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SCIENCE NEWS BY AGU

Planetary Dunes

River Lessons from Mining Mishaps

Seismically Swaying Matterhorn

VERDANT AMAZONIA

Dust and detritus are surprising sources of nourishment for one of the most imperiled places on Earth.

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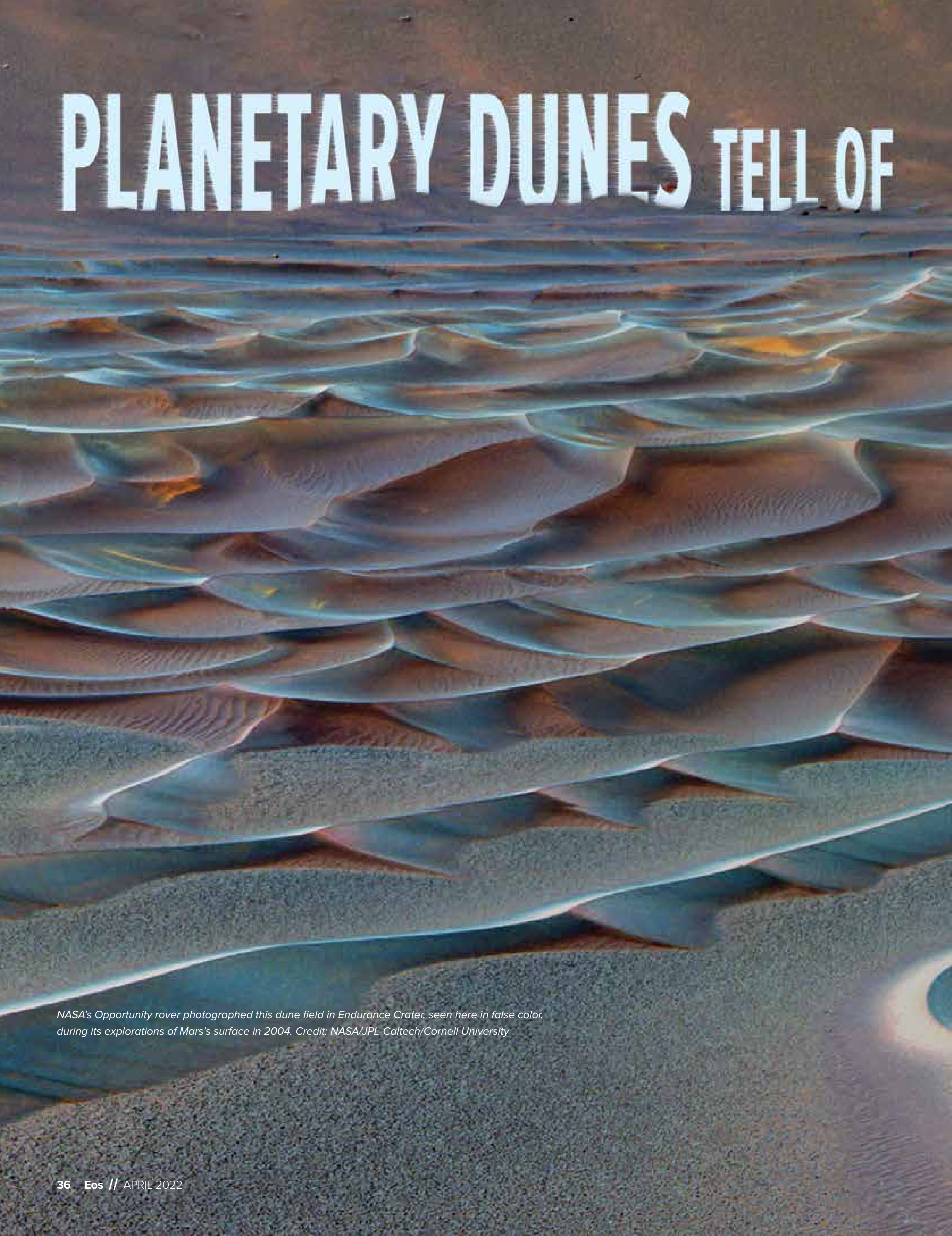
PLANETARY DUNES TELL OF



NASA's Opportunity rover photographed this dune field in Endurance Crater, seen here in false color, during its explorations of Mars's surface in 2004. Credit: NASA/JPL-Caltech/Cornell University

OTHERWORLDLY WINDS

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and James Zimbelman

On Earth and throughout our solar system, ripples and dunes in sand and dust offer insights into how winds blow, liquid currents flow, and solid particles fly and bounce over the terrain.

Dune fields are common on beaches and in deserts—think of the imposing sand hills and sinuous ripples of the Sahara in Africa or the Karakum in Central Asia, for example—as well as underwater on the beds of rivers, lakes, and oceans. The varied shapes, sizes, and orientations of both modern dunes and those preserved in the geologic record tell of the conditions under which they formed, particularly the strengths and patterns of winds and ocean currents. This information offers us valuable windows into environments and climates at different places and at different times in Earth's history.

The same is true of dunes off Earth, making these features especially interesting to scientists investigating planetary conditions and evolution elsewhere. In fact, the current inventory of known dune fields in the solar system exceeds 8,000, including evidence of aeolian activity on the surfaces of smaller planetary bodies with transient atmospheres.

On Mars, more than 4,000 fields displaying a wide variety of dune forms have been mapped. Dunes have been imaged in two fields on Venus. The Rosetta spacecraft observed dunelike features on the nucleus of comet 67P/Churyumov-Gerasimenko, where a tenuous and transient atmosphere—

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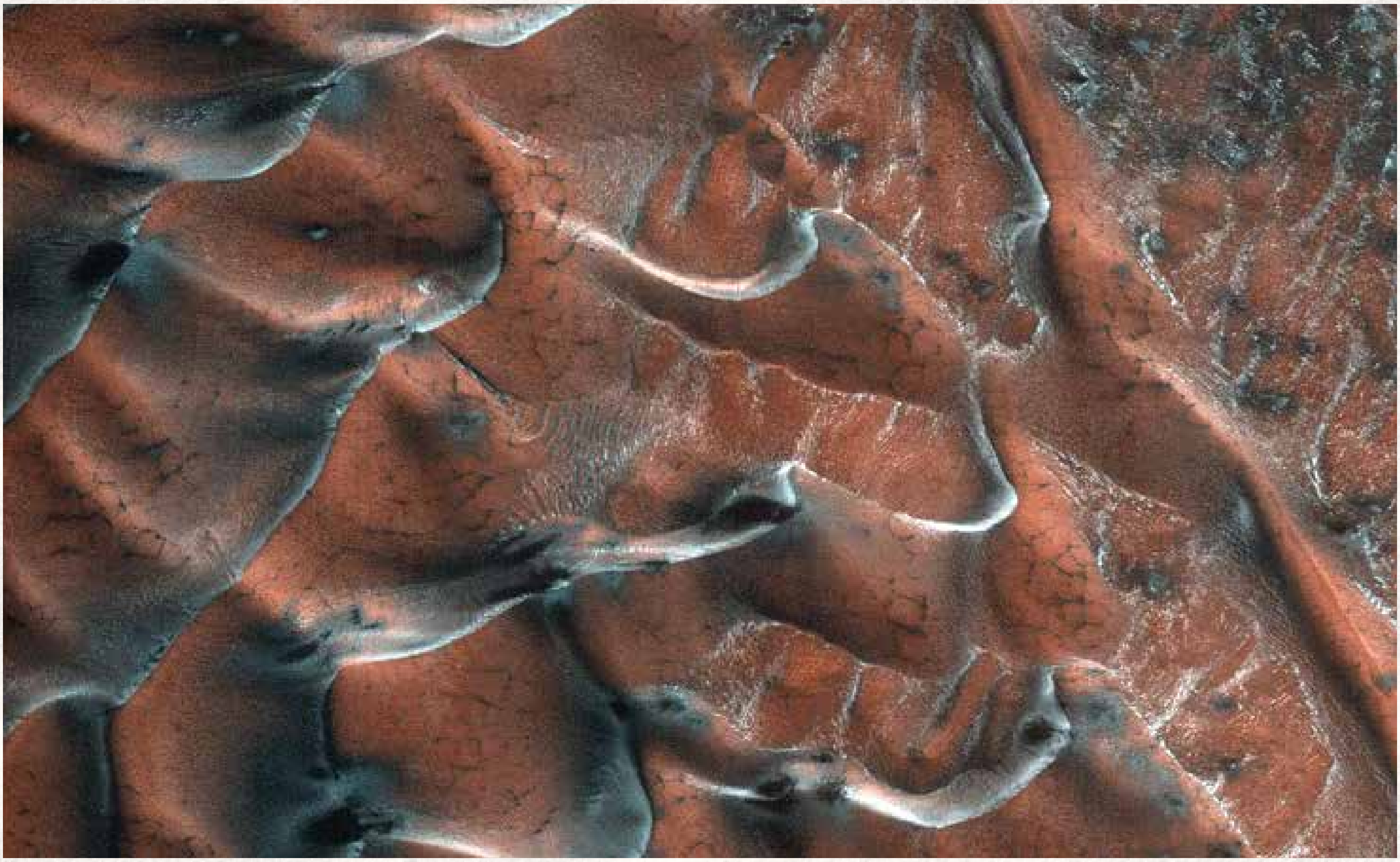
formed by vaporization of ice as the comet passes close to the Sun—may mobilize surface particles. Meanwhile, Titan, Saturn's largest satellite, has moon-circling longitudinal dunes near its equator; Triton, Neptune's largest moon, and Io, Jupiter's volcanically active moon, both have surface features indicating windblown sediment transport in transient atmospheres; and Pluto features dunelike forms on the frozen-nitrogen surface of Sputnik Planitia.

As exploratory missions continue to supply observations and as theoretical and technical advances emerge, the inventory of extraterrestrial dunes—and our understanding of how these features form in different environments—is sure to grow, offering more complete views of neighboring and distant worlds. Here we discuss the current state of knowledge about planetary dune processes and the need for future studies, including developments and ideas highlighted at (and since) the 6th International Planetary Dunes Workshop, held in 2020, that will inform the 2023-2032 National Academies of Sciences, Engineering, and Medicine's Planetary Science and Astrobiology Decadal Survey.

Blowing Dust and Bouncing Sand Grains

Most wind-mobilized, or aeolian, sediment grains can be placed into two broad categories: dust and sand. Dust is carried in sus-



Frost-tipped dunes in a crater on the northern plains of Mars are seen in this image taken by the High Resolution Imaging Science Experiment (HiRISE) camera on the Mars Reconnaissance Orbiter. Credit: NASA/JPL-Caltech/University of Arizona

A dust storm encroaches on dark north polar barchan dunes on Mars. Credit: ESA/DLR/FU Berlin, CC BY-SA 3.0 IGO (bit.ly/ccbysa-igo-3-0)

pension and can be transported far from its origin. Sand is heavy enough that it either rolls along the ground or readily falls back to the surface after being lofted by winds, perhaps kicking up additional grains of sand and dust in a process called saltation. Saltating grains launch dust off the surface to form the atmospheric dust load (see sidebar), they abrade planetary surfaces to expose buried rock records, and they build bedforms that record wind patterns. Indeed, most aeolian landforms are associated with saltation.

On Earth, aeolian dunes can take on many shapes and sizes, such as parabolic, seif (or longitudinal), barchan, dome, or star. Many of these same forms have been observed elsewhere in the solar system. Barchan is the most common dune type on Mars, for example, whereas seif dunes dominate the equatorial regions of Titan. The morphology of Martian bull's-eye dunes is perhaps the most distinct from features known on Earth.

Aeolian ripples on Earth, formed by saltating (or impacting) grains of sand, have shapes similar to seif dunes but are much smaller and usually have a single well-defined slip face. This type of ripple also occurs on Mars, as does a second type of ripple formed from fluid drag, similar to ripples that form in riverbeds on Earth. These ripples are larger, more asymmetric, and more sinuous than impact ripples. Both types of ripples coexist on Mars's dry surface because the Martian atmosphere is thin, whereas Earth's thicker atmosphere allows impact ripples to overpower any formation of fluid drag ripples.

Dunes dwarf the Dragonfly lander on Titan in this artist's rendering. Credit: NASA/Johns Hopkins University Applied Physics Laboratory

Unmasking Venusian Dunes

Earth's two closest planetary neighbors, Venus and Mars, present opportunities to study sand, dust, and dunes under very different atmospheric conditions. Venus has a thick, opaque atmosphere of carbon dioxide and sulfuric acid that limits visual observation of the surface. The only two known dune fields on Venus were discovered in the early 1990s using radar data from the Magellan mission. Menat Undae, in the southern hemisphere, and Al-Uzza Undae in the northern hemisphere, span roughly 100 and 150 kilometers, respectively.

Why are there only two? Scientists have been working on this mystery for decades. Some have hypothesized that more dune fields exist but are not visible in the Magellan data, and others that the winds are too weak, even with the dense atmosphere, to cause saltation and form many dunes. Data from three new missions selected to go to Venus should greatly improve our understanding of the planet's surface and atmospheric conditions and help address this mystery. These missions—two radar-equipped orbiters (NASA's VERITAS, or Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy; and the European Space Agency's EnVision) and a probe (NASA's DAVINCI+, or Deep Atmosphere Venus Investigation of Noble Gases, Chemistry, and Imaging Plus)—are all scheduled for launch late this decade or early in the next.

Monitoring Martian Dust

Among Earth's neighbors, only Titan and Mars are known to experience dust storms. On Mars, where we have abundant observations from orbit and on the surface, dust is thought to be lofted mainly via saltation, contributing to phenomena ranging in scale from meters-wide dust devils to global-scale dust storms.

In the absence of oceans or a significant hydrological cycle, variability in atmospheric dust loading largely dictates uneven heating of Mars's surface and atmosphere, and thus weather patterns and climate. Scientists must understand the distribution of atmospheric dust to produce reliable climate and forecasting models, which will be invaluable in identifying safe landing sites and predicting inclement weather for human missions to Mars.

Dust measurements from orbit, such as measurements that could be made by Doppler lidar, are thus needed to monitor Mars's atmospheric dynamics, wind speeds, and dust transport and identify major dust atmospheric pathways.

Studies of aeolian processes and dune formation mechanisms on Venus are relevant to the study of dune fields under thick atmospheres on other worlds, like Titan or some planets outside the solar system (e.g., most Earth-sized exoplanets discovered so far appear to have atmospheres and climates more like Venus's than Earth's). For example, if the Venus surface predominantly contains "microdunes" that were too small for the Magellan radar to resolve, future identification of these features along with detailed characterization of the Venusian atmosphere will elucidate microdune formation processes relevant to these other planetary bodies with thick atmospheres.

Furthermore, Venusian low wind velocities under high atmospheric pressure may be similar to ocean currents in terms of fluid flow and density. On Earth, ocean currents create dunelike bedforms as a result of water flowing over a surface of movable particles, and similar processes could occur in other places where bodies of liquid water or other fluids exist. Thus, Venus could represent an analogue for processes on both ocean worlds and exoplanets with thick atmospheres.

Aeolian Bedforms in a Low-Density Atmosphere

Mars has a much thinner atmosphere than Earth, and so provides an opportunity to study atmospheric conditions and aeolian processes intermediate between those on Earth and on bodies that lack atmospheres, like comets and Pluto. In addition, because Mars appears substantially more hospitable than most extraterrestrial bodies and thus is the aim for human planetary exploration, it is a prime target for acquiring in situ observations of active planetary surface-atmosphere processes.

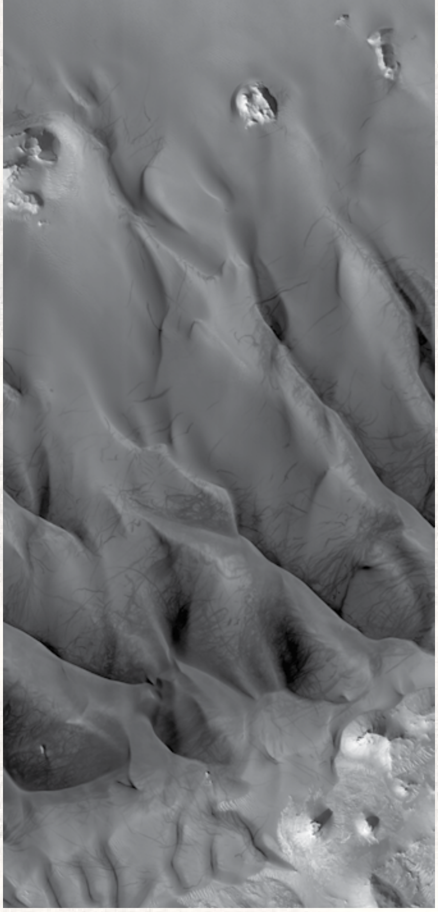
Such observations could greatly advance the development of new models of aeolian processes that could be applied to other planetary bodies. Mars's atmospheric, surface, and environmental conditions are different from Earth's—enabling researchers to expand on existing models created on the basis of terrestrial data—but are still similar enough that terrestrial models remain a reasonable starting point.

Scientists have made solid progress in studies of aeolian processes on Mars by applying knowledge of terrestrial analogues, as well as with data from wind tunnel experiments and orbital and surface (i.e., rover) observations of Martian landforms and surface environments. For example, observed bedforms on Mars provide records of present and past winds, often showing the effects of multiple wind directions, which can be used to validate climate models.

A landed mission focused on studying Martian aeolian environments and processes would add to this progress by providing crucial ground truth for validating and improving the robustness of existing models for application to low-atmospheric-density regimes. Simulations could then be more confidently extended to model analogous processes operating within near-vacuum conditions like those on Pluto or on a comet. The flight-qualified instruments (e.g., for measuring sediment flux and wind speed profiles) and mission architectures needed to collect relevant in situ observations can feasibly be developed within the next decade.

Powered Flight on Alien Worlds

Powered flight enables detailed investigations of expansive, hard-to-reach dune fields on Earth, and the same would be true



Dune fields exist on many bodies in our solar system, including on Mars, as seen in this image taken by HiRISE. Credit: NASA/University of Arizona

An analogue field study shows dust devils at Smith Creek Valley in Nevada. Credit: Steve Metzger

Aeolian dunes spread out against a background of rugged mountains in Colorado's Great Sand Dunes National Park and Preserve. Credit: National Park Service

on other worlds. The successful flights of Ingenuity on Mars beginning in 2021, marking the advent of powered flight on another planet, may represent a defining moment in enhanced planetary dune exploration and science. Even though Ingenuity is primarily a technology demonstration, it has already conducted aerial reconnaissance for the Perseverance rover.

In addition to aerial reconnaissance, the next generation of Mars uncrewed aerial systems (UASs) should be designed to conduct in situ reconnaissance and characterization of dune fields. These tools offer the promise of much higher spatial resolution than is possible from orbit and the ability to explore the interiors of dune fields and other regions not reachable by ground transit. UASs could also support in situ analyses by rovers (e.g., by collecting samples and bringing them to the rovers) for more comprehensive investigations.

NASA's eight-bladed Dragonfly rotorcraft, scheduled to launch for Titan in 2027 and arrive in 2034, will carry a flying science package to the Saturnian moon. Dragonfly will land near the edge of Shangri-La—a large, dark region on Titan's surface—amid linear dunes seen in radar imagery collected by the Cassini spacecraft. Once there, it will determine the composition and grain sizes of the dune sediments, along with wind speeds and directions.

SCIENTISTS HAVE MADE SOLID PROGRESS IN STUDIES OF AEOLIAN PROCESSES ON MARS BY APPLYING KNOWLEDGE OF TERRESTRIAL ANALOGUES, AS WELL AS WITH DATA FROM WIND TUNNEL EXPERIMENTS AND ORBITAL AND SURFACE OBSERVATIONS.

The dune grain composition is of particular interest because the sediment is hypothesized to consist of complex organic compounds rather than silicate-derived debris as seen on Earth, Mars, and Venus. Titan's organics form in the atmosphere through irradiation of simple carbon and nitrogen compounds like methane and molecular nitrogen, but the mechanisms for forming sediment-sized particles on Titan remain unknown.

The Golden Age Is Afoot

As more data are acquired and more detailed computer models are used to dig into multiscale views of aeolian processes, improvements in data and model storage—both the content and the capacity stored—and access are needed.

Planetary aeolian studies rely on comparisons among data and insights from models, observations from analogue experiments conducted in the laboratory and in field environments on Earth, and spacecraft observations from other worlds. Whereas spacecraft observations are routinely archived in centralized data repositories, like the Planetary Data System, analogue data and output from aeolian and climate models are more commonly stored on individual or institutional servers, reducing the potential reuse of these results.

Data from analogue studies are increasingly being archived as the research com-

Dust devil tracks have removed dust from dark dunes on Mars in this HiRISE image. Credit: NASA/JPL/University of Arizona

munity has recognized the need to do so, and archiving policies are being modernized (e.g., requiring better metadata and metadata controls) to increase data searchability, accessibility, and usability. However, model outputs still are rarely considered data and often are not archived, in part because these outputs can be superseded rapidly as models are upgraded and model outputs are continually improved, making decisions of what should be saved and stored difficult. For example, should an output data set be archived every time an input parameter is tweaked and the model is rerun? If improvements are made to the model and all of the previous runs are redone, should all of those data be archived as well? If only selected outputs are saved, what standards (besides limitations on data storage space) should be applied to ensure a uniform curation process?

Conversations and ideas raised at the Planetary Dunes Workshop, and documented in white papers submitted for the Planetary Science and Astrobiology Decadal Survey 2023–2032, covered how best to handle modeling output and planetary analogue data (bit.ly/planetary-white-papers). And a recent NASA report incorporating research community input suggested that repositories be designated for both analogue data and model outputs. The same report emphasized the need to improve data discoverability, accessibility, and usability across all data types, regardless of where they are archived (go.nasa.gov/3HDBosd).

In addition to considerations of data, researchers are beginning to support the notion of developing a unified model of bedform morphology, one encompassing all of the characteristic shapes that form at interfaces between sandy or dusty surfaces and moving fluids observed throughout the solar system.

Until the past 15 years, models of bedform morphology were largely treated separately depending on the environmental conditions under which they formed. This paradigm started to change after Philippe Claudin and Bruno Andreotti demonstrated a consistent relationship explaining the wavelengths of a range of aeolian features, including Venusian microdunes and aeolian dunes on Earth and Mars (bit.ly/scaling-law-dunes). A unified framework would be invaluable for consistently interpreting the modern and former environments in which aeolian bedforms are built, offering us clearer views of past, present, and maybe even future conditions on Earth and other planetary bodies.

RESEARCHERS ARE BEGINNING TO SUPPORT THE NOTION OF DEVELOPING A UNIFIED MODEL THAT ENCOMPASSES ALL OF THE CHARACTERISTIC SHAPES THAT FORM AT INTERFACES BETWEEN SANDY OR DUSTY SURFACES AND MOVING FLUIDS OBSERVED THROUGHOUT THE SOLAR SYSTEM.

The next 2 decades will be an exciting time for planetary dune research. Indeed, with extensive continuing studies of Mars's varied aeolian systems, Ingenuity's and Dragonfly's flights, and multiple Venus missions, researchers may look back on this period as the golden age of the field.

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