Aeolian Processes and Landforms Across the Solar System: Science and Technology Requirements for the Next Decade

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I. Introduction and Motivation. Aeolian processes and phenomena have sculpted landscapes and influenced planetary climate states across the Solar System, including planetary bodies with transient atmospheres (Fig. 1). For planetary purposes, an aeolian process refers to interactions between a moving fluid and a granular surface (sediment) where usually the fluid is a planetary atmosphere. Depending on atmospheric and surface conditions (e.g., gravity, atmospheric density, and viscosity), the best terrestrial analogs could be subaqueous activity (e.g., Venus - Fig. 1e, f), snow fields, or pyroclastic flows (e.g., comets or other Solar System objects with transient atmospheres). Common transport mechanisms are creep (rolling on the surface), saltation (hopping), and suspension. These transport mechanisms construct landforms, erode landscapes, and produce a wide range of morphologies with scales ranging from centimeters to thousands of kilometers.

Aeolian processes often modify landforms constructed by other processes. Aeolian landforms, in turn, are often modified by other processes, hence having a cyclical relationship. These multiple and layered interactions provide an opportunity for interdisciplinary research but are also a challenge to disentangle geologic and climate conditions; that is, the distant past, the recent past, and the present may be simultaneously recorded. The principle of equifinality may further complicate interpretations, with different processes potentially leading to similar morphologies (Beven, 1996). Expertise from a variety of fields is needed to understand what is being observed and includes, but is not limited to, meteorology, climate science, astrobiology, geology, planetary protection, and polar science. These other disciplines must also consider the effects of aeolian processes within their studies. In many ways, planetary aeolian processes and phenomena (e.g., Table 1) are ideal for comparative planetology because such qualitatively well-

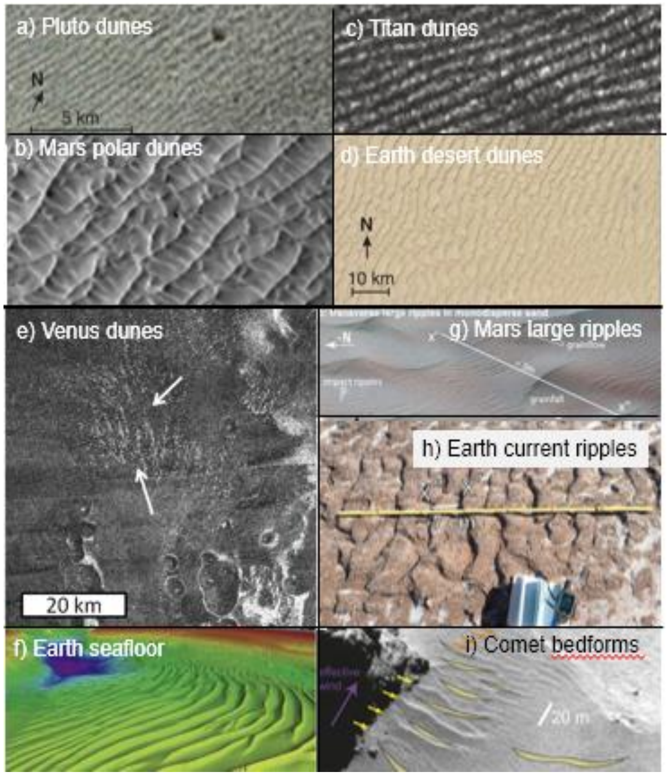


Figure 1: Examples of aeolian features on different planetary bodies: (a-d) Planetary features with remarkable geomorphic similarities, leading to hypotheses of aeolian dune fields. (e-j) Examples from the diverse suite of bedforms found on other bodies, which may be more analogous to terrestrial subaqueous bedforms than subaerial ones (proposed terrestrial analogs are shown in f and h, for Venus and Mars/comet, respectively). Image credits: (a) Telfer et al., 2018, (b-d) Diniega et al. 2017, (e, f) Neakrase et al., 2017, (g, h) Lapotre et al., 2018, (i) Jia et al., 2017.

understood processes appear to be acting across numerous bodies and generating similar morphologies.

Finally, aeolian processes can be both an asset and a hazard to both robotic and future human exploration. An excellent example is Mars' solar-powered rovers. A large-scale dust storm can obscure the sun and coat solar panels with dust, thus starving the rover of both operational and sustainment power. However, dust devils in turn can clean the solar panels, thus increasing both the power generation capability and mission duration. A better understanding of planetary aeolian processes and phenomena is needed to ensure less risk and greater resiliency for future missions—both robotic and human.

II. Goals and Objectives. Discussions of planetary atmosphere-surface interactions (including aeolian processes, phenomena, and the resulting landforms) are often tied to a specific planetary body. Considering this, a series of workshops were initiated in 2008 to facilitate an interdisciplinary and interplanetary body approach to further our understanding of these atmosphere-surface interactions (Titus et al., 2008, 2010, 2012, 2015, 2017). The most recent workshop, held 12-13 May 2020, transitioned to a virtual format due to the COVID-19 pandemic, with a specific focus on the planetary aeolian community's vision for the next decade. Discussions centered around dynamics and resulting landforms, missions and models, and facilities. Participants identified the need for a planetary aeolian goals-and-objectives document that is inclusive of multiple planetary bodies, processes, and phenomena that all intersect where the surface meets the atmosphere. This white paper is the first iteration of that vision, with definitions of Goals/Objectives that organize the broad range of existing and needed planetary aeolian studies.

Goal 1. Determine where dynamic atmosphere-surface interactions have occurred as recorded by observed aeolian features/phenomena and quantify the likely amount (or volume) of sediment currently stored. *(Plain language: Where are the wind-generated features and how much sediment is there?)*

- Obj 1A. Identify traces of aeolian activity across the Solar System.
- Obj 1B. Quantify the areal extent and the volume of material required to produce observed features.

Goal 2. Define the processes and evolution of wind-field-dependent landforms (e.g., aeolian bedforms, wind streaks, yardangs, sastrugi) in relationship to atmospheric conditions and availability of sediment over time. *(Plain language: What can we learn about current and past wind circulation patterns and the availability of sediment from the geomorphology of the landforms?)*

- Obj 2A. Characterize the physical conditions and processes that control wind-field-dependent landforms under modern conditions.
- Obj 2B. Characterize the history, likely dynamic atmospheric-surface interaction, and processes that controlled aeolian bedforms and erosional landforms in the recent past.
- Obj 2C. Identify relevant analogs (including those constructed in the laboratory (Burr et al., 2020)) based on the specific planetary conditions (e.g., fluid viscosity, fluid/particle density ratio, dimensionless numbers such as Reynolds number).

Goal 3. Use aeolian depositional and erosional landforms/strata to aid geologic and paleoclimate reconstructions. (Plain language: *What do landforms tell us about planetary history?*)

- Obj 3A. Determine how ancient aeolian bedforms and erosional landforms may be recognized within planetary sedimentary records.
- Obj 3B. Determine the inventory, sources, sinks, and composition of available sediment.
- Obj 3C. Document how aeolian features and phenomena are incorporated into and preserved in the geologic record.
- Obj 3D. Determine the potential for biopreservation in ancient aeolian materials (on Earth, fossils and oil are often found in aeolian sediments).
- Obj 3E. Determine aeolian erosion rates of different geologic materials (is this why Titan has so few craters?) to determine exposure times.

Goal 4. Determine potential risks and other operational considerations that planetary aeolian processes and landforms present for robotic and human exploration. (Plain language: *What risks and opportunities do processes generated by wind pose for robotic and future human exploration?*)

- Obj 4A. Increase our capability to predict and model environmental aeolian hazards (e.g., dust storms, sand abrasion, electrostatics) in order to protect human and robotic explorers.
- Obj 4B. Increase our capability to access aeolian-derived or -modified landscapes in order to reduce operations and mobility risks to human and robotic explorers. (Plain language: *Avoid getting stuck in sand or dust! Aid in situ resource utilization (ISRU) system designs in a sandy/dusty environment.*).
- Obj 4C. Determine the likelihood of forward contamination by aeolian processes (e.g., rafting of microbes on dust grains) to ensure planetary protection.

The goals are organized by mission/technological complexity, where Goal 1 can generally be accomplished with visible imagery or active radar data taken from orbital or flyby spacecraft. Goal 2 generally requires high resolution imagery or active radar acquired from orbit. Aerial platforms (helicopters) would provide additional capabilities. Goal 3 generally requires both orbital remote sensing (beyond visible to include (but not limited to) near-infrared, short-wave infrared, thermal, and gamma ray) and in situ analysis. Goal 4 generally requires in situ capabilities, but also includes atmospheric monitoring from orbit.

Table 1: Examples of planetary aeolian features or phenomena.

Feature or Phenomena	Formation timescale	Size (Spatial Scale)	Process	Planetary body
Dust devils	Minutes	10-1000 m	Convection	Earth, Mars
Dust storms	Hours to months	1-1000s km	Suspension	Earth, Mars, Titan
Streaks formed from gas jets	Hours to days	1-10 km	Polar/ sublimation	Mars, Triton

Wind streaks/rock wind tails	Seasonal-100s yr	0.01-1000 km/0.01-10s m	Erosional, depositional, sometimes both	Mars, Venus, Earth, Pluto, Triton?
Ripples	sec to hours	0.01-10s m	Saltation	Earth, Mars, comet P/69
Megaripples	Decades	0.01-10s m	Traction	Earth, Mars
TARs and other enigmatic bedforms	10s yr-Ka	1-100s m	Saltation with traction	Mars, Earth
Dunes	1 yr - Ma	0.01-1000s km	Saltation	Venus, Earth Mars, Titan, Pluto?, Io?
Megadunes	Ma	10-1000s km	Saltation	Earth, Mars, Titan
Lunettes	Ka-Ma	0.1-10s km	Lacustrine	Earth
Ventifacts	Ka-Ma	0.01-10 m	Erosional	Earth, Mars
Yardangs	Ka-Ma	1m-100s km	Erosional	Earth, Mars, Venus, Titan
Sastrugi	minutes to days	0.01-10s m	Niveo-aeolian	Earth, Mars [1]
Abraded landscapes (e.g., inverted topography)	Ma	0.01-1000s km	Erosional	Earth, Mars [2], Venus, Titan?
Deflation hollows and basins	Ma	1-100s km	Erosional	Earth, Mars, Titan?
Duststone/loess deposits	Ka-Ma	1-100s km?	Depositional	Earth, Mars [3]
Sand sheets	Ka	1-1000s km	Depositional	Titan [4], Earth [5], Mars [6]
Aeolian sandstones	Ka-Ma	1-100s km?	Lithification	Earth, Mars, Titan?

Table notes: [1] Rodriguez et al., 2017. [2] Farley et al., 2014 [3] Kreslavsky and Head, 2002 [4] Lopes et al., 2016. [5] Kocurek, G., & Nielson, J. (1986) [6] Runyon et al., 2017.

III. Exploration Roadmap for the Next Decade. Planetary aeolian studies not only span the Solar System, but also the range of research methods, including remote sensing, analog field studies, numerical modeling, laboratory experiments, and more recently, planetary in situ studies. Recent and future in situ studies on Mars are of enough detail and sophistication that these could be considered studies of new "analog sites" (e.g., Diniega et al., 2020a, b).

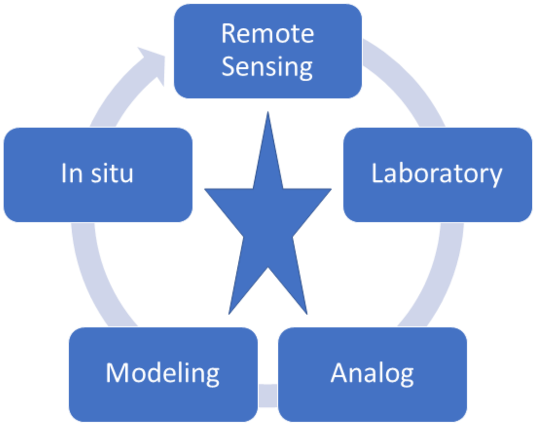
Individually, each research approach brings new knowledge, but the synergy of these combined approaches brings new understanding. Greeley & Iversen (1985) proposed a similar integrated approach (or framework) to aeolian studies which proved to be very successful. The research framework proposed by Diniega et al. (2017), with a focus on dunes and dune fields, expanded on these ideas by adding an in situ component. Fig. 2 is a simplified version of this framework.

The goals and objectives, as outlined in section II, are best addressed using a combination of approaches (or integrated framework) to achieve the greatest results.

<u>Goal 1</u>, conducting a Solar System inventory of aeolian activity, can be achieved with medium resolution (10-100 m/pix) global surveys combined with follow-up, high-spatial resolution (1-10 m/pix) imagery. For some planetary bodies with opaque atmospheres, such as Venus or Titan, radar may be used instead of a visible imaging system. For example, a Mars

Global Digital Dune Database (MGD^3, Hayward et al., 2007) was generated using near-global Thermal imaging (100/pix). This work initially identified ~2000 medium to large dune fields and their aerial extent; later surveys based on HiRISE imaging has yielded identification of another ~2000 smaller dune fields (Fenton, 2020).

Fig. 2: Framework for Aeolian Research



- Remote Sensing
  - Survey, Targeted, Monitoring
  - Passive, Active
- Laboratory
  - Wind Tunnels, Flumes
  - Physical studies of sediment properties
- Analog
  - Subaerial, Subaqueous
- Modeling
  - GCMs, Mesoscale, LES
  - Creep, Saltation, Suspension
- In situ
  - Lander, rover, drone

Goal 2, using high resolution imagery of aeolian feature morphologies, can be achieved with high spatial resolution imaging with stereo capability, or active sensors that can determine topography (lidar, radar). Continuing with MGD^3 as an example, higher resolution MOC imagery was used to determine wind directions from morphology, and MOLA topography was used to estimate volume. The MGD^3 was also provided to the Mars HiRISE operation team for added guidance in targeting. This resulted in a rich dataset of Mars dunes and through repeat imaging, ultimately demonstrated that some dunes on Mars are still active (Fenton et al., 2006; Bourke et al., 2008). The interpretation of these spacecraft datasets is supported by analog studies, computer simulations, and experiments (such as wind tunnel experiments).

Goal 3 can be accomplished with a combination of orbital and landed assets. Infrared imaging spectroscopy (both reflection and thermal) can provide global datasets concerning composition, grain size, and cementation state. In situ studies provide local field site validation for the global datasets. For Mars, the sediment is basaltic but there is still a debate as to whether the sediment source is local or regional (e.g., Fenton et al., 2019). The sediment on Titan appears to be organic (McCord et al., 2006), but the exact source of saltatable grains is still under investigation.

New capabilities are coming online over the next decade that incorporate multiple approaches. The Mars 2020 Helicopter and the Titan Dragonfly are examples of planetary drones where remote sensing and in situ studies will be conducted by the same platform.

Networks of meteorological stations designed to monitor the atmospheric surface layer would provide needed data on the direct atmospheric interaction with the granular surface. Even one station that can concurrently measure both sediment flux and environmental drivers, so as to characterize the full surface-atmosphere interaction and calibrate/test models of such processes would fill a critical gap in our understanding of aeolian phenomena. The measurements needed are temperature, humidity, pressure, 3D winds, and saltation profiles (Diniega et al., 2020). For example, Beagle 2 (a British Mars lander) included a piezoelectric saltation sensor.

Goal 4 is more operationally based but makes use of the same types of data collected for Goal 3. Aeolian processes can be either be a hazard to exploration (e.g., dust can reduce the efficiency of solar panels) or an opportunity to be leveraged (e.g., dust devils cleaning solar panels). In the case of Mars, planet-encircling dust storms (PEDS) can terminate not just robotic operations, but the robotic platform itself due to extended periods of insufficient insolation for power, even in hibernation. However, we currently lack the capability to predict when a PEDS might occur (Newman et al., 2020).

For aeolian studies, each planetary body is in a different stage of exploration and understanding. Table 2 identifies which spacecraft/instruments could be flown and which of the four goals could be addressed over the next decade. This table is not meant to be all encompassing but to provide examples of what could be achieved.

Table 2: Planetary Aeolian Questions for the next decade.

Planetary Body	Needed in Next 10 Years	Goals Supported	Driving Science Questions
Venus	Imaging Radar	1, 2	Are there more dunefields than the two observed by Magellan?
Mars	Landed Meteorological monitoring, Continued High Resolution Imaging, Lidar/SAR/IR, Drones, Wind measurements, from the surface to the PBL	1, 2, 3, 4	What is the physics within the atmospheric surface layer that determines the initiation of a regional or global dust storm? Under what mechanisms and to what heights does dust get lofted? How many dunes are currently active? What are the modern global circulation patterns at the surface? For the fundamental physics: what is the sand grain/velocity profile and height achieved by the saltation cloud? Under what conditions is dust lofted and at what rate? What is the variation in sediment?
Io	Orbiter Imaging	1, 2	Where are there bedforms? What are they made of?
Titan	Drones, Orbiters Imaging/SAR	1, 2, 3	What is the provenance and composition of the dune sediment? What is the physics of its transport? How old are the dunes and other aeolian deposits?
Triton/ Pluto	Orbiter Imaging	1, 2	Where are there bedforms? What are they made of?
Comets	Imaging	1, 2	Are the observed features bedforms? How are their sediments entrained? What are they made of?

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