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Extraterrestrial dunes: An introduction to the special issue on planetary dune systems

Mary C. Bourke [a,b,*], Nick Lancaster [c], Lori K. Fenton [d], Eric J.R. Parteli [e], James R. Zimbelman [f], Jani Radebaugh [g]

[a] Planetary Science Institute, 1700 E Ft Lowell, #106, Tucson AZ, USA
[b] School of Geography and the Environment, University of Oxford, South Parks Road, Oxford OX1 3QY, United Kingdom
[c] Desert Research Institute, Reno, NV 89512, USA
[d] Carl Sagan Center, NASA Ames Research Center, MS 245-3, Moffett Field, CA 94035, USA
[e] Departamento de Física, Universidade Federal do Ceará, 60455-900 Fortaleza, Ceará, Brazil
[f] Center for Earth and Planetary Studies, MRC 315, National Air and Space Museum, Smithsonian Institution, Washington, D.C. 20013-7012, USA
[g] Department of Geological Sciences, Brigham Young University, Provo, UT 84602, USA

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ABSTRACT

Aeolian dune fields have been described on Earth, Mars, Venus and Titan. The plethora of data returned from recent planetary missions has enabled a new era in planetary geomorphic studies. Much of our understanding of planetary dune systems comes from the application of Earth analogs, wind tunnel experiments and modeling studies. Despite the range of atmospheric pressures, composition and gravity, many of the dune forms on extraterrestrial surfaces are similar to those on Earth, although some have notable differences in bedform scale and composition. As an introduction to the special issue on planetary dune systems this paper summarizes the current state of knowledge of planetary dune studies and highlights outstanding questions that require further investigation.

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1. Introduction

Aeolian sand dune systems are known to occur on four bodies in our solar system (Earth, Mars, Venus and Titan). Despite the range of atmospheric pressures, composition and gravity (Table 1) many of the dune forms appear similar *albeit* with notable difference in dune scale and composition on some bodies.

The high volume of data returned recently from planetary surfaces has triggered a new era in planetary geomorphic studies. Consequently researchers are currently in the exploration and discovery phase of extra terrestrial dune systems. Similar to the approach of Earth scientists during the late 19th and early 20th centuries (e.g., the French studies of the Sahara, Rolland, 1881; Aufrere, 1932), significant effort is currently dedicated to describing dune and dune field attributes and to the production of maps of global distribution. Much of the planetary dune mapping is still ongoing. Progress is limited on bodies such as Titan by incomplete data coverage whereas on others significant progress has been made (e.g., the work of Hayward et al., 2007 on Mars). Such initiatives for planetary mapping have stimulated the production of a dune atlas for Earth dune systems (Lancaster, 2008).

Planetary geomorphic studies are conducted using remote sensing data returned from missions. Whereas the majority of these data are obtained from space-borne platforms, landers and rovers also return images captured on the surface. Much of our understanding of planetary dune systems comes from the application of Earth analogs. In addition, important findings have resulted from wind tunnel experiments and modeling studies that employ the different atmospheric and gravity parameters pertinent to each of the bodies.

Each new mission utilizes instruments with higher spatial and spectral resolution. These produce a stream of new data that sometimes deliver unexpected results (e.g., the discovery of a strong sulfate signature in one the North Polar Ergs, on Mars, Langevin et al., 2005). Earth analogs become increasingly useful as discoveries of the similarities and differences in dune systems on the different bodies continue to emerge. In some cases these analogs find renewed application on Earth. For example, Schatz et al. (2006) use the morphology of oil-soaked barchans in Saudi Arabia (Kerr and Nigra, 1952) to suggest that dune cementation/induration may cause the unusual elliptical shape of some barchans in the North Polar region on Mars. In turn, cohesion is invoked to explain the formation of linear dunes in China and on Titan (Rubin and Hesp, 2009). Planetary

* Corresponding author. PSI, 1700 E Ft Lowell, #106, Tucson, AZ 85719, USA. Tel.: +1 520 6226300.
E-mail address: mbourke@psi.edu (M.C. Bourke).

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Table 1
Properties of planetary environments. Data synthesized from Greeley and Iversen (1985) and Lodders and Fegley (1998).
Table from Zimbelman (2008).

	Earth	Mars	Venus	Titan
Gravity (m/s^2)	9.81	3.73	8.88	1.36
Atmospheric pressure (mb)	1013	7	90,000	1600
Atmospheric composition (%)	N_2, O_2 (77, 21)	CO_2, N_2 (95, 2.7)	CO_2, N_2 (96, 3.5)	N_2, CH_4 (90, 10)
Surface temperature (°C)	22	−23	480	−200

geomorphology improves our understanding of extraterrestrial forms and processes and also moves forward our understanding of dune systems on Earth.

Alongside the more traditional geomorphic approaches, numerical modeling of dunes and dune patterns has advanced significantly in recent years and provides valuable insight into fundamental properties of dune morphology and sediment transport (Livingstone et al., 2007). Numerical simulations have proven to be extremely helpful in determining wind systems, predicting the timescale of dune migration, and testing hypotheses on the formation of planetary dune fields. At the same time, the possibility of using models to make indirect estimates of the sediment properties of planetary dunes is motivating continued research on improvement of the numerical calculations for the equations of sediment transport (Andreotti and Claudin, 2007; Parteli et al., 2007b).

The first international workshop on planetary dune systems was held in Alamorgordo, New Mexico in 2008 (Titus et al., 2008). Forty-five Earth and planetary scientists and their students traveled from eight countries to deliver a series of oral and poster presentations and to participate in discussions on the current state of knowledge. Through constructive and vigorous discussions, some areas for future research initiatives were identified. The workshop resulted in the publication of 22 scientific papers, 8 of which follow in this special issue of *Geomorphology* (Feldman et al., 2008; Balme et al., 2008; Bourke et al., 2009; Horgan et al., 2009; Lorenz and Radebaugh, 2009; Necsoiu et al., 2009; Bourke and Goudie, 2009; Yizhaq et al., 2009; Bourke, 2010; Bristow et al., 2010a; Bristow et al., 2010b; Scheidt et al., in press; Bishop, in press; Diniega et al., 2010-this issue; Fenton and Hayward, 2010-this issue; Gillies et al., 2010-this issue; Radebaugh et al., 2010-this issue; Rodriguez et al., 2010-this issue; Silvestro et al., 2010-this issue; Szynkiewicz et al., 2010-this issue; Zimbelman, 2010-this issue).

This paper summarizes the current state of knowledge of planetary aeolian geomorphology and highlights outstanding questions that require further investigation.

2. Planetary dune systems

2.1. Dunes on Earth

Sand dunes on Earth occur in three major environments: (1) low and mid latitude arid and semi-arid areas; (2) high latitude (cold desert) regions; and (3) coastal areas. Common to all these environments are a supply of sand-sized sediment, winds to transport that sediment from source zones; and climatic and/or topographic conditions that promote deposition of sand.

Most sand dunes on Earth occur in contiguous areas of aeolian deposits called ergs or sand seas (with an area of >100 km^2) (Wilson, 1973). Major sand seas occur in the deserts of the Sahara, Arabia, central Asia, Australia, and southern Africa, where sand seas cover between 20 and 45% of the area classified as arid. The majority of dunes are composed of quartz and feldspar grains of sand size, although dunes composed of gypsum, carbonate, and volcaniclastic sand as well as clay pellets also occur.

Investigations on Earth have used field surveys and experiments, in combination with aerial and satellite images, to identify basic types of dune and the processes that form them; and to trace the origins of the sediments (for reviews see Pye and Tsoar, 1990; Lancaster, 1995; Livingstone et al., 2007; Thomas and Wiggs, 2008). Such studies provide a baseline for comparative analyses of dunes on other planetary bodies. A key aspect of the formation and development of Earth dunes and sand seas is the role of Quaternary changes in climate and sea level, which give rise to changes in sediment supply, availability and mobility and result in the formation of different generations of dunes, as well as episodic accumulation of large dunes (Kocurek and Lancaster, 1999a).

2.2. Dunes on Mars

Globally dune fields on Mars are estimated to cover an area of 904,000 km^2 (Hayward et al., 2007, 2008; Fenton and Hayward, 2010-this issue). Similar to Earth, the global distribution of Martian dunes is related to wind patterns and they likely lie proximal to the sediment source regions (Thomas, 1982; Ward and Doyle, 1983; Greeley et al., 1992b; Thomas and Gierasch, 1995; Fenton, 2005).

Sand dunes are found in a series of generally unconfined sand seas that surround the North Polar ice cap; on the floors of impact craters, in the inter-basin plains of the southern hemisphere, and in low latitude topographic traps such as troughs and channels. Individual dunes on Mars have been identified as barchan, barchanoid, transverse, star, linear and dome (Cutts, 1973; Breed, 1977; Breed et al., 1979; Tsoar et al., 1979; Thomas et al., 1984; Cwick and Campos-Marquetti, 1984; Edgett and Christensen, 1994; Lee and Thomas, 1995) (Fig. 1). Unusually-shaped dunes which currently defy existing classification systems are also a significant proportion of dunes on Mars (comprising ~30% of mid-low latitude dune fields, Hayward et al., 2007). These morphologies are likely the result of variable wind regimes and modification by volatiles (Schatz et al., 2006; Parteli and Herrmann, 2007a). A survey of barchan morphometry found that they are, on average, larger than barchans in many dune fields on Earth, with stoss slope lengths of 215 m and dune widths of ~400 m (Bourke et al., 2004a). Recently the production of digital elevation models from HiRISE stereo images allows 3-D perspective views (Fig. 2) and a more accurate estimates of dune height, volume and morphometric profiles of dunes than had been previously possible (e.g., Bourke et al., 2006; Zimbelman, 2010-this issue).

The majority of sand dunes on Mars are composed of unweathered basaltic (Paige et al., 1994; Herkenhoff and Vasavada, 1999) or andesitic (Bandfield, 2002) fragments. At two locations, sand dunes contain a significant proportion of hydrated minerals. The first is the vast Olympia Undae erg (300,605 km^2), located close to the North Pole. The east end of the erg has a strong gypsum signature that extends westward (Langevin et al., 2005; Roach et al., 2007; Lahtela et al., 2009). This is most likely a signature of a dust plume from the source region although others propose an alternate source may underlie the sand sea (Szynkiewicz et al., 2009; Szynkiewicz et al., 2010-this issue). The second location is a sulfate-rich aeolianite (the Burns formation) at the Opportunity Rover landing site (Grotzinger et al., 2005). Both sites suggest that aeolian interaction with fluvial, lacustrine and high groundwater systems have been important environmental controls at specific sites on Mars in the past.

2.3. Dunes on Venus

The Magellan mission used Synthetic Aperture Radar (SAR) to image more than 98% of the surface of Venus (Saunders et al., 1992), and sand dunes were identified by the specular pattern they produced in some of the SAR images (Greeley et al., 1997). Only two prominent

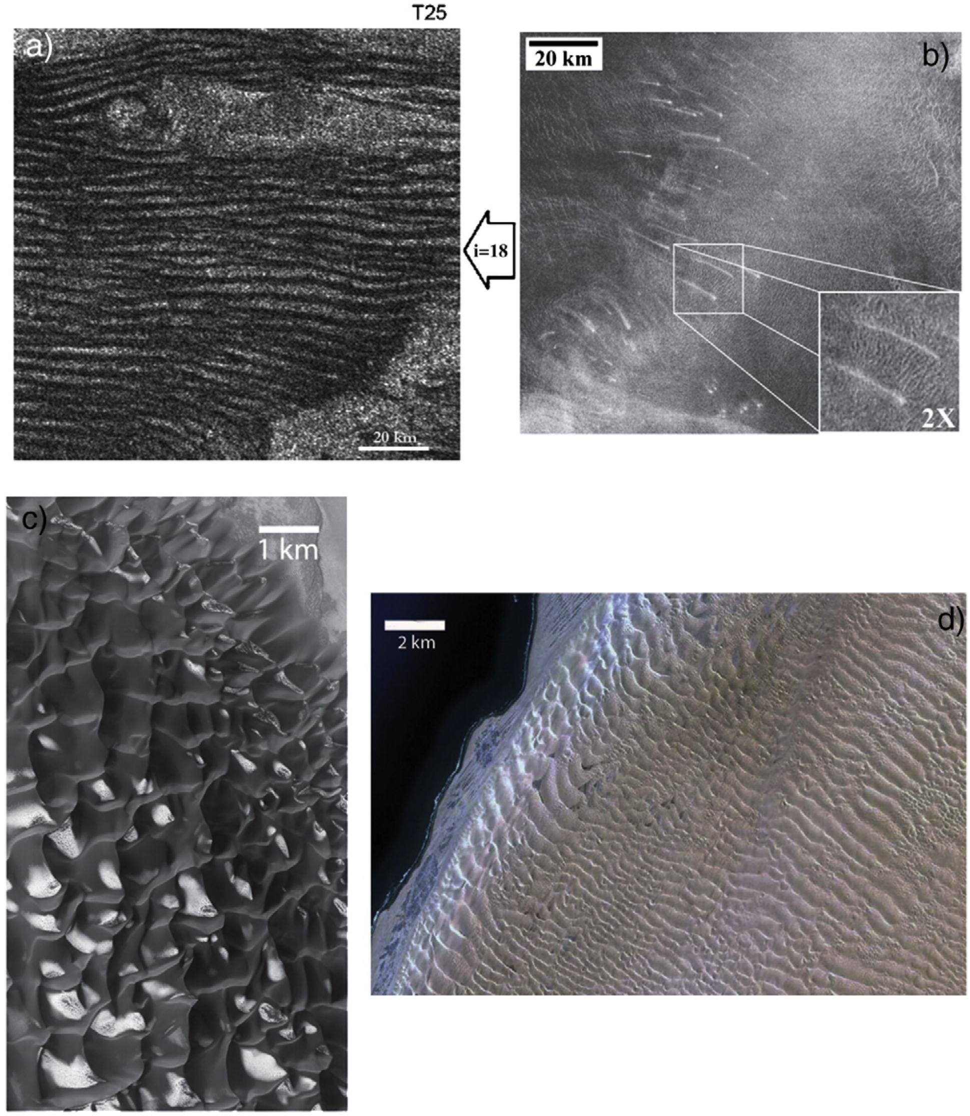
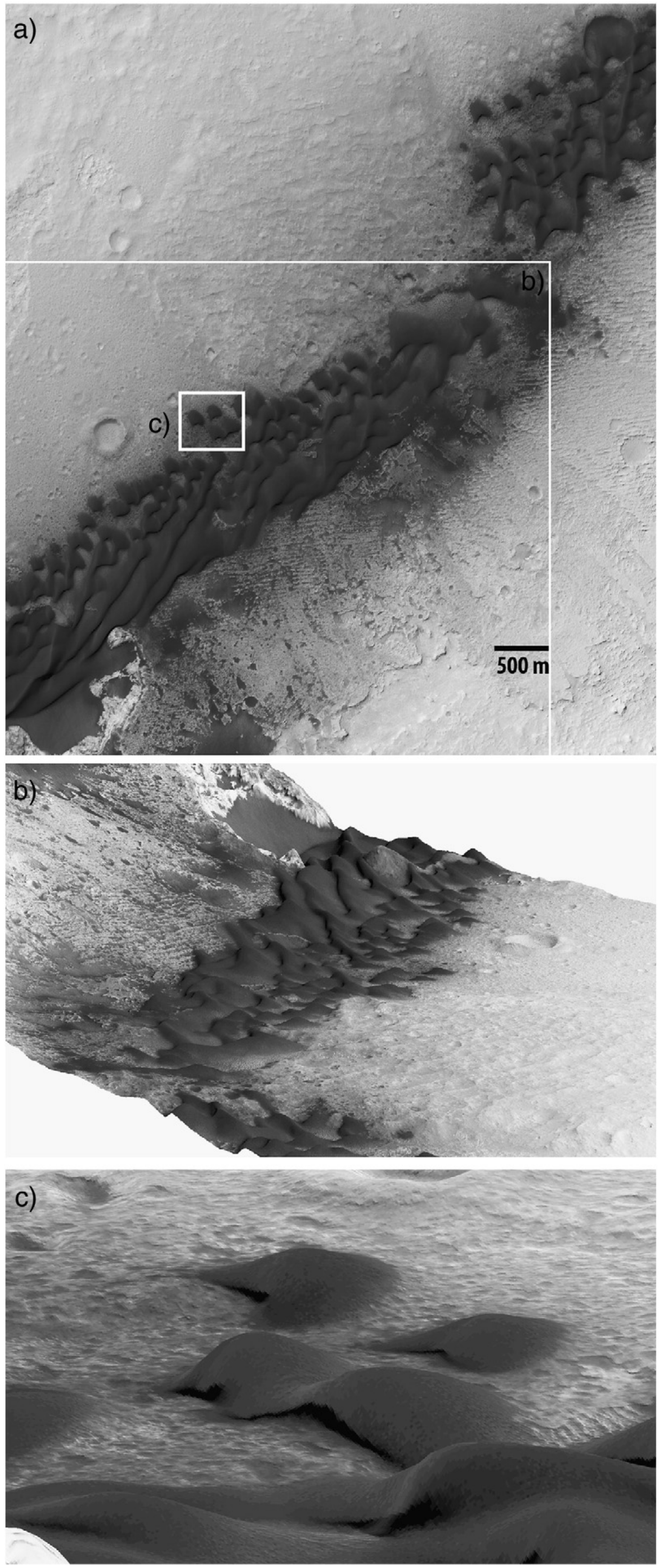


Fig. 1. Examples of planetary dune fields. a) Dunes on Titan are seen in this Cassini Radar image as dark lines overlying a bright substrate. The dunes are seen to divert around topographic obstacles, evident as bright/dark pairs in the Radar image and sand-free inter-dunes are also evident. The image was obtained February 22, 2007 at 300 m resolution near 10°N and 30°W. b) Fortuna-Meshkanet dune field on Venus. Portion of Magellan SAR F-Map 66N084, with effective resolution of ~100 m/pixel. 2× enlargement shows dune ridges transverse to the orientation of wind streaks, consistent with the formation as aeolian bedforms. c) Transverse dunes in a southern hemisphere crater on Mars (47.2°S; 34°E). High albedo areas are remnant patches of seasonal CO_2 frost. HiRISE image PSP_010854_1325, 50.9 cm/px. d) Transverse dunes in the Cunene Sand Sea, Namibia (17°23′25.54″S; 11° 50′ 58.55″E). Mission data for the various bodies are available from: Titan: http://saturn.jpl.nasa.gov/index.cfm. Mars and Venus: http://pdsmaps.wr.usgs.gov/maps.html. Mars: searchable map database: http://themis.asu.edu/maps.
Image d courtesy of Google Earth.

dune fields were recognized in the Magellan SAR images: the Aglaonice dune field (now known as Menat Undae) is located at 25°S, 340°E, covering ~1290 km^2, and the Fortuna-Meshkenet dune field (Al-Uzza Undae), located at 67°N, 91°E, covering ~17,120 km^2 in a valley between Ishtar Terra and Meshkenet Tessera (Greeley et al., 1992a, 1997). Thousands of wind streaks are seen in the Magellan data, as were some features interpreted to be yardangs, but sand dunes only cover approximately 0.004% of the surface.

The dunes in the Fortuna-Meshkenet field consist of arcuate ridges 0.5 to 10 km in length, with widths of 0.2 to 0.5 km and an average spacing of 0.5 km; these dunes are oriented transverse to wind streaks visible in the immediate area (Greeley et al., 1997). The Magellan SAR images do not provide strong constraints on the heights of the dunes on Venus, but SAR images obtained with differing look directions suggest that slopes on the dunes are likely <25°. Some locations in the southern hemisphere of Venus may have ‘micro dunes’, with a spacing on the order of only 15 cm, as inferred from possible Bragg scattering in some SAR images (Weitz et al., 1994). All dunes on Venus formed within the hot, dense carbon dioxide atmosphere that has existed for much longer than the ~0.5 Ga crater retention age of the visible surface on the planet (e.g., Phillips et al., 1992; Schaber et al., 1992). The dense atmosphere includes a perpetual cloud cover that hides the entire surface of Venus from direct view from orbit, except through the use of radar. Lander images returned by Venera 8 and 9 (Florensky et al., 1977) and Venera 13 and 14 (Basilevsky et al., 1985; Head and Basilevsky, 1999) show that the surface of Venus includes an abundance of fine-grained particles capable of being moved by the wind, but no aeolian bedforms were imaged within the limited field of view available to the lander cameras.


a)
b)
c)
500 m
b)
c)

2.4. Dunes on Titan

The existence of dunes on Titan, a moon of Saturn has been known only since early in the Cassini prime mission, in the spring of 2005 (Elachi et al., 2006; Lorenz et al., 2006). Since then, it has become clear that dunes are a dominant landform on Titan, with dune fields covering an estimated 15–20% of the surface (Lorenz and Radebaugh, 2009). The 12–18 million km^2 of dunes is the largest cover of dune fields in our solar system. The Radar on Cassini using a 2.17 cm wavelength SAR mode at 300 m resolution, observed dunes in all imaged regions equatorward of $\pm 30°$ latitude, and up to $\pm 55°$ latitude in isolated cases, as radar-dark lines (Elachi et al., 2006). Dunes have also been observed in limited high-resolution areas dark to Cassini ISS (Imaging Science Subsystems, 938 nm, Porco et al., 2005) and spectrally distinct to Cassini VIMS (Visual and Infrared Mapping Spectrometer, in the near-infrared, Soderblom et al., 2007; Barnes et al., 2008).The features appear to overlie materials having more subtle radar variations, and they meander around or terminate at features of apparently high topography. The dunes on Titan are 1–2 km wide, spaced 1–4 km, and can be hundreds of kilometers long (Fig. 1). It has been proposed that these features are longitudinal (linear) dunes, because of the morphologic similarity to linear dunes found in the Namib, Saharan, Arabian, U.S. Southwest, and west-central Australian deserts on Earth (Lorenz et al., 2006; Radebaugh et al., 2008), and the interaction with higher terrain.

Over ten thousand individual dunes have been observed by Cassini Radar (Lorenz and Radebaugh, 2009), though there are likely thousands more, as currently radar coverage of dune areas is predicted to be no better than 30% (in the middle of the Cassini Extended Mission). Dunes are spaced up to 4 km apart in higher latitudes and have bright inter-dunes suggesting they are sand-free areas. Closer to the equator, dunes are organized into vast sand seas, sometimes several thousand kilometers in extent. In these regions, dunes are closely spaced, highly linear in form, and often have radar-dark inter-dune material, similar to sand seas in the Namib (Radebaugh et al., 2008). Radar backscatter reflection from Cassini-facing, or up range, surfaces has been observed in the region known as Belet, indicating the radar-dark features are topographically high compared with the surroundings, and further confirming the classification as dunes (Radebaugh et al., 2008).

Dunes on Titan, dark to Radar, ISS, and VIMS, indicate they are absorbing up to 2.17 cm wavelengths. This, along with the spectral signature as observed by VIMS, indicates the composition is likely dominated by organics derived from atmospheric chemical processes. A possible contribution may also come from water-ice particulates eroded by runoff from methane rainfall and transported by fluvial action (Soderblom et al., 2007) to supply sediment for dune building. The atmosphere of Titan has an Earth-like surface pressure of 1.5 bars and density 4× that of the surface on Earth. Winds are modeled to be 1–2 m/s, based on the presence of dunes and some measurements by the Huygens descent probe (Tomasko et al., 2005). Given that the morphology of dunes on Titan is almost uniformly linear, formation models developed for terrestrial linear dunes have been applied to dunes on Titan, *albeit* with fewer model constraints because of the obvious limitation of interpreting meso-scale morphology from RADAR data (e.g., Andreotti et al., 2009; Douady et al., 2009; Rubin and Hesp, 2009). New ideas emerging from this work will help in developing a better understanding of the formation of linear dunes on Titan and Earth.

3. How do fundamental differences in atmospheric properties affect the forms and processes of dunes?

3.1. Are the dune forms and processes similar on planetary surfaces across the solar system?

Comparisons of remote sensing images indicate that several types of dune are common to a number of planetary bodies. Linear dunes are the most widespread type of dune on Earth and Titan, but they occur less frequently on Mars (Edgett and Blumberg, 1994). Star dunes appear to be restricted to multi-directional wind regimes on Earth; dunes that have similarities to star dunes occur in some inter-crater dune fields on Mars. Transverse dunes (e.g., barchans, barchanoid, dome) are the most widespread type of dune on Venus and Mars (Breed, 1977; Hayward et al., 2007). Types of dune that form in association with vegetation (e.g. parabolic dunes, nebkhas) are restricted to Earth and dunes associated with topography have been noted on Earth, Titan, and Mars.

Given the similarities between dune morphology on different planetary bodies, it is reasonable to assume that they are dynamically similar (despite differences in particle size and composition as well as atmospheric density) allowing the use of terrestrial analogs to interpret formative processes on other worlds and facilitating numerical models for dune formation and development. In addition, the existence of morphologically similar dunes on a variety of planetary bodies enables inferences about planetary wind regimes. For example, crescentic dunes are widespread on Mars, indicating narrow bimodal or unidirectional wind regimes. On Titan, the existence of giant linear dunes with morphologies similar to those of the Namib and Rub al Khali on Earth suggests bi-directional wind regimes. Asymmetric barchans in close proximity to the linear dunes support the inference of a bimodal wind regime (Fig. 9, Radebaugh et al., 2010-this issue).

A very productive approach is the incorporation of different environmental parameters (e.g. atmospheric density, gravity) into fundamental expressions for airflow and sediment transport to thereby compare and contrast dune-forming processes on different planetary bodies. A universal parameter is the ratio between fluid and particle density, which, together with grain diameter, determines the threshold wind velocity for transport and the magnitude and frequency of sand transport events (Greeley and Iversen, 1985). Following this approach, Claudin and Andreotti (2006) have developed an expression for the wavelength (l) of instabilities in a sand bed which evolve to nucleate dunes. This scales with the drag length $\left(L_{\mathrm{drag}} = \frac{\rho_s}{\rho_f} d\right)$ (1) where d is the grain diameter and ρ_s/ρ_f is the ratio between the fluid and particle density; the elementary dune wavelength is ~20 m on Earth, ~600 m on Mars, and 10–20 cm on Venus.

Numerical modeling of sand transport has substantially improved our understanding of planetary dune processes. The main factors controlling the planetary threshold for aeolian transport and the flux of saltating particles have been investigated with different models based on the physics of aeolian transport at the level of the particles and of the particle trajectories (White, 1979, 1981; Iverson and White, 1982; Lorenz et al., 1995; Marshall et al., 1998; Andreotti, 2004; Duran and Herrmann, 2006; Gillies et al., 2010-this issue).

Almeida et al. (2006) presented a quantitative study of the motion of sand particles through saltation by using a computer model which encompasses a direct calculation of the interaction between the wind and the particles. The authors confirmed Bagnold's (1941) scaling

Fig. 2. Sand dunes in Gale crater on Mars. a) Portion of HiRISE image PSP_009505_1755 (27.3 cm/pixel, 4.5°S, 137.5°E, during the Northern Summer). North is up. Location of b and c are shown. b) HiRISE image rectified to DEM. Display resolution is at 10 m/pixel and vertical exaggeration is ×5. c) 3-d perspective on dunes. Location is shown in a).

relation for the sand flux, $q \sim u_*^3$ for large values of shear velocity u_*, but found that, when u_* is close to the threshold for saltation, u_{*t}, q scales with $(u_* - u_{*t})^2$. By adapting the calculations to Mars, Almeida et al. (2008) found that Martian particles saltate in giant hops traveling 10–100 times higher and longer than terrestrial counterparts. In a recent study, Kok (2010) demonstrated that saltation occurs at lower wind speeds on Mars than previously proposed and is maintained by wind speeds an order of magnitude less than those required to initiate it.

The higher kinetic energies of the saltating grains on Mars, a consequence of the higher grain velocities, ensure that grain-bed collisions during saltation are more efficient in splashing new particles than they are on Earth (White, 1979). In addition to providing an effective mechanism for setting dust into suspension (Greeley, 2002), this parameter has improved model results for the shape of Martian dunes (Parteli et al., 2007a).

A numerical modeling approach has been successfully used to elucidate the underlying formative processes of unusual dune shapes observed on the floor of Martian craters and in the Martian North Polar Region under complex wind regimes. Parteli and Herrmann (2007b) modeled many of the different exotic Mars dune shapes noting that some dune shapes were obtained only when the approach angle of winds was obtuse: this finding challenges the thesis that Mars wind regimes are essentially unimodal (Lee and Thomas, 1995).

Gillies et al. (2010-this issue) model the effects of atmospheric density and surface roughness elements on sediment transport thresholds on Mars. They find that compared to Earth, the shear stress partitioning caused by Martian roughness is non-linear in that the drag coefficients for the surface as well as for the roughness itself show Reynolds number dependencies for the reported range of Martian wind speeds. As a result, shear stress partitioning effects will critically affect thresholds of particle entrainment on Mars, so that developing models of regional sediment transport, or relating sand transport to wind patterns produced by global or regional climate models, will be a very complex exercise. In general, however, higher regional shear stresses are required to initiate particle entrainment for surfaces that have the same physical roughness as defined by the roughness density term on Mars as compared with Earth, mainly because of the low Martian atmospheric density.

Important advances have been made in concepts of dune pattern evolution, resulting in part from concepts of self-organization of complex systems (Werner and Kocurek, 2003). Observed patterns of dunes result from a set of initial conditions of wind and sediment supply, together with the subsequent self-organizing evolution of the patterns as dunes merge, link, and split (Kocurek and Ewing, 2005). This process has been modeled (Diniega et al., 2010-this issue), examined statistically (Ewing et al., 2006) and applied to Mars (Ewing et al., in press).

3.2. What are the controls on dune size and spacing?

Dunes on Titan are similar in scale to those on Earth whereas those on Mars are significantly larger. The controls of dune size (height and spacing) have been the subject of considerable discussion for many years (e.g., see Lancaster, 1988). It is known that dunes can occur at different scales as part of a hierarchy of aeolian bedforms: ripples, simple dunes, and mega-dunes (draas, compound and complex dunes) (Wilson, 1972). The size of elementary or simple dunes is determined by the dynamical instability of a sand bed undergoing saltation, and it scales with the drag length (the distance over which the saltation flux becomes saturated, Elbelrhiti et al., 2005). The larger size of dunes on Mars has been attributed to the longer length of the saltation path in the thinner atmosphere (Claudin and Andreotti, 2006). Dunes also occur at a giant or mega-dune scale, as a result of long-continued growth in conditions of abundant sand supply. The limits to (mega-) dune growth appear to be set by the depth of the atmospheric boundary layer (Andreotti et al., 2009), so that dunes will not continue to grow indefinitely. Preliminary estimates of elementary dune wavelength on Titan suggest that l would be 10–20 cm, much smaller than the resolution of Cassini radar. This suggests that the observed dunes may be mega-dunes formed by the amalgamation of smaller forms (Lorenz et al., 2006; Andreotti et al., 2009).

Alternative approaches include the influence of aerodynamic roughness at different scales on bedform instability (Pelletier, 2009), showing via numerical modeling that ripples form with a wavelength 3000 times that of a plane bed, and dunes form at a wavelength 500 times that of a rippled surface. The size and spacing of dunes may also be limited by dune field size and shape (Ewing and Kocurek, 2010).

3.3. Why are the majority of dunes on Mars, Titan and Venus simple in form with an absence of complex and compound morphology?

Development of compound and/or complex dunes (or mega-dunes) involves superimposition of smaller dunes of like (compound) or unlike (complex) morphology on the larger form. Earth analogs suggest two possible scenarios for superimposition of dune-scale bedforms: (1) development of simple dunes as a result of the dynamical instability of planar surfaces experiencing sand transport. In this case, small dunes will emerge spontaneously when the larger dune exceeds a certain size (Elbelrhiti et al., 2005). As stated above, the minimum wavelength for such dunes has been shown to be ~20 m on Earth, but ~600 m on Mars (Claudin and Andreotti, 2006). Small superimposed dunes and mega-dunes are clearly in equilibrium with current conditions; and (2) modification of an existing mega-dune, in many cases formed in past climatic conditions, as a result of changes in wind regime (e.g., Lancaster et al., 2002).

On Mars, the mean spacing of dunes in the North Polar sand seas (NPSS) is on the order of 500 m (Lancaster and Greeley, 1990); and 500–600 m in southern hemisphere craters (Claudin and Andreotti, 2006). Based on the scaling of elemental dune wavelength with the drag length (see above), Martian dunes with a kilometer scale wavelength are, therefore, not mega-dunes (Claudin and Andreotti, 2006). Martian dunes are not large enough to correspond to scenario (1) and the “simple” or “elemental” form is a result of the nature of saltation of sand-size particles. On Mars the complex dunes that have been noted were likely the result of dune collisions (Bourke and Balme, 2008). Some of the inter-crater dune fields in which dunes are superimposed on larger aeolian deposits can, however, be classified dynamically as mega-dunes (e.g., Silvestro et al., 2008).

3.4. Transverse aeolian ridges (TARs): are they ripples, dunes, or a new type of bedform unique to Mars?

TARs are one of the most enigmatic bedforms on Mars and the origins have been the subject of discussion. They comprise a class of aeolian bedforms that are morphologically and dimensionally distinct from the low albedo dunes on Mars and were first noted in Viking images (Zimbelman, 1987) and more recently in images from the Mars Orbiter Camera (Thomas et al., 1999; Malin and Edgett, 2001). These features are smaller than the dark dunes and likely form transverse to local winds. The size and simple morphology have led some to suggest that they may be aeolian ridges, granule ripples or mega-ripples.

Ripples, dunes, and mega-dunes on all planetary bodies form part of a hierarchical system of self-organized bedforms developed in sand-sized material (Wilson, 1972). Bedform hierarchies are widely recognized on Earth, and the recent advances in image resolution enable recognition of similar hierarchies on Mars. At least three orders of aeolian features on Mars are imaged by HiRISE, with decreasing wavelength, superposed on each other, with crests that are orthogonal to the next larger order (Bridges et al., 2007). For example, “dunes” (wavelengths ~10 to 40 m) have large ripples (wavelengths 4 to 8 m) on the flanks, some of which have even smaller ripples (wavelengths 1 to 3 m) (Bridges et al., 2007; Thomson et al., 2008). Following Claudin and Andreotti (2006), the features identified as dunes by Bridges et al. (2007) may be ripples, indicating that differences in atmospheric density can strongly influence this scale of aeolian bedform.

Current thinking is that TARs with heights >1 m are most likely dunes (although see scaling issues for planetary dune systems above); features with height <0.5 m (particularly if they have a pattern radial to an adjacent sand patch) are most likely granule ripples. TARs >1 m high have remarkably symmetric profiles perpendicular to the crests; the only terrestrial aeolian feature displaying a comparable symmetric profile are reversing sand dunes, which occur in a bimodal wind regime. When height and distance are scaled by the width of the feature, dunes generally have scaled heights that are twice as large as scaled heights for granule ripples (Zimbelman, 2010-this issue). It is still unknown, however, whether TARs are small aeolian dunes or large ripples or perhaps features that transition from ripples to dunes (Williams et al., 2002; Zimbelman and Wilson, 2002; Wilson et al., 2003; Balme et al., 2008).

4. What is the composition of extraterrestrial aeolian bedforms?

4.1. Particle sizes

On Earth, the majority of dunes are composed of fine to medium sand (mean grain size 160–330 µm), which is very well to moderately sorted (Ahlbrandt, 1979). Important variations in particle size and sorting exist across individual dunes, within sand seas, and between different locations, the latter reflecting sand sources as well as the energy of the wind regime.

Thermal inertia calculations are used to estimate the grain size of the majority of aeolian deposits across the Martian surface. Thermal inertia is a measure of the thermal response of a material to the diurnal heating cycle. Loose, fine-grained materials conduct heat poorly and have low thermal inertias; coarse-grained materials, bedrock, and indurated materials conduct heat more easily and have high thermal inertias. Under ideal circumstances in which a surface is composed of unconsolidated, well-sorted particulates (such as may occur on sand-covered terrain), the thermal inertia can be used to estimate an effective particle size. Layering, sloped surfaces, induration, and contamination by rocky material (all of which can occur in dune fields) can easily distort estimates of particle sizes. The thermal inertia data for Martian dunes suggest that they have an average particle size of medium to coarse sand (500 ± 100 µm, Edgett and Christensen, 1991; 300–600 µm, Presley and Christensen, 1997).

It has been proposed that some Martian dunes could be composed of sand-sized aggregates of dust (Greeley, 1979; Saunders et al., 1985; Saunders and Blewett, 1987; Herkenhoff and Vasavada, 1999). Indeed, the Mars Exploration Rovers imaged the very smooth imprint of the APXS contact plate onto sand-like surface deposits suggesting compaction of sand-sized aggregates at some locations (Sullivan et al., 2008). Dust aggregates may only survive saltation, however, up to a few tens of kilometers (Saunders et al., 1985, 1986) and experimental work has shown that uncemented aggregates survive saltation impact for a distance of 40–60 km and cemented for distances of 120–160 km (Greeley and Kraft, 2001). Sand dunes may indeed contain aggregates at some locations on Mars. The extensive pathways of sediment transport, as evidenced by the size of ergs in the North Polar region and in the southern intra-crater dune fields (Silvestro et al., 2010-this issue), however, make this unlikely in large sand accumulations.

Images taken by the Microscopic Imager of ripple surfaces in Gusev Crater show that the surface of ripples were dominated by poorly sorted, 200–300 µm sand with minor amounts of air fall dust grains. Grain sizes in the underlying ripple strata were finer with most sand around 100 µm and smaller (at limit of resolution) (Sullivan et al., 2008). In a study of ripple sediment in rover images at Meridiani Planum, the grain size is suggested to be 87 ± 25 µm (Claudin and Andreotti, 2006).

No definitive measure of actual grain size exists on Venus beyond what can be inferred from the Venera images, which typically do not resolve features smaller than about 1 mm. Wind tunnel experiments demonstrated that the particle size most easily moved by wind under Venusian conditions are grains 75 µm in diameter smaller than the comparable easiest moved particles on Earth and Mars (Iversen et al., 1976; Greeley and Iversen, 1985).

Based on atmospheric and gravity data and estimates of wind speeds, sand particles on Titan are expected to saltate at ~180 to 250 µm, just slightly smaller than typical dune sands on Earth (Lorenz et al., 2006).

4.2. Composition

Dunes on Earth are composed mainly of quartz and feldspar, derived originally from weathered quartz-rich terrains. Dunes with significant carbonate content occur adjacent to sources in shallow marine environments (e.g. Arabian Gulf); gypsum dunes occur adjacent to playa sources (e.g. White Sands, New Mexico). Volcaniclastic dunes are scattered across the globe, but provide some unique compositional variability (Edgett and Lancaster, 1993).

The large dark dunes on Mars are dominated by mafic mineralogy (e.g., Aben, 2003; Rogers and Christensen, 2003; Tirsch and Jaumann, 2008). The thermal inertia data for Martian dunes suggest that they are composed of unweathered basaltic grains (Paige et al., 1994; Herkenhoff and Vasavada, 1999). Bandfield (2002) noted that the spectra of the dunes in the north polar region indicate a mixture of clasts with a bulk composition similar to andesite.

Significant amounts of hydrated calcium sulfates, most likely gypsum, in the North Polar dunes of Olympia Planum (<~30 wt.% but possibly higher values locally, Horgan et al., 2009) suggest that water has played a role in the sedimentary history of the North Polar dune sand (Langevin et al., 2005). Hypotheses for the origin of polar gypsum range widely in nature — from atmospheric weathering of iron sulfides (Langevin et al., 2005) to deposits from a hypersaline, sulfate-rich polar outflow from Chasma Boreale (Fishbaugh et al., 2007), among several others. A recent study mapping the distribution of hydrated minerals on the circumpolar ergs reveals that these minerals are more extensive than previously thought, and indicate that the source(s) may be widespread in the North Polar Layered Deposits (NPLD) (Horgan et al., 2009).

The North Polar Dunes on Mars may also contain snow and ice. A combined modeling and geomorphic approach was used to determine water-ice equivalent hydrogen content of 30 ± 5% buried approximately 5 cm beneath the surface in Olympia Undae dunes (Feldman et al., 2008). They proposed a stratigraphic model where the polar dunes contain niveo-aeolian deposits, similar to dunes in Victoria Valley, Antarctica (Bourke, 2004; Bourke et al., 2009). Dunes on Mars are covered by a seasonal frost composed of CO_2 and H_2O ice for upto 70% of the Martian year. This significantly reduces the time available for sediment transport (Bourke et al., 2008). Defrosting processes, however, are estimated to transport 0.25 to 0.5 m^3 by meter width each year down avalanche slopes of larger dunes (Gardin et al., in press).

Based on the reflectance in the near-infrared, the widespread longitudinal dunes on Titan are thought to be composed at least partly of organic compounds such as hydrocarbons or nitriles (Soderblom et al., 2007), with perhaps some component of eroded water ice.

No constraints exist for the composition of the two largest dune fields seen in Magellan SAR images on Venus. The compositional results from the Venera platforms, however, indicate that the vast majority of the surface of Venus is basaltic in composition. It is likely, therefore, that sand will be basaltic in composition.

5. What are the major sediment sources for aeolian bedforms?

On Earth, most aeolian sand is formed by weathering and erosion of crustal rocks, consisting mainly of quartz and feldspar (e.g., Pye and Tsoar, 1990). Most of this sand is formed and concentrated by moving water, producing beaches and contributing to alluvium and lacustrine deposits. Other major sand sources include eroding sandstones (which may be composed of former aeolian sand themselves), glacial till, chemical precipitates, and volcanic materials. Sources of large terrestrial sand systems are often poorly constrained, particularly when sediment is no longer actively being contributed from source regions. Mineralogical studies, from remote sensing and extensive field sampling have been used to identify sand sources (e.g., Ramsey et al., 1999; Muhs, 2004), indicating that detailed study may be necessary to determine the degree and timing of source influxes to dune fields. For example, spatial variation in geochemical data across the White Sands dune field in New Mexico has been used to determine that dune sediments were derived from the deflation of lakebed sediments at increasing depths over time (Szynkiewicz et al., 2010-this issue). Such analysis is not generally possible on other planetary bodies, although its continued application to terrestrial dune fields is promising.

The sand sources of most dune fields on Mars are not known, with one prominent exception. The sand seas ringing the North Polar residual ice cap are derived mainly from a lower unit of the NPLD (e.g., Byrne and Murray, 2002; Edgett et al., 2003; Tanaka et al., 2008). Other dune fields on Mars have more ambiguous source regions. Inter-crater dune fields studied to date are thought to have local sources in eroding materials within the same craters in which the dune fields are located (Fenton, 2005; Stockstill-Cahill et al., 2008; Silvestro et al., 2010-this issue). Likewise, dune fields in Valles Marineris appear to have source materials that have eroded from nearby steep walls (Chojnacki and Moersch, 2009). The enigmatic TARs – which have morphologies attributable to both dunes and granule ripples (e.g., Zimbelman, 2010-this issue) – also form close to steep slopes and layered terrains, which are considered their most likely source material (Balme et al., 2008). None of these aeolian bedforms have been conclusively linked to source regions; it is likely that *in situ* studies are necessary to establish such a connection.

Sand sources on Titan and Venus are even less well-defined than those on Mars. Possible sources on Titan include fluvial activity (produced by liquid methane) or some unknown process producing organic sand through erosion of materials ultimately derived from photochemical processes high in atmosphere of Titan (Soderblom et al., 2007; Lorenz et al., 2008). The presence of dunes only at equatorial latitudes ($\pm 30°$) may have implications for source regions: sand may be preferentially blown towards the equator from higher latitudes, or sand may preferentially erode from sources (or perhaps precipitate) only at low latitudes. The opaque atmosphere of Titan precludes visible imaging that may help resolve dunes, the sources and the sedimentary history. Determining sources of this organic, icy sand requires a spacecraft dedicated to studying the atmosphere and surface of Titan; thus, Titan may remain a tantalizing mystery for many years to come.

No apparent sources are evident in the SAR images for the particles which comprise the two largest dune fields on Venus; these materials may have been generated locally or they may also be the result of transport across vast distances.

5.1. What do sand transport pathways reveal about sediment budgets?

Sand dunes and dune fields do not exist isolated from the environment; rather they are components of aeolian sand transport systems. Aeolian sand transport systems are fairly discrete accumulations of windblown sand, including at least a transport pathway along which sand migrates, and potentially including sand sinks (e.g., dune fields, drifts, sand ramps, and sand sheets) and identifiable sand sources (e.g., eroding sedimentary layers). The preferential migration or accumulation of sand is controlled by spatial changes in rates of transport and temporal changes in sediment concentration, such that accumulation occurs where the influx of sand from upwind exceeds the outflux of sand downwind (Kocurek and Havholm, 1994). On Earth, some factors that typically cause such changes consist of variations in wind regime, topography, sea level, vegetation, and climate (e.g., Fryberger and Ahlbrandt, 1979). As a result, the dynamics and morphology of aeolian sand transport systems are intimately linked to the sedimentary and climatic history of the regions in which they form. Similar factors likely control the formation of aeolian sand transport systems on other planetary bodies, although specific conditions may be quite different. For example, on Mars, sea level and vegetation will not influence the development of transport systems. Ice in dunes at high Martian latitudes (e.g., Feldman et al., 2008), however, is likely to slow dune migration, as has been observed on Earth (e.g., Bourke et al., 2009; Necsoiu et al., 2009; Bristow et al., 2010a).

A useful way of reconstructing the record of a transport system state involves identifying how three controlling variables have changed over time: sediment supply, sediment availability, and the transport capacity of the wind (Kocurek and Lancaster, 1999a). Successive influxes of aeolian sand into a dune field over time often leave a mark by creating "generations" of dunes of distinct types, sizes, orientations, and compositions that reflect the system state at each construction period (e.g., Beveridge et al., 2006; Szynkiewicz et al., 2009). Developing such detailed models for aeolian sand system sediment states on other planetary bodies has not yet been attempted, largely because of the lack of quantitative field data that can link sand to source regions and estimate sediment ages.

Pathways for aeolian sediment transport have only been identified at a few locations on Mars (Bourke et al., 2004b; Rodriguez et al., 2010-this issue; Silvestro et al., 2010-this issue) and in general have proven difficult to identify (e.g., Fenton, 2005). As on Earth, this may indicate that sand is no longer being added to dune fields in most areas, and suggests that dune-building is not currently an active process in most areas on Mars. One major exception to this is the northern polar sand seas, many of which clearly connect to upwind sources in the NPLD and reflect a complex wind regime that has generally driven sand away from the residual polar cap (Tanaka and Hayward, 2008). Silvestro et al. (2010-this issue) identified several transport pathways connecting six intra-crater dune fields in the southern highlands, and proposed that one main episode of first-generation dune-building was followed by a second period during which a different wind regime reworked some of the first-generation dunes. In other areas, yardangs, ventifacts, and perhaps TARs are thought to demarcate areas where significant sand transport has occurred in the past, even though currently no sand deposit is either present or downwind; in some cases these features appear to record ancient wind regimes that no longer align with present-day winds (e.g., Greeley et al., 1993; Greeley et al., 2000; Balme et al., 2008). Clearly, Mars has a long history during which aeolian sand systems have shaped and been shaped by its surface.

6. How can dune field/dune age be estimated on planetary surfaces?

Planetary scientists are restricted in the approaches they may adopt to determine the age of extraterrestrial surfaces. Many of the methods used on Earth (e.g., chronometric methods such as radiocarbon, photoluminescence, short-lived isotopes; or hybrid methods that use calibrated models: e.g., weathering rind thickness, lichen growth or desert varnish geochemistry) cannot be used because of the absence of organic matter, atmospheric composition and history of atmospheric events. Although numerical methods are being tested, refined and instruments developed for sample return and *in situ* analysis on planetary rovers, most of this work is still in the developmental phase (Lepper and McKeever, 2000; Franklund and Lepper, 2004; Doran et al., 2004; Jain et al., 2006; Kalchgruber et al., 2006; McKeever et al., 2006; Jain et al., 2007; Kalchgruber et al., 2007; Blair et al., 2007; Morthekai et al., 2007; Lepper, 2008; Morthekai et al., 2008; Tsukamoto and Duller, 2008; Detschel and Lepper, 2009).

Three approaches are used to determine the age of aeolian bedforms in extraterrestrial environments: crater retention age estimates, geomorphic and geological relationships and numerical modeling of rates of landform development.

6.1. Crater retention age

Absolute ages for specific surface areas on Mars are determined by applying the lunar crater production curve using Martian crater scaling laws (Soderblom et al., 1974; Neukum and Wise, 1976; Hartmann, 1977; Neukum and Hiller, 1981; Ivanov, 2001; Neukum et al., 2001; Stöffler and Ryder, 2001). To estimate the absolute model age of aeolian bedforms and, therefore, the last active phase, many researchers use the Martian impact cratering model of Hartmann and Neukum (2001) and the polynomial coefficients of Ivanov (2001). This approach allows them to obtain isochrons from the frequency distributions of crater sizes (Hartmann, 2005). This method has been undertaken for TARs and southern hemisphere dunes on Mars. In using this technique, the uncertainty of the age for young surfaces (i.e. those <2 Ga) is within a factor of 2. This arises primarily from the uncertainty in the Mars/Moon cratering rate ratio (Hartmann and Neukum, 2001; Ivanov, 2001).

A crater retention age determines either the timing or rate of crater modification/burial/erosion and does not necessarily produce a true age estimate of a surface. A surface may be much older than its crater retention age because of exhumation or modification. Therefore, crater retention age estimates are considered minimum age estimate.

No reports exist of impact craters on sand dunes on Mars. The crater retention age method, however, may still be applied where the area of dunes is carefully constrained. Fenton and Hayward (2010-this issue) estimated an age of <10,000 years for southern hemisphere 'inactive' dune fields. Craters have been reported on TARs. Reiss et al. (2004) measured crater populations from MOC images on TARs on the floor of Nirgal Vallis and provided an age estimate of 140,000 to 380,000 years. These ages have upper limit ages that range from 390,000 years to 1.4 Myr. Berman et al. (2009) performed crater counts on higher resolution HiRISE images for TARs located in the equatorial southern intra-crater regions. Equatorial TARs have crater retention ages of 1–3 Ma. No craters were observed on the southern intra-crater TARs, suggesting crater retention ages of <100 ka.

Reiss et al. (2004) propose that the age of the last active phase of the TARs may be related to periods of higher atmospheric pressures on Mars. These conditions are suggested to be met during higher obliquities (i.e. greater than 30°) which were last met around 400 ka (Laskar et al., 2002). The southern intra-crater TARs are thought to be 'active' (Berman et al., 2009).

No reports document impact craters on the dunes of either Titan or Venus. This method cannot be applied, however, as scaling laws for these bodies, including the role played by the relatively dense atmospheres, has not yet been fully developed.

6.2. Geomorphic/geologic relations and modification of dune form

The age of aeolian dune fields on Mars is considered to be younger than most other exposed surfaces. Whereas the absence of impact craters on dunes suggests a relative young age, the superposition of dunes on equally young surfaces also supports this. An example is the occurrence of dunes on an extensive polygonal surface in the north polar latitudes of Mars. The youngest age of this polygonal surface is ~50–100 ka (Levy et al., 2009). The occurrence of impact craters on TARs and not on dunes suggests that TARs in many locations may be considerably older and inactive relative to the nearby dunes; Balme et al. (2008) found that dunes superpose TAR's in 66% of images surveyed. Wilson and Zimbelman (2004) noted that TARs appear unaffected by the migration of Large Dark Dunes over them, suggesting that the TARs may be indurated.

Several examples of dunes that were/are superposed by other landforms suggest relative inactivity. These range from exhumed and cratered bedforms (Malin and Edgett, 2001; Reiss et al., 2004; Fenton and Hayward, 2010-this issue), to TARs superposed by gullies (Malin and Edgett, 2001) to dunes embayed by sediment veneers from the north polar cap (Rodriguez et al., 2007). The avalanche faces of large dunes have been modified by gully erosion (Mangold et al., 2003; Reiss and Jaumann, 2003; Miyamoto et al., 2004; Bourke, 2005) and North Polar dunes and equatorial ripples show features indicative of crusting and induration (Feldman et al., 2008; Sullivan et al., 2008).

6.3. Evidence of current dune mobility

Using sand flux equations, Claudin and Andreotti (2006) proposed that dunes on Mars form five orders of magnitude more slowly than on Earth under present-day conditions. In an alternative approach, Parteli and Herrmann (2007b) found that a barchan with a given volume moves ten times faster on Mars than it would move on Earth, provided the average formative wind shear velocity has the same relative value (friction velocity/threshold friction velocity or u_*/u_{*t}) on both planets. By taking into account the frequency and duration of the rare Martian saltation events as estimated from orbiters and landers (Arvidson et al., 1983; Moore, 1985; Sullivan et al., 2005; Jerolmack et al., 2006), however, Parteli and Herrmann (2007a) calculate that Mars barchans need thousands of years to move 1 m. Similarly, Zimbelman et al. (2009) find that granule ripples on Mars, if they are ~25 cm tall (comparable to many ripples crossed by the Opportunity Rover in Meridiani Planum), could take thousands of years to move only 1 cm, given the very low inferred frequency of saltation events under present conditions on Mars. Interestingly, the fraction of time u_* is above u_{*t} agree with the half period of the axis precession of Mars (2.5×10^4 years) which some expect to be a major factor causing global changes of the Martian climate and of the average direction of the strongest winds on Mars (Arvidson et al., 1979; Haberle et al., 2003). Other modeling efforts note that orbital changes will not strongly influence wind directions on Mars (Fenton and Richardson, 2001).

Despite these model estimates, change has been observed in sand deposits at Meridiani and Gusev Crater (Geissler et al., 2008; Sullivan et al., 2008), the North Polar dunes (Bourke et al., 2008) and some inter-crater dune field locations (Fenton, 2006; Chojnacki et al., 2010; Silvestro et al., 2010) that indicate sand is mobile at a variety of locations across Mars. This suggests that some locations may be more conducive to the entrainment of sediment or that model estimates require revision.

Dunes are perhaps the youngest features on Titan. No other processes (e.g., crater impact or fluvial erosion) have been seen to modify the aeolian landforms at the Cassini Radar resolution. One example of a river cutting through dunes may have been seen by Cassini VIMS (Barnes et al., 2008). Using model wind speeds based on atmospheric density and gravity, dunes are estimated to form over 10^4 years, and large dune fields may take ~10^6 years to assemble (Lorenz et al., 2006, supplementary information).

7. Can dunes be reliably used to indicate formative wind regimes (past and present)?

7.1. What are the relations between dune form, dune orientation and winds?

The crestline orientation of aeolian dunes on Mars has been used along with other features to indicate paleowind directions in the North Polar Sand Seas (Tsoar et al., 1979; Greeley et al., 1992b;

Thomas and Gierasch, 1995; Ward and Doyle, 1983; Tanaka and Hayward, 2008). The orientation of dune crestlines yields the direction(s) of the constructional winds, but not in as simplistic a fashion as is sometimes portrayed in the literature, in which a crestline is taken as perpendicular to a given formative wind. For the scale of bedforms that applies to most dunes on Earth and Mars in which the bedform reconstitution time is longer than the period of cyclic change in wind direction, dune crestlines are as perpendicular as possible to *all* constructive winds (*i.e.*, the gross bedform-normal concept of Rubin and Hunter, 1987). Using this approach, it is only possible to determine the *range* of winds that give rise to a particular dune pattern. Even for barchan dunes, the assumption of unidirectional winds may be erroneous. On Earth, barchans occur in regions where the directional index is normally 0.7–0.9 (unidirectional sand transporting regimes have a value of 1.0) (Bourke and Goudie, 2009).

7.2. Do dunes respond to climate change and how would one tell this?

The response of dunes to climate change as a result of changes in atmospheric composition and orbital parameters (e.g. Milankovitch Cycles on Earth, obliquity changes on Mars) is governed by changes in sediment supply, availability and mobility, which determine the state of the sand transport system (Kocurek and Lancaster, 1999b).

Changes in controlling variables may result in the formation of different generations of dunes, each determined by a set of initial conditions of sediment supply and wind regime, together with the subsequent evolution of the patterns over time by merging, linking, migration of defects and creation of terminations. The creation of different generations of dunes may involve formation of new areas of dunes by input of new sediment, or reworking of existing dunes. Climate change may also result in the stabilization of dunes by reductions in sediment availability or mobility. On Earth, the primary response to these changes is stabilization of dunes by growth of vegetation (Yizhaq et al., 2008); on other planetary bodies, surface crusts or ground ice may be important.

Different types of dunes have been shown to have varying sensitivity to changes in controlling variables. The change in dune pattern can only occur at terminations (the ends of dunes), so dunes that have few terminations (e.g. linear dunes) will tend to be less responsive to change and persist (with modification) over longer periods of time compared to dunes with more frequent terminations (e.g. most crescentic dunes). The timescales involved for dunes to adjust to changed conditions can be estimated via the reconstitution time, or the time required for the dune to migrate one wavelength, which is a function of dune size (and sediment volume) and net rates of sand transport. Large dunes may, therefore, persist over timescales greater than the period of climate change and appear as relics of past climate conditions and preserve a record of past wind regime characteristics.

Recognition of the effects of climate change on dune systems on all planetary bodies is primarily via analysis of patterns of dune morphology and composition leading to identification of different generations of dunes by spatial variations in dune morphology — giving rise to statistically distinct populations of dunes with different crest orientation, spacing, and length (Ewing et al., 2006); variations in the composition of dune sediment, color, and particle size; differences in dune activity; and geomorphic relations between dunes of different types (e.g. crossing patterns, superposition of dunes)(Lancaster, 1999).

Complex spatial patterns of dunes have been recognized in many terrestrial sand seas and linked to discrete periods of dune formation and/or reworking. Increased complexity of dune systems appears, therefore, to be a clear indicator of the magnitude and frequency of past climate changes, so extensive areas of simple patterns of dunes of a similar morphology such as the crescentic dunes of the North Polar sand seas of Mars, or the low latitude linear dune fields of Titan suggest extended periods of uniform conditions of winds and sediment supply (Kocurek and Ewing, 2005).

The trend of dunes in relation to formative winds is an important indicator of present and past wind regimes. As noted above, field and laboratory experiments show that the crest lines of all dunes are oriented in a direction subject to the maximum sand transport across the crest (the gross bedform-normal direction) (Rubin and Ikeda, 1990). This approach can be used to identify dune trends that are not in equilibrium with modern sand transporting winds and to model the past wind regimes that could have produced the identified trends (Lancaster et al., 2002; Sridhar et al., 2006).

8. Conclusion

Despite great progress in recent years, several areas of research into planetary dunes remain critical to enhanced understanding of dune systems and the relations to planetary environments, past and present. These include, but are not limited to:

1. Quantification of atmospheric parameters important to aeolian processes (e.g. wind speed and direction); wind shear stress is necessary for understanding fundamental aspects of sediment transport on planetary surfaces, yet such data are rarely acquired by landers and rovers. Inclusion of such instruments on future planetary missions is needed to advance understanding of the dynamics of wind transport of sediment on planetary surfaces.
2. Modeling of dune morphodynamics has progressed rapidly in recent years. Additional numerical and analog (e.g. flume) studies are a priority for understanding observed dune morphology and patterns and the relations to wind regimes, past and present
3. More research is required to constrain physical properties (e.g. grain size, degree of induration and cementation) and composition of dune sediments on Mars, Titan, and Earth and how these properties affect remote sensing signatures in VNIR, thermal, and microwave wavelength regions.

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