Towards a Classification Scheme for Aeolian Fluid Ejection: Observations During High-Pressure Wind Tunnel Experiments.

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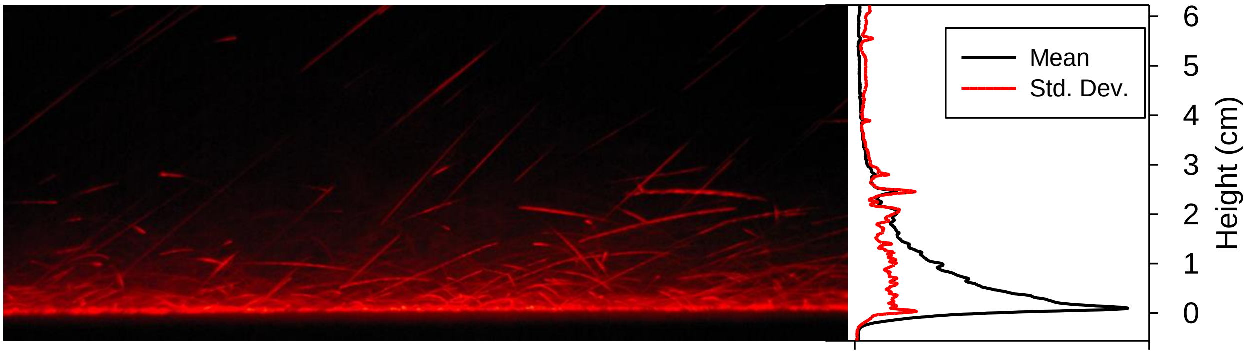

Figure 1: Laser light illumination of sediment transport via traditional saltation and reptation pathways. Mean and standard deviation are calculated from light intensity statistics for each row. (source: Sutton, Dune Simulation Wind Tunnel.).

Introduction: Ongoing research with the Titan Wind Tunnel (TWT) [1] into the wind conditions required to initiate aeolian transport in high density atmospheres, analogous with Titan [2, 3], suggests differences between the transport modes observed under those conditions and those modes found on Earth. Sediment transport on Earth is dominated by impact entrainment, resulting in the saltation and reptation of grains (Fig. 1); whereas on Venus and Titan transport is dominated by fluid entrainment. This transport 'mode switching' may affect the surface-atmosphere interaction, the momentum transfer between the boundary layer and the saltation cloud; a relationship that is assumed by many aeolian models. Hampering our understanding is the lack of a clear classification of entrainment modes. Classification is an important aspect of scientific advancement as it promotes observation, communication, structured theory development, and formalizes the language into a falsifiable structure [4, 5]. We are currently conducting a comprehensive observational study of fluid entrainment modes and are developing a formal classification scheme applicable to Venus, Titan, and other similar environments (Fig. 2).

Fluid entrainment occurs when the fluid drag and lift forces acting on a grain resting on the bed overcome the inertia, weight and intra-particle cohesion, causing the grain to move. This fluid regime is typically characterized by the shear velocity (u_*), which is related to the bed shear stress (τ_0),

$$u_* = \sqrt{\frac{\tau_0}{\rho_f}},$$

where ρ_f is the fluid density. The minimum flow conditions required to initiate motion on a static bed is then described by the fluid threshold shear velocity, $u_{*_{tF}}$.

Impact entrainment describes the dislodgement of a grain via impact by another grain already in transport (i.e. saltation). During this cascading system of ejections and impacts, a grain is ejected from the surface with an initial vertical velocity that carries it higher into the boundary layer. There it encounters increasing horizontal wind speeds that accelerate the grain beyond its initial horizontal velocity. This increase in grain velocity leads to an increase in momentum transfer upon impact with the bed, and results in an ejection or rebound of a grain with sufficient vertical velocity to repeat the process [6]. The threshold for this behavior is denoted as $u_{*_{tI}}$.

On Earth aeolian transport is dominated by saltation because $u_{*_{tF}} > u_{*_{tI}}$. The relative position of these thresholds is due to the ability of the saltating grain to extract momentum from the faster flowing air higher in the boundary layer, increasing its impact energy beyond that which the grain had upon ejection [6].

However, under high-density atmospheric conditions this effect is diminished and the relative thresholds change positions: $u_{*_{tF}} < u_{*_{tI}}$. Under these conditions an ejected grain is exposed to much higher drag due to the increased ρ_f and kinematic viscosity, ν, which reduces the height to which the grain may rise and limits its exposure to the higher wind speeds further from the bed, resulting in lower impact speeds and reduced likelihood of impact entrainment occurring [7].

The aeolian transport cloud then strongly interacts with the boundary layer through complex feedback mechanisms that are governed, in large part, by the ejection angle and velocity [6, 7, 8, 9]. This coupling of surface and atmosphere has generated significant interest in development of a stochastic 'splash' function to describe these conditions under *impact entrainment* regime [10, 11, 12]. Much of our understanding of aeolian geomorphology relies on a 'systems' model built on grain scale behavior that may not well describe conditions on Venus and Titan. Figure 3 shows the relative environments in which sediment transport is occurring in the Solar System, with Venus and Titan occupying a specific gravity range an order of magnitude different than either aeolian or fluvial environments on Earth.

Because aeolian transport studies on Earth are conducted in a regime where fluid entrainment occurs at higher wind speeds than impact entrainment, fluid entrainment is difficult to isolate and thus seldom observed. Thus, an adequate nomenclature describing fluid ejections has never been developed.

Proposed classification: We are proposing a classification scheme based on our observations in the Titan Wind Tunnel [2, 3] at the Planetary Aeolian Laboratory at NASA Ames. While observations are still being collected, and instrumentation is being upgraded to enhance our ability to capture and isolate incipient movement, an initial scheme of grain motion is presented in Fig. 2.

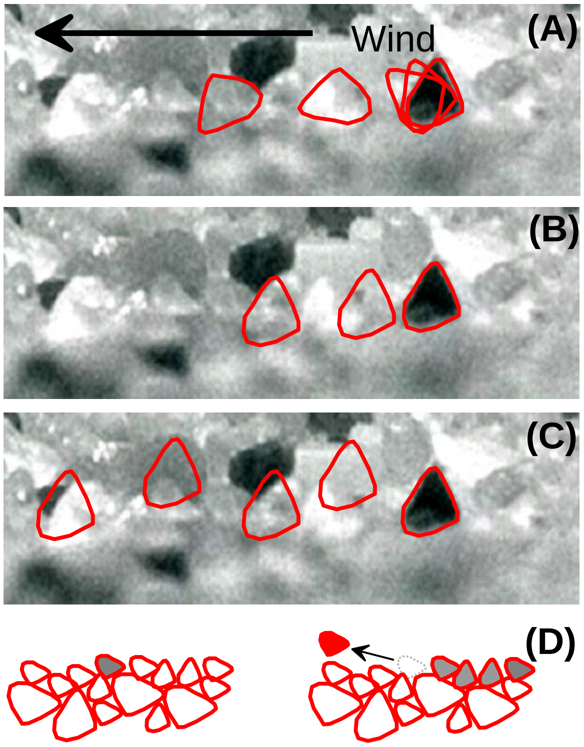

Figure 2: Examples of different modes of fluid entrainment: A) is a rotational entrainment. B) is a translational entrainment, C) is a skipping entrainment, and D) is entrainment by undermining. Background in A-C is a bed of silicate sand in the Titan Wind Tunnel.

Grain motion classification: Figure 2A shows a rotational entrainment, in which the peak of the grain rotates around a stationary or slower moving base. A translational entrainment is depicted in Fig. 2B, in which the grain moves without an initial rotational component. In neither case do the grains have a significant vertical velocity. Figure 2C shows a skipping movement, where the grain repeatedly comes in contact with the bed. Finally, Figure 2D illustrates a collective behavior in which a grain is ejected, resulting in either a loss of physical support or a change in fluid flow properties at the grain scale, and this destabilizes the grain(s) immediately upwind. This results in a flurry of ejections.

Grain initiation: Initiation of the movement also can be divided into, presently, two categories of prior behavior: those instances in which grains vibrate prior to being entrained, occasionally approaching bed fluidization, and those instances where the grain is 'plucked' from a static position, and where an impacting grains aids in the ejection.

Future work and implications: A classification of modes of i) sediment fluid entrainment, and ii) transport under fluid entrainment dominated conditions, will provide new insight into the inception of motion on Earth and also improve description of the active transport modes on Venus and Titan. Further, the classification will aid in the development and testing of sediment initiation models for Earth [e.g. 13], and help in adapting Earth parameterized transport models to Venus and Titan conditions.

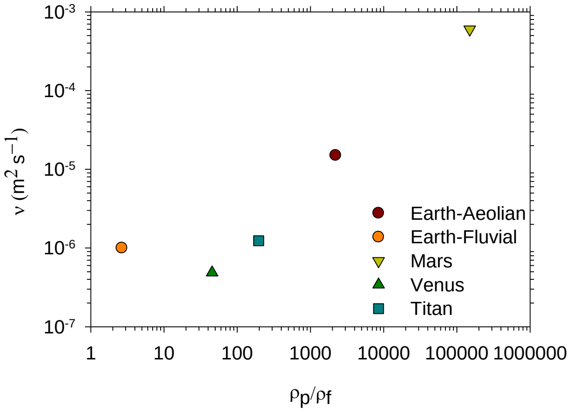

Figure 3: Comparison of terrestrial and extraterrestrial aeolian and fluvial environments, in terms of kinematic viscosity and specific gravity of sediments.

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