LABORATORY INVESTIGATIONS RELEVANT TO THE EROSION OF ICE ON TITAN.
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Introduction: As images of Titan's surface have been returned over the past few years, it has become abundantly clear that erosion is a dominant geological process on Titan. Vast "sand seas" of dunes imaged by the Cassini RADAR [1] and the rounded gravel and cobbles on the surface imaged by the Huygens probe [2] both point to the mobility and processing of sediment on the surface. Branching, sinuous valley networks observed in many areas of Titan [2, 3] point to fluvial erosion as an important process modifying Titan's surface. The paucity of impact craters on the surface [4] makes the question of the rate of erosion on Titan especially interesting.

Titan is the only icy satellite to display such Earth-like surface processes. As we begin to investigate the detailed physical mechanisms that control these processes, we are currently hampered by a lack of knowledge about some of the relevant physical properties of ice. Here we discuss some of our efforts to fill this gap, and mention other studies that could be undertaken to further our understanding of geological processes on Titan's surface.

Erosion of bedrock stream channels: The central process likely to be setting the overall erosion rate on Titan is the incision of stream channels into the ice "bedrock" that composes the core of topographic features such as mountain chains and crater rims. The dark materials seen in the bottoms of the stream channels at the Huygens landing site are probably exposures of this water ice-rich material [5]. The physical mechanisms by which stream channels are incised into bedrock is currently a subject of active terrestrial research (e.g. as reviewed in [6]). On Titan one of the most effective mechanisms of fluvial incision [7] is likely to be wear of the streambed by saltating bedload.

Sklar and Dietrich [8] have developed a model of the physical mechanisms that control wear by saltating bedload, confirmed by experimental work on various rock samples. This model accounts for enough of the underlying physics that it can be applied directly to the Titan environment, explicitly accounting for the different gravity, fluid, and material parameters [7]. However, there is one unknown material property that controls the rate at which ice will be eroded.

Bedrock at the bottom of a stream channel is slowly chipped away by low-velocity impacts as sediment particles hop and roll along the streambed. The rate at which these chips are detached from the bedrock is proportional to the kinetic energy of the impacts and the capacity of the material to store elastic energy, as defined by $\sigma^2 / 2E$ where σ is the tensile yield strength and E is Young's modulus [8]. The nondimensional constant of proportionality that controls the rate is called the abrasion susceptibility coefficient, and it needs to be determined experimentally.

Abrasion susceptibility of water ice: Initial, crude attempts to measure the abrasion susceptibility of water ice at Titan temperatures were attempted by repeatedly dropping small weights onto ice disks cooled with liquid nitrogen [7]. These experiments showed ice to be about two orders of magnitude more susceptible to abrasion than most rocks. With lower gravity and less dense sediments on Titan, there is less kinetic energy delivered to a streambed by sediment impacts. If water ice is as weak as these experiments showed, the two factors cancel out and we should expect the rate of incision on Titan to be very similar to that on Earth [7]. However, these initial experiments were flawed by imprecise control of the input energy and ambient temperature, and lack of facilities for precisely measuring the wear rate.

We are currently running a new set of experiments to determine the abrasion susceptibility of polycrystalline water ice under better-controlled conditions and with better measurement facilities. Details of the experimental methods are described in a companion abstract [9]. Since the wear rate is a function of both the abrasion susceptibility and the tensile strength, the first step is to firmly nail down the tensile strength of our experimental samples. We are currently exploring the dependence of ice tensile strength on temperature, and testing the hypothesis that below a temperature of about 220 K tensile strength becomes insensitive to further reductions in temperature.

Other relevant parameters: Though it is one of the dominant factors controlling erosion, understanding the incision of fluvial channels into ice bedrock is only part of the full picture. In particular, there are several aspects of Titan hydrology and regolith processes that must be explored in order to build a more accurate picture of stream flow on Titan. To make progress in understanding Titan surface processes, we suggest that other studies should be undertaken in the future to investigate the following:

• *Coating organics onto ice grains:* How do organics in Titan's cold surface environment interact with water ice on the surface? When looking at sediments on the surface, are ice particles likely to be separated from solid organic particles, or can organics form surface coatings on the ice particles? This is important for understanding the range of possibilities for Titan regolith mixtures. It is also important for interpreting the spectral data from Titan's surface [5].

• *Infiltration of liquid methane into ice-based regolith:* What are the wetting properties of liquid methane in a porous water ice matrix, and what flow rates would be predicted through ice regolith? How would these be affected by the presence of organics in the regolith, either as separate particles or as surface coatings on the ice? This is important for understanding the subsurface hydrology on Titan, including aquifer holding capacity, discharge rates from springs, and the relationship between precipitation and runoff.

• *Mechanical properties of saturated ice regolith:* How does the saturation of ice-based regolith with liquid methane affect its mechanical properties, and how much fluid is needed to reach its liquid limit? How does the presence of organic particles or coatings change these mechanical properties? This is important for understanding hillslope processes, sediment supply into streams, and the role of landslides in modifying Titan's landscape.

Conclusion: In the coming months we will be measuring abrasion rates, ice tensile strength, and elastic modulus across a range of temperatures representative of conditions on Titan and other planetary surfaces. These measurements will provide a good quantitative description of the abrasion suscpetability of ice, including its possible dependence on temperature. Once we have measured this key parameter we will have a much more solid understanding of the efficacy of fluvial abrasion on Titan. This will lay the groundwork for investigating the rates of landscape evolution on Titan, and for understanding the surface geology of this strangely Earth-like icy satellite.

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