EXPERIMENTALLY-DERIVED SALTATION THRESHOLD WIND SPEEDS FOR TITAN: UNDERPREDICTION BY TERRESTRIAL MODELS.

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Introduction: The discovery of aeolian dunes on Titan [1-3] puts that body into a class previously thought exclusive to Earth, Mars, and Venus [4]. In view of the deposition of organic aerosols from the atmosphere, the distinct compositions of dune and inter-dune surfaces suggest recent dune activity [5]. However, models of the present-day atmosphere give predominantly east-to-west winds (see discussion in [6]), in contrast to the west-to-east flow inferred from the streamlines of dunes around obstacles [2].

Saltation of sand is required to form dunes [4,7]. Thus, the discovery of Titan dune demonstrates that wind speeds on Titan have exceeded the minimum (threshold) speeds required to initiate saltation. For the terrestrial planets, wind tunnel experiments collected under ambient and analog conditions provide the basis for our models of threshold wind speeds. However, for non-terrestrial-planet conditions, the accuracy of these models has been untested.

Hypothesis: Our null hypotheis is that the terrestrially-based threshold models accurately predict threshold wind speeds for Titan. To test this hypothesis, we conducted experiments in the Titan Wind Tunnel [8,9].

Data and Methods: Our approach included: 1) deriving experimental values ($u*_{tTWT}$) of threshold wind speeds, 2) using threshold models to convert those experimental data to Titan surface conditions ($u*_{tTitan}$), and 3) comparing those experimentally-based results to purely model-based results.

For the experiments, we used the Titan Wind Tunnel [10] to conduct threshold experiments with a variety of particulate materials for a total of 23 different unique combinations of particle size and density. Threshold friction wind speed ($u*_t$) is defined [4,7,10,11] as a function of A (a dimensionless parameter dependent on both the particle Reynolds number at threshold friction wind speed [$Re*_t = u*_t D_p / \nu$] and the interparticle forces [$I_p = I_p f(D_p)$]), and of particle, gas, and gravity characteristics:

$$u*_t = \simeq A(Re*_t, I_p)((\rho_p/\rho) g D_p)^{1/2} \qquad \text{(Eq. 1)}$$

where ν is the kinematic viscosity of the gas, ρ_p and ρ are the particle and gas densities, g is gravity, and D_p is the particle diameter. For these experiments, we used kinematic viscosity as the similitude parameter, because it provides the correct ratio of lift and drag forces and thus the correct Reynolds number conditions [10].

Results: The experimentally-derived values of $u*_{tTWT}$ were compared to predictions for the experimental conditions by two models of threshold fiction wind speeds, one model by Iversen and White [10] (IW) and one by Shao and Lu (SL) [11]. In this comparison, the experimentally-derived values are ~40-50% higher, outside of uncertainty estimates, than predicted by either model [9].

The TWT threshold friction speeds were converted to Titan threshold friction speeds ($u*_{tTitan}$) for both models. We modified the IW model to use the same dependence of I_p on D_p as the SL model for easier comparison. The modified IW model and SL model both underpredict the experimentally-based $u*_{tTitan}$ values by ~40-50% (Figure 1). Thus, the experimentally-based values for Titan are not predicted by either model, disproving our hypothesis.

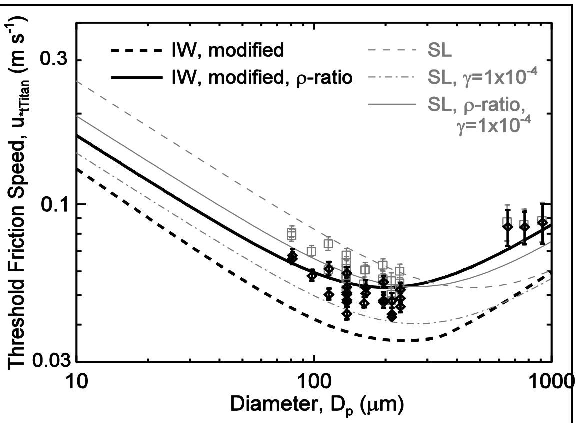

Figure 1: Experimentally-derived threshold fiction wind speeds on Titan. Dashed lines are the nominal models; solid lines include the density-ratio term. The modified IW model has the same dependence of I_p on D_p as the SL model. Both nominal IW and SL models underestimate the experimental data points. The SL model is also shown for the minimal gamma value to improve fit (dash-dotted line), and the minimal gamma plus the density ratio (solid).

Correcting the models: Correcting the models requires shifting the model curves to match the experimental results. Algebraic analyses of the various model formulations by Iversen and colleagues [10,12,13] suggest the most reasonable approach to accomplishing this shift. As a specific form of Eq. 1, the complete formulation may be written

$$u*_t = A_1[(1 + A_4 I_p/(\rho_p g D_p^3)) / (f(Re*_t) + g(\rho_p/\rho))(\rho_p g D_p/\rho)]^{1/2} \qquad \text{(Eq. 2)}$$

where A_4 is a constant that quantifies the interparticle force (I_p) and $g(\rho_p/\rho)$ is a density ratio term. The value for A_4 in the various model formulations varies by roughly an order of magnitude depending on whether the exponent for the particle diameter is fit to data or assumed, but this variation does not significantly change the magnitude of the curve. The Reynolds number dependence, *f(Re*t)*, derived based on fitting to diverse datasets for discrete Reynolds number ranges [6,11], is unlikely to be significantly in error. The *A1* values have also been derived from fitting to a broad experimental dataset, and so likely robust.

The magnitude of the modified IW model curve may be increased through the inclusion of a density ratio term, $g(\rho_p/\rho)$. This term was introduced to improve the model fit to experimental data for Venus analog conditions, data that, like those from the TWT, were higher in value than predicted [14]. The density ratios for the TWT experiments (~80 – 200) and for Titan (~200) are similar to each other and to the value for the Venus analog experiments (~40), which (under density similitude) matches the value for Venus. In comparison, the density ratios for Earth and Mars are of order 10^3 and 10^5, respectively. Inclusion of the density ratio for Titan conditions shifts the modified IW model up by ~50% (Figure 2). Inclusion of the density ratio term in the SL model also shifts the curve up, although the model still underpredicts the experimentally-derived data (Figure 2). Whereas the modified IW and SL models compare well for Earth and the various Martian conditions [11], they show an observable difference for Venus [11] and an even greater difference (~100% around the optimum Dp of ~200 µm) for Titan (Figure 1). That both Venus and Titan have lower density ratios than either Earth or Mars substantiates using the density ratio to correct the Titan curves.

The density ratio term was originally derived algebraically from a balance of forces for threshold conditions that include grain impacts [12]. However, the data of record in our TWT experiments were the observations taken during increasing wind speeds, before significant upwind saltation was occurring. By analogy with Titan (and Venus) [15], fluid threshold in the TWT (and VWT) experiments is lower than impact threshold and so would be encountered first during increasing wind speeds. We thus infer that our experimental data, probably like the Venus Wind Tunnel data [14], record fluid threshold without a contribution from grain impacts. *A1* is inferred to be a function of drag and moment. That both *A1* and the density ratio term change the magnitude of the Iversen model curve implies that a low density ratio affects the drag and moment in some fashion.

Conclusions and Implications: Our results disprove our null hypothesis, and provide parameters (e.g., shear stress, Figure 2) for improved modeling of sand transport on Titan. The higher-than-predicted threshold values support a scenario of elongation of the dunes by rare strong westerly winds instead of prevailing easterlies [6]. However, our experimentally-derived threshold values at z=300 m (Figure 2) exceed the reported model threshold values at this height [6], so that use of the new threshold values in modeling dune elongation is necessary to test this hypothesis.

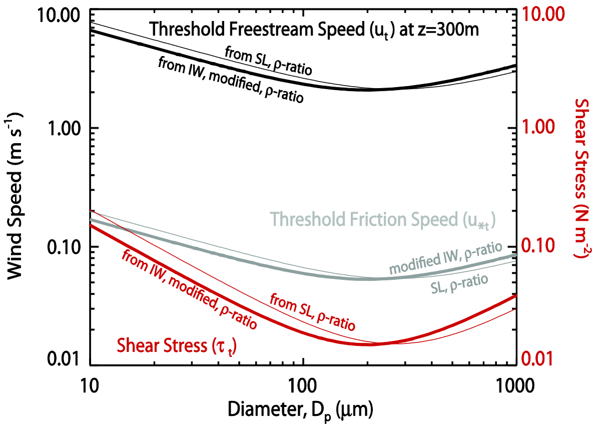

Figure 2: Derived parameters from Titan threshold fiction speeds . The $u*_{t\ TWT}$ *data (grey lines) from Figure 1 are shown as threshold shear stress* ($\tau_t = \rho u*_t^2$, *red lines and right ordinal scale), and as freestream wind speed at 300 meters altitude (black lines).*

While demonstrating the importance of the density ratio term in calculating threshold friction speeds in thick atmospheres, these results also substantiate its unimportance in modeling high density ratio conditions ($\rho_p/\rho > 1000$). For other extreme aeolian conditions, including transport by jets on comets [15], entrainment may be modeled by the modified Iversen and White [11,13] formulation without the density ratio term.

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