface and a smooth surface of the same composition could present different properties to radar. Conversely, two materials with different compositions, but similar backscatter functions (for example, butane muds and pentane muds), could both appear the same to radar. Any differences between structure and composition can cause the radar backscatter of two terrains to appear different. Thus, two terrains that appear similar to radar may have similar composition and structure, while two terrains that appear different to radar have a difference in either composition and/or structure. It is also important to note that, depending on the properties of the surface materials, radar can penetrate into the subsurface on the order of 10s of cm depending on surface properties. Differences revealed by radar imaging may reflect differences in composition or structure of the subsurface. In contrast, visible or infrared measurements, such as VIMS or ISS, probe the near surface, on the order of hundreds of microns. It is thus possible for two materials to appear different to radar while appearing to be the same by hyperspectral imaging.

Cassini SAR swaths now cover 43% of the surface and have revealed a wide variety of geologic features, including channels (Langhans et al., 2012), mountains and tectonic features (Radebaugh et al., 2007), highly dissected labyrinthic terrain (Malaska et al., 2010), radar-dark lakes (Stofan et al., 2007; Mitri et al., 2007; Hayes et al., 2008), vast fields of dunes (Lorenz et al., 2006; Radebaugh et al., 2008), and putative cryovolcanic flows (Lopes et al., 2007, 2013). The SAR swaths have been used for preliminary planetary geomorphological mapping and the identification of several different terrain geomorphological surface units (Stofan et al., 2006; Wall et al., 2010; Lopes et al., 2010; Williams et al., 2011; Cornet et al., 2012). When available, additional information can be obtained by analyzing topographical relationships where SAR swaths overlap to provide stereo digital elevation models (DEMS) (Kirk et al., 2009) or where beam overlaps in individual SAR swaths can be processed to provide topographical strips using technique referred to as SARTopo (Stiles et al., 2009).

Our focused effort was to examine the relationships between Titan's surface features using SAR to determine potential sources and sinks for Titan's dune materials and mid-latitude plains. Our goal was to determine the direction of transport for the different units, and observe which units (dunes or plains) are located up-vector (towards the source) or down-vector (towards the sink). A terrestrial example would be examining aeolian sand dunes whose origin was a river delta: the sand dunes would be oriented downwind from the river delta source region.

To do this type of analysis on Titan, we used key terrain units on Titan that indicate the direction of mass transport. Our hypothesis was that, like in the terrestrial example above, Titan material transport would go from source to sink, and thus the source units would be located closer to the originating side of the mass transport vector, while the sinks would be on the terminating side of the mass transport vector. Previous work by Lorenz and Radebaugh (2009) used the SAR images to determine the global pattern of Titan's dunes. Their analysis examined individual dune orientations that were observed up to the T44 flyby (May 28, 2008). They determined that the dunes were predominantly oriented from west to east and showed divergence and recombination behind bright terrain obstacles. The bulk of their analysis was confined to the lower latitude regions from 30°N to 30°S based on the morphological expression of radar-dark dunes.

Our goal was to determine material transport directions on a global scale. It should be noted that we are looking for material transport as indicated by the movement of material. For fluvial transport, this will follow the hydrological gradient. The global pattern would thus be expected to follow the global topographical gradient published in Lorenz et al. (2013). For aeolian movement, materials will follow the wind regime when the wind is strong enough to move the grains (Tokano, 2010; Burr et al., 2015). This may be significantly different than the predictions of global circulation models (GCMs). It has been reported by Lucas et al. (2014), that the dune sediment transport direction is an indicator of storm wind direction, and may not be an indicator of the "normal" daily wind pattern. It is possible that the dune and other feature orientations could be caused by much longer-term cycles based on Croll–Milaknovitch orbital cycles (Aharonson et al., 2009). Recent work by Ewing et al. (2015) has suggested that dune orientation and morphology indicate shifts in wind and sediment availability coupled to variation in Saturn's orbit. Our map may only indicate the average direction of transport from storm winds, however, if this is the dominant mechanism of material transport, we would expect an overall alignment of all the other features with the pattern of dune winds indicated in Lorenz and Radebaugh (2009). Our interest is finding out where the material goes when the material is transported.

2. Description of terrains used for analysis

Several units have been identified on Titan as potential indicators of material flux direction. These include linear dunes, bright lineated plains, and streak-like plains. We updated and extended the initial work on dunes done by Lorenz and Radebaugh (2009) to include swaths up to T108 and also included the orientations of other terrain units such as bright lineated plains and streak-like plains.

Linear or longitudinal dunes are predominantly located in sand seas or ergs in the equatorial region of Titan, in the regions of Senkyo, Belet, Ching-Tu, Shangri-La, Fensal, and Aztlan (see labels in Fig. 12 for locations). These appear in SAR as dark parallel lines against a variable backscatter substrate (Fig. 1). The dune seas appear as dark regions relative to the rest of Titan by ISS at 0.94 μm and also correlate to a "dark brown unit" as determined by VIMS using spectral responses at 5.20–4.80, 2.00, 1.28 μm mapped as R, G, B (Barnes et al., 2007a). The linear dunes have been suggested to grow through several mechanisms, including forward