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Review Article

Dunes on Saturn's moon Titan as revealed by the Cassini Mission

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ABSTRACT

Dunes on Titan, a dominant landform comprising at least 15% of the surface, represent the end product of many physical processes acting in alien conditions. Winds in a nitrogen-rich atmosphere with Earth-like pressure transport sand that is likely to have been derived from complex organics produced in the atmosphere. These sands then accumulate into large, planet-encircling sand seas concentrated near the equator. Dunes on Titan are predominantly linear and similar in size and form to the large linear dunes of the Namib, Arabian and Saharan sand seas. They likely formed from wide bimodal winds and appear to undergo average sand transport to the east. Their singular form across the satellite indicates Titan's dunes may be highly mature, and may reside in a condition of stability that permitted their growth and evolution over long time scales. The dunes are among the youngest surface features, as even river channels do not cut through them. However, reorganization time scales of large linear dunes on Titan are likely tens of thousands of years. Thus, Titan's dune forms may be long-lived and yet be actively undergoing sand transport. This work is a summary of research on dunes on Titan after the *Cassini* Prime and Equinox Missions (2004–2010) and now during the Solstice Mission (to end in 2017). It discusses results of *Cassini* data analysis and modeling of conditions on Titan and it draws comparisons with observations and models of linear dune formation and evolution on Earth.

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1. Introduction

One of the primary goals of the *Cassini* spacecraft, launched for the Saturn system in 1997, was to survey the landscape of Saturn's largest satellite, Titan. With an atmosphere of N_2 made optically opaque by hydrocarbon hazes, little of the surface had ever been seen. Upon arrival of *Cassini* to Saturn and Titan in 2004, one of the least-predicted (Lorenz et al., 1995) surface features was seen in great abundance across Titan: sand dunes (Elachi et al., 2006; Lorenz et al., 2006; Barnes et al., 2008; Radebaugh et al., 2008). Dunes herald a mature environment, in which one or more processes have acted on the surface long enough to produceextensive and morphologically consistent landforms. Dunes indicate sand has been generated on Titan in great volumes, transported to a location, and blown by wind into persistent patterns. By other measures, Titan's surface is mature. There are networks of river channels carved into bedrock of water ice and/or organic sedimentary layers by methane, which has been evaporated from polar lakes and seas, collected into clouds and rained onto the surface (Collins, 2005; Stofan et al., 2007; Lorenz et al., 2008a). Mountains are found in isolated blocks, eroded plateaus and belts, and they appear to have undergone extensive erosion (Radebaugh et al., 2007; Moore and Pappalardo, 2011). There are few impact craters for a planetary surface and they are often covered by organic deposits or highly degraded (Lorenz et al., 2007; Wood et al., 2010a; Neish and Lorenz, 2012; Moore and Pappalardo, 2011). It appears an atmosphere with 1.5 bar surface pressure and density 4× that of Earth and an active methane hydrologic system have shaped the surface of Titan into one possessing mature and Earth-like geomorphic landforms (Lunine et al., 2008; Lopes et al., 2010).

Dunes on Titan are dominant features, covering an estimated 16% or 15 million km^2 (Rodriguez et al., in revision), narrowed from 12–20% or 10–17 million km^2 in earlier studies (Lorenz et al., 2008b; Radebaugh et al., 2010a; Le Gall et al., 2011). By comparison, dunes cover up to 4% ofEarth's surface, or up to 30% of the area classified as arid (Lancaster, 1995; Bourke et al., 2010), 0.06% of the surface of Mars (though dust and sand streaks can be found ubiquitously there) (Fenton and Hayward, 2010), and 0.004% of the surface of Venus (Bourke et al., 2010). Dunes on Titan are found between 30° N and 30° S latitude and nearly encircle the globe at the equator (Elachi et al., 2006; Radebaugh et al., 2008; Lorenz and Radebaugh, 2009). They are dominantly linear in form and are generally organized into large sand seas, regions of relatively high sand volume (Fig. 1). Over sixteen thousand linear dunes (Lorenz and Radebaugh, 2009) have been observed on Titan by the *Cassini* SAR (Synthetic Aperture RADAR, 2.17 cm, Elachi et al. 2006). Since SAR coverage of dune areas is close to 40% in the middle of the Solstice Mission, there are likely thousands more dunes not yet observed.

Dunes exist in regions dark to *Cassini* ISS, with global but lower-resolution coverage (Imaging Science Subsystems, 938 nm, just to the infrared of optical; Porco et al., 2005), and have been observed to be spectrally distinct from surrounding terrains in lower-resolution images with global coverage from *Cassini* VIMS (Visual and Infrared Mapping Spectrometer, in the near-infrared; Soderblom etal., 2007; Barnes et al., 2008; Rodriguez et al., in revision). Some select, high-resolution VIMS images also reveal spectrally distinct dunes and adjacent interdunes (Barnes et al., 2008). Spectral and radiometric observations of dunes reveal they are likely composed of organic particulates derived from atmospheric processing of methane (Soderblom et al., 2007; Barnes et al., 2008; Clark et al.,

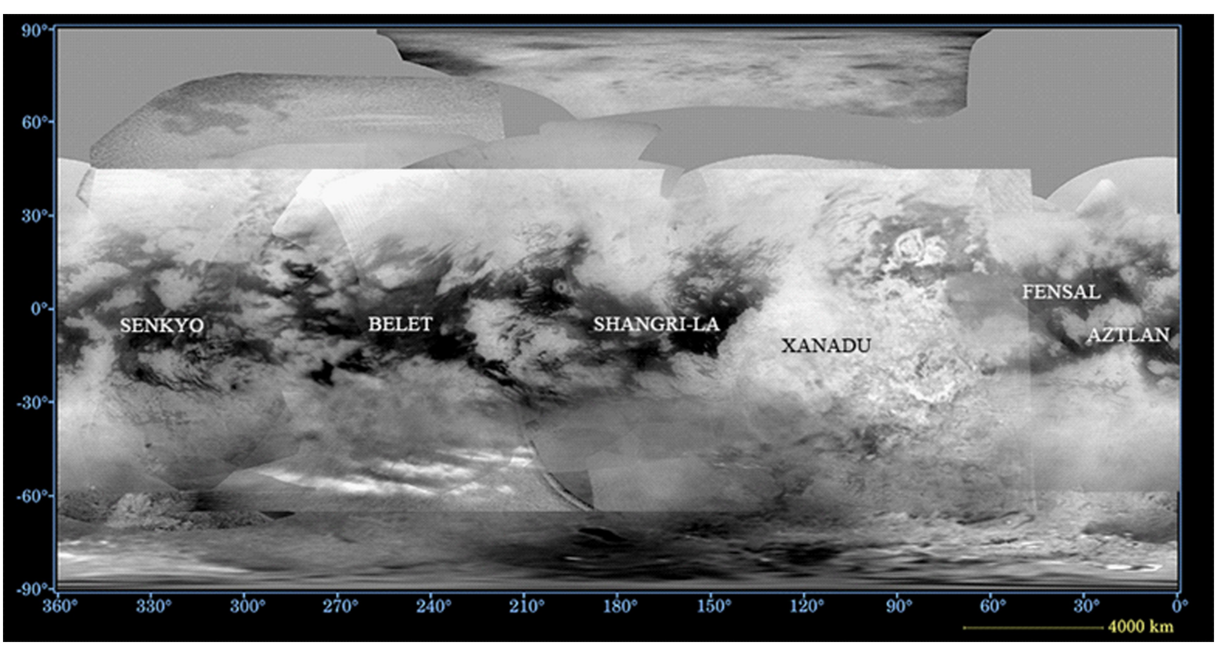

Fig. 1. Global map of sand sea distributions on Titan. Areas dark to visible-to-near-IR instruments near the equator generally correlate with dune regions. Each labeled region was originally named for being a region of anomalous albedo, and since then, Belet, Shangri-La, and Fensal/Aztlan have also become names for sand seas. The basemap is from ISS (visible-to-near-IR camera) images; mosaic assembled Feb. 2009 with an update from January 2013. Updated from NASA image PIA11149.