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Physics of saltation and sand transport on Titan: A brief review

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ABSTRACT

Key physical aspects of saltation and sand transport on Titan are reviewed, and the sensitivity of saltation parameters to assumptions about sand composition (most likely of 'heavy' organics) is explored. The possibility of significant triboelectric charging of sediments in Titan's low-conductivity environment is noted, and given Titan's low gravity electrostatic forces could substantially influence the saltation mechanics. Saltation paths are likely too short to permit observable ripples, while dunes may grow from an elemental size of ~1.5 m to a spacing of ~3 km, limited by the thickness of the atmospheric boundary layer. Most of Titan's dunes are of this size, indicating completed growth and that dividing sand volume by sand fluxes will yield only a lower limit on the dune age. Sand fluxes are estimated.

1. Introduction

Saturn's moon Titan was unexpectedly (Lorenz et al., 1995) discovered to have large areas covered in giant linear dunes (Lorenz et al., 2006). These dunes cover more than 10% of the surface (Lorenz and Radebaugh, 2009) – a larger area fraction than any other planetary body – almost exclusively in a band at the equator bounded by ±30° latitude. The dunes appear in Cassini radar images with a resolution of ~350 m or more to be morphologically identical, and indeed rather similar in size, to large linear dunes on Earth, such as those in the Namib or Arabian deserts (e.g. Lorenz et al., 2006; Radebaugh et al., 2008, 2010). An initial survey (Radebaugh et al., 2008) suggested typical lengths of 30–50 km and a width of about 1 km and spacing of 1–3 km (see also Le Gall et al., 2011).

The discovery of these remarkable and extensive features has stimulated a considerable body of work in mapping their extent and the variations of geomorphological properties with location. However, the fundamental mechanism for their formation, namely the saltation of particles, has received rather little attention. If geomorphological observations are to be quantitatively interpreted in terms of Titan's history, it is essential that the saltation and sand transport processes be understood. It is the purpose of this paper to recapitulate previous work on the topic, to reconsider some prior assumptions, and suggest directions for future investigations.

2. Saltation threshold

The mobility of surface particles in response to surface winds depends on a number of factors. A range of planetary environments defined by gravity and atmospheric pressure (as a proxy for density) are noted in Fig. 1. Venus is an extreme case, with the atmosphere being only about 20 times less dense than the particulates. Titan has an atmosphere only modestly thicker than Earth's, but the mobility of particles is enhanced by its Titan's low gravity. Thus in comparative planetological terms, Titan is an interesting intermediate between Earth and Venus. In practical terms, it is worth noting that the handling of powdered or granular materials (including astronaut's foodstuffs) in a pressurized habitat or spacecraft on the Moon would be very nearly representative (atmosphere thinner by a factor ~4, but gravity the same) of conditions on Titan.

To quantify the mobility of particulates it is conventional to balance fluid dynamic forces against weight and interparticle cohesion. Greeley and Iversen (1985) were the first to consider saltation thresholds on Titan in their book. They computed – assuming the same threshold parameterization as for sands on the terrestrial planets – an optimum diameter for saltation of 180 μm, with a threshold friction speed of 0.04 m/s (the diameter at which the threshold friction speed is a minimum is traditionally referred to as the 'optimum'). This assumed, however, a particle density of some 1900 kg/m^3, which represents the average density of Titan as a whole.

Allison (1992) noted in an early evaluation of Titan's planetary boundary layer that wind-blown dust might be an occasional feature of Titan meteorology, with a threshold friction speed of 0.017 m/s based on a Stokes' law estimate of sedimentation speed of 50 μm particles. However, the Reynolds number for such flow may be too high for Stokes' law to be accurate, and so this result should be considered with caution.

Lorenz et al. (1995) – stimulated by an abstract by Grier et al. (1993) – applied Greeley and Iversen's methods, this time using a particle density of 1000 kg m^{-3}, and found an optimum size of about 250 μm diameter, although with the same threshold speed as Greeley and Iversen (1985). This in fact should not be too

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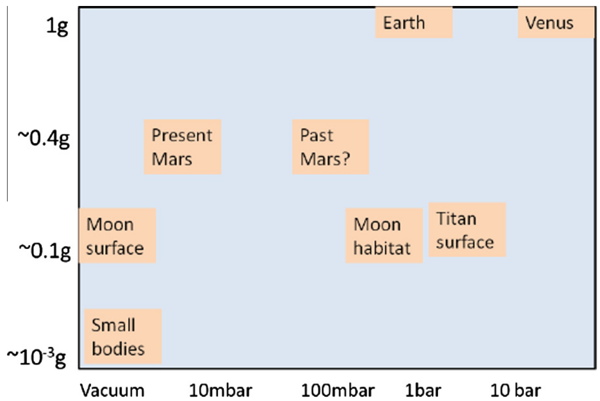

Fig. 1. Eolian Transport Conditions for various environments. The discovery of dunes on Titan brings particular interest in studying eolian processes in that environment. It is worth noting that conditions there (in terms of gravity and atmospheric density) are quite similar to those inside a spacecraft or base on the Moon.

surprising, in that the optimum is driven as much by the assumed cohesion as it is by the assumed weight (i.e. particle density).

Kok et al. (2012) made an extensive review of wind-blown sand and dust on planetary bodies, reporting the results of a comprehensive saltation model. They also found (assuming a particle density of 1000 kg m^{-3}) an optimum fluid threshold speed ~0.04 m/s for a particle size of 250 μm diameter. Kok et al. (2012) note the important distinction between the classic 'fluid' threshold required to initiate motion, and the 'impact' threshold, where saltation can be self-sustaining. On Earth and especially Mars, the latter speed is lower, meaning it is easier to maintain saltation than to start it. However, on Venus and Titan, with much denser atmospheres, the fluid threshold is actually lower.

Kok et al. (2012) note an elegant expression for the fluid saltation threshold by Shao and Lu (2000), which is rather more succinct than the piecewise formulation used by Greeley and Iversen (1985), originally due to Iversen and White (1982). Specifically,

$$u_{*th} = A_N[\{(\rho_p/\rho_a) - 1\}gD_p + \gamma/(\rho_a D_p)]^{0.5}$$

Where the empirical dimensionless parameter $A_N \sim 0.111$ and the parameter γ describes interparticle forces, where $\gamma = 1.6 \times 10^{-4}$ to 5×10^{-4} N m^{-1} are used for dry dust and sand on Earth.

This expression neatly allows us to expose the dependence as a function of assumed particle properties. For example, it is easy to imagine that Titan 'sand' might in fact be porous aggregate particles made from much smaller atmospheric haze particles that have clumped together but nonetheless retain some porosity, and so a density of 500 kg m^{-3} might be encountered. As shown in Fig. 2, the saltation threshold function changes only modestly from the 1000 kg m^{-3} assumed by Lorenz et al. (1995). This remains a preferred value on the assumption (e.g. Lorenz et al., 2006; Lorenz, 2010) that the predominant sand-forming materials are photochemically-derived, as supported by an association of an aromatic spectral signature (Clark et al., 2010) with the dunefields. While many simple organics and nitriles at Titan surface temperatures have bulk densities in the range 700–900 kg m^{-3} Raulin (1987), photochemical sediments may include a substantial component of more refractory and denser compounds including polycyclic aromatic hydrocarbons (PAHs) such as pyrene and phenanthrene, which have room temperature densities of 1150–1270 kg m^{-3}. Since most polymers contract at ~90 K by 1–2% compared to their room temperature values, the cryogenic densities are probably 5% or so higher than the room temperature values.

The cohesion parameter could, for Titan materials, be quite different from that assumed for terrestrial rocks. Fig. 2 shows that even using the range noted by Lu and Shao (1999), the optimum diameter could be double the ~300 μm that has been assumed for all Titan work (following Lorenz et al., 1995) since the discovery of dunes on Titan.

It is well-known even to 4-year-olds that moistening sand makes it stick together more effectively. In other words, the cohesion for dry sand is typically moisture-limited. Indeed, although cohesion values are not reported, Greeley and Iversen (1985) present data (their Table 3.2) which shows that even 0.6% of water to sand will double the threshold speed.

The physics of cohesion is actually far from trivial. While the cohesion parameter has the dimensions of force per unit length, the same as those for surface tension, the values here are actually about 400 times smaller than the macroscopic surface tension of water, and indeed the forces on surfaces of grains can be a complex function of microscopic roughness, relative humidity and other factors (e.g. Jones et al., 2002 and references therein). The handling of powdered and granular material with Titan-like composition (e.g. plastics) in industrial settings is not obviously different from the handling of sands, so the values indicated above for cohesion are certainly reasonable assumptions for Titan particulates, but it should be recognized that neither the cohesion, nor by implication the optimum particle size, is actually known. The surface tension of liquid hydrocarbons is a factor of ~4 smaller than water, so perhaps an equivalent amount of ethane moisture on Titan would have at most a comparable effect to water on sands on Earth. Depending on the polarity of the constituent molecules or functional groups, solid organics can be more or less hydrophilic or hydrophobic, and similarly may have lower or higher affinities for nonpolar solvents such as ethane and methane. In fact, little work beyond a measure of solubility in some solvents (McKay, 1996) has been done on Titan tholins. However, some recent experiments (Sotin et al., 2009) have shown an interesting wetting behavior of water ice by methane and ethane: 'When methane drops came into contact with an ice substrate, the interaction is similar to how water soaks into a sand matrix'. Further experimentation, to study the effects of hydrocarbon moisture on the cohesion of a broader range of materials (such as tholins or PAH's as described above) would be of considerable interest.

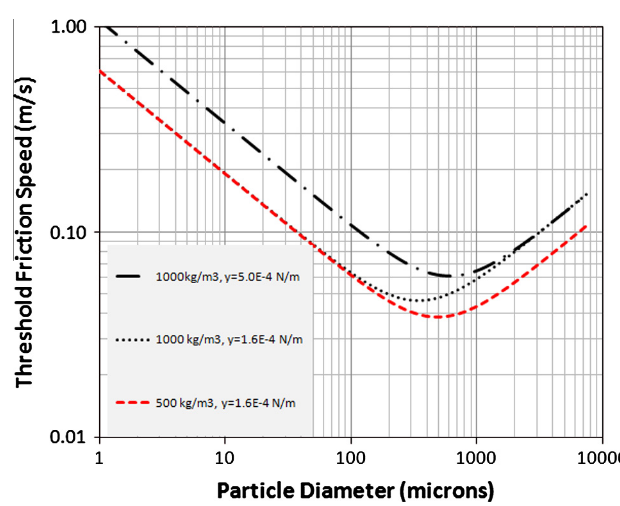

Fig. 2. Saltation threshold on Titan (g = 1.35 m/s^2, ρ_a = 5.4 kg/m^3). Parameters that have been assumed in the past (ρ_p = 1000 kg/m^3 and $\gamma = 1.6 \times 10^{-4}$ N/m) have an optimum diameter of about 300 μm and a threshold speed of 0.045 m/s. Plausible variations in particle density or cohesion lead to somewhat higher optimum particle diameters (~500–600 μm) and a range of fluid threshold friction speeds (0.03–0.06 m/s).