

## STABILITY OF EOLIAN BEDFORMS ON PLANETARY SURFACES: RECENT ADVANCES AND REMAINING QUESTIONS. M. G. A. Lapôtre<sup>1</sup>, R. C. Ewing<sup>2</sup>, L. Rubanenko<sup>1</sup>, P. Claudin<sup>3</sup>, S. Carpy<sup>4</sup>, and A. Gunn<sup>1,5</sup>.

<sup>1</sup>Stanford University, Stanford, CA 94305, USA (mlapotre@stanford.edu). <sup>2</sup>Texas A&M University, College Station, TX 77843, USA. <sup>3</sup>ESPCI – CNRS, 75005 Paris, France. <sup>4</sup>CNRS – Nantes University, 44322 Nantes, France. <sup>5</sup>Now at Monash University, Clayton, Victoria 3800, Australia.

**Introduction:** As winds and other gas flows mobilize regolith on planetary surfaces, they often form sedimentary structures, including ripples and dunes [1]. Because such bedforms form in concert with environmental flows, they have the potential to disclose information about both modern and ancient planetary surface conditions [2]. However, deciphering the record left behind by bedforms in planetary landscapes and sedimentary rocks requires a robust quantitative understanding of the interplay between the flow and the granular regolith bed. Eolian bedforms are ubiquitous in the Solar System – with documented occurrences on Venus, Earth, Mars, Titan, Pluto, and the 67P/Churyumov-Gerasimenko comet [3–5] as well as candidate bedforms on Io – constituting an unparalleled opportunity to utilize the diversity of Solar System bodies as a landscape-scale, comparative-planetology experiment in eolian science [6]. On Earth, three main types of eolian bedforms are known – impact ripples, coarse-grained ripples, and dunes. Impact ripples form in response to feedback between bed topography and the propensity of grains sitting on the bed to be splashed into transport from impact with an incoming saltating grain [7]. Impact ripples are characterized by linear crestlines perpendicular to flow and have decimeter-scale wavelengths on Earth; similarly sized impact ripples are also observed on Mars [8]. Coarse-grained ripples (or megaripples) require the presence of a wider grain-size distribution, with two grain-size populations moving through distinct transport modes. On Earth, coarse-grained ripples form when coarser grains mobilized through creep armor the crest of bedforms while finer grains saltate, enabling more complex crestline geometries and longer, meter-scale wavelengths [9]. They disappear rapidly when wind speeds exceed that required to saltate the coarse grains [9]. Coarse-grained ripples have also been documented on Mars from the ground and from orbit [8,10]. Finally, dunes arise from a hydrodynamic instability, with an initial wavelength around 10–20 m on Earth, and coarsen (i.e., become larger) through time. Similar, multi-decameter to kilometer-scale dunes are observed globally on Mars [11], in at least a couple of fields on Venus [12], and all around Titan’s equatorial region [13]. Until recently, these three bedform types (and their known formation mechanics) have served as the basis from which the vast majority of planetary eolian bedforms have been interpreted. However, ground and orbital observations of the martian surface, accumulated over the past couple of decades, suggested that this

Earth-centric framework may not be general enough to apply to planetary bedforms whose formation occurs under untested “parameter spaces” [6,8]. Notably, Mars hosts a variety of meter-scale bedform types that do not seem to occur on Earth. Dark-toned ripples, or “large martian ripples,” resemble Earth’s coarse-grained ripples in size and shape but lack a concentration of coarser grains near their crests [8]. They are distinct in size from decimeter-scale impact ripples – with no well-sorted bedforms with ~20–80 cm wavelengths – and they are distinct in size from the larger dunes – with no active, non-dusty bedforms with ~20–80 m wavelengths [8]. Finally, light-toned multi-meter to decameter bedforms are also common on Mars. Although their origin remains poorly understood, they are largely thought to be the dusty, inactive remnants of older bedforms, and are typically grouped under the name of “Transverse Aeolian Ridges,” or TARs (not included in this discussion) [14]. Adding to the mystery of Mars’ meter-scale bedforms, meter-to-decameter scale bedforms were also recently observed under the extremely rarefied and ephemeral exosphere of the 67P comet [4]. The recognition of these alien ripples and lack of high-resolution data open the possibility that other bedform types await to be discovered on Venus, Titan, and other planetary bodies.

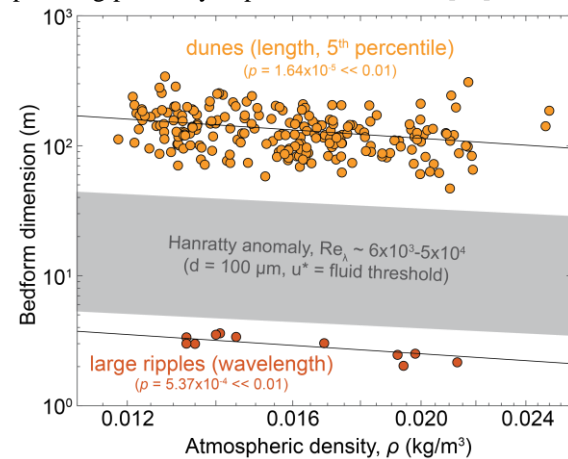
### Recent Advances and Planetary Bedform Stability:

Over the past several years, a wealth of new in situ data from other planetary bodies has reinvigorated research in eolian transport and bedform formation, including theoretical, numerical, experimental, analog, and remote-sensing studies. Notably, wind-tunnel experiments demonstrated that the initial size of impact ripples does not vary significantly when atmospheric pressure is decreased to Mars-like values [15]. In contrast, the wavelength of large martian ripples, globally, was shown to decrease with increasing atmospheric density [8,16] (Fig. 1). Such a trend is expected where feedbacks from the fluid dominate over those from impacts such as with drag ripples forming under liquid flows like current ripples on Earth’s riverbeds [17]. The morphology of large martian ripples (including the occurrence of sinuous crestlines and near-angle of repose slip faces with grainfall and grainflow) has led Lapôtre et al. (2016) [8] to propose that large martian ripples may, in some aspect, be analogous to drag ripples. Since that proposal, two endmember models have been formulated to explain the formation of large martian ripples. One model hypothesized that large martian ripples are impact ripples [18]. Under this

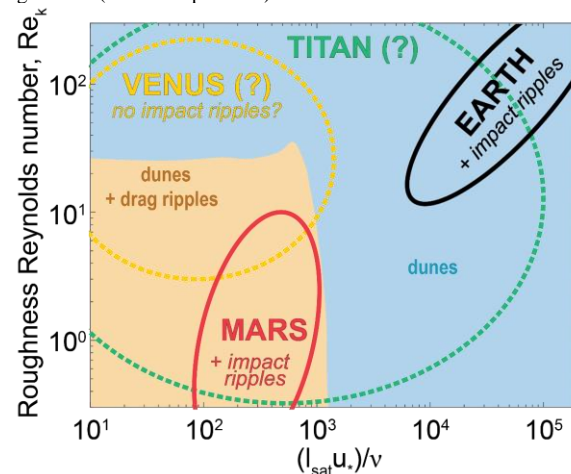
model, impact ripples initiate with decimeter wavelengths but may grow through time and reach meter-scale equilibrium sizes owing to Mars' low-density atmosphere. However, this model predicts a continuum of ripple sizes between  $\sim 10$  cm and a few meters – counter to existing observations. In contrast, a second model proposed that large martian ripples arise from the same hydrodynamic instability that generates larger dunes, but that a gap in wavelength exists between the large ripples and dunes owing to a hydrodynamic anomaly [19], first evidenced experimentally by T. Hanratty [20] and characterized by a shift in the locus of maximum sediment flux downstream of the bedform crest. The same anomaly is thought to generate the scale gap between drag ripples and fluvial dunes in rivers. A similar mechanism was proposed to explain the formation of bedforms on the 67P comet under thin sublimation flows [21]. This model is, to date, consistent with all existing observations. Notably, the wavelength of Mars' large ripples and smallest dunes appear to robustly bound the wavelength gap born from Hanratty's anomaly [22] (Fig. 1), lending further support to the model.

**Predictions and Remaining Questions:** Because their formation requires impact splash to be efficient at mobilizing sediments, impact ripples are thought to only form in planetary environments characterized by high sediment-to-atmospheric density ratios ( $\rho_s/\rho$ ). With  $\rho_s/\rho \sim 40$ , it is unclear whether Venus could host a population of impact ripples, opening the possibility that only one type of eolian bedform forms on Venus (but could occur at multiple scales as with compound dunes on Earth). In addition, splash efficiency is also affected by cohesion of the substrate [23], such that the largely unconstrained properties of Titan surface materials make any predictions of bedform stability challenging (Fig. 2). Further analyses will be required to identify the nature of large martian ripples. If they are impact ripples, then why do we observe a gap in wavelength? What would control their equilibrium wavelength and explain their decrease with increasing atmospheric density? Conversely, the Hanratty anomaly has been little studied, and further experimental investigations are needed to better understand the conditions under which it arises. Based on existing data reporting this anomaly and constraints on planetary environments, it is unknown whether drag ripples could exist on either Venus or Titan. Altogether, establishing the types of eolian bedforms that may form on the surfaces of other planetary bodies – and how to decipher them for clues about environmental history – will require advances in bedform formation mechanics and hydrodynamics as well as new constraints on material properties and transport conditions across the Solar

System. These knowledge gaps can be addressed in the coming decades through a combination of experimental and numerical investigations, and data collected by upcoming planetary exploration missions [24].



**Fig. 1:** Wavelength of large ripples and length of smallest barchan dunes (5<sup>th</sup> percentile [22]) on Mars as a function of atmospheric density (calculated from elevation), with wavelength gap predicted from Hanratty's anomaly shaded. Correlations are statistically significant (Wald test p-values).



**Fig. 2:** Proposed phase diagram for the stability of eolian bedforms in well-sorted sediments (adapted from [19]). The roughness Reynolds number varies with an appropriate roughness length scale, wind shear velocity ( $u_*$ ) and kinematic viscosity ( $\nu$ ). The transport saturation length ( $l_{sat}$ ) varies with the mode of transport and fluid and sediment properties.

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