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Sand transport on Mars

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ABSTRACT

Whether the winds of the present Mars are shaping the variety of dune forms observed on the Martian surface has remained an open question that challenged planetary scientists for decades. In order to elucidate this issue, we have studied sand transport and dune formation from two different points of view. The first approach consists of solving the equations of aeolian transport at the level of the particles, whereas we study the trajectories and the velocities of sand grains during Martian wind storms. Next, we adapt a well established continuum model for sand dunes, which successfully reproduces the shape of Earth dunes, in order to study the formation of dunes under atmospheric conditions of Mars. Based on our results, we provide estimates for the wind strength, dune velocity and the timescale of changes in wind directions on Mars.

1. Introduction

The ubiquitous occurrence of dunes on the surface of Mars provides evidence that, as on Earth, *saltation*—which consists of grains moving in ballistic trajectories and ejecting new particles after colliding with the ground—is the dominant mode of sand transport on Mars. However, whereas the wind strength of terrestrial deserts is a large fraction of time above the minimal threshold for saltation, sand transport on Mars occurs only a few times a decade during extreme gusts of aeolian activity that last for not longer than a few minutes [1]. During such storms, Martian winds reach velocities that are 10 times higher than those on Earth deserts [1–3]. As consequence, Martian saltation events are much more intense than those on Earth, particles travelling higher and faster on Mars, and ejecting large amounts of sand and dust into the atmosphere of Mars [4]. A quantitative understanding of the Martian saltation is of crucial importance for the study of the geologic evolution of Mars. Also, it is of great interest to know the migration velocity of the apparently static Martian dunes [5,6]. Here we adopt two different approaches. First, we investigate sand transport at the "microscopic" level, by calculating the trajectories of single grains and their interaction with the wind field. Next, we use a continuum model for saltation which allows us to study the three-dimensional shape of Mars dunes as function of the strength and directionality of Martian winds.

2. Model for saltation

We perform numerical simulations of grain saltation inside a long two-dimensional channel (wind tunnel) [7,8]. The fluid (air) is incompressible and Newtonian, with density ρ_a and dynamic viscosity η, and we use the FLUENT commercial package of fluid dynamics in order to solve the Reynolds-averaged Navier–Stokes equations with the standard κ–ϵ model describing turbulence. By generating a pressure difference between the extremities of the tunnel, the logarithmic wind profile $u(z)$ without particles is obtained, i.e. $u(z) = 2.5u_* \log(z/z_0)$, where u_* is the wind shear velocity defining the aeolian shear stress $\tau = \rho_{\mathrm{air}} u_*^2$, z is the height above the ground and $z_0 \approx 10^{-4}$ m is the surface roughness. Next, streams of particles are injected from the inlet at the ejection angle of grain-bed collisions, $\theta_{\mathrm{eje}} = 36°$, with a velocity of 60 cm/s. Gravity $\boldsymbol{g}$ and drag are the only forces considered in the calculation of the particle velocity $\boldsymbol{v}_{\mathrm{p}}$,

$$d\boldsymbol{v}_{\mathrm{p}}/dt = F_D(\boldsymbol{u} - \boldsymbol{v}_{\mathrm{p}}) + \boldsymbol{g}(\rho_{\mathrm{p}} - \rho_{\mathrm{fluid}})/\rho_{\mathrm{p}}, \tag{1}$$

where $\boldsymbol{u}$ is the wind velocity, ρ_{p} is the particle density, and $F_{\mathrm{D}} = 18\eta C_{\mathrm{D}}\mathrm{Re}/(24\rho_{\mathrm{p}} d^2)$, where d is the grain diameter, C_{D} is the drag coefficient calculated numerically [9] and $\mathrm{Re} = \rho_{\mathrm{fluid}} d|\boldsymbol{u} - \boldsymbol{v}_{\mathrm{p}}|/\eta$ is the particle Reynolds number. At each iteration, the momentum change of every particle as it passes through a control volume is added to the fluid in order to capture the interaction between the air and the particles,

$$\boldsymbol{F} = \sum_{\mathrm{particles}} F_D(\boldsymbol{u} - \boldsymbol{v}_{\mathrm{p}})\dot{m}_{\mathrm{p}}\Delta t, \tag{2}$$

where Δt is the time step and $\dot{m}_{\mathrm{p}}$ is the flow rate of particle mass. The fraction of the grain momentum after and before the collision

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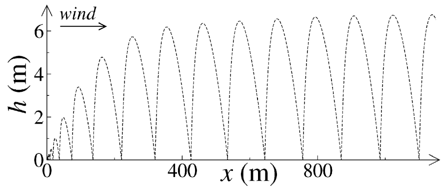

Fig. 1. The dashed line shows a typical trajectory of saltating grains on Mars as obtained in the calculations [8]. In comparison, Earth saltation loops are 100 times shorter and lower [7].

with the bed is taken as 0.4, which is consistent with experimental observations. In the simulations of saltation on Mars, where $g = 3.71\ \mathrm{m/s^2}$, we take grain density $\rho_{\mathrm{p}} = 3200\ \mathrm{kg/m^3}$ and diameter $d = 500\ \mu\mathrm{m}$ as observed from the Missions [10], and use the average values $\rho_{\mathrm{a}} = 0.02\ \mathrm{kg/m^3}$ and $\eta = 1.3 \times 10^{-5}\ \mathrm{kg/m\,s}$ of the Martian atmosphere (on Earth we have $g = 9.81\ \mathrm{m/s^2}$, $\rho_{\mathrm{a}} = 1.225\ \mathrm{kg/m^3}$, $\eta = 1.8 \times 10^{-5}\ \mathrm{kg/m\,s}$, $\rho_{\mathrm{p}} = 2650\ \mathrm{kg/m^3}$ and $d = 250\ \mu\mathrm{m}$ [11]). In the simulations, we consider the maximum number of grains a wind of given strength can sustain in saltation, i.e. the saturated flux, which corresponds to the maximum flux beyond which grain trajectories decrease in height and the particles end on the ground.

The simulations show that, when the velocity of Mars winds are of the order of the ones occurring during Mars sand storms (u_* above 2.0 m/s [1–3]), the trajectories of Martian particles (Fig. 1) are 100 times longer and higher than those of Earth grains under typical wind strength valid for Earth deserts (u_* between 0.3 and 0.6 m/s). Furthermore, the typical velocities with which Mars grains impact onto the ground are 10 times larger than the ones of terrestrial grains. Thus, grain-bed collisions are expected to be much more intense on Mars as compared to the situation on Earth.

Our simulations represent an important contribution to the understanding of aeolian transport and dune formation on Mars, since they allow us to study quantitatively the trajectories and the velocities of the grains when saltation is fully developed. Due to the enormous computational costs, however, a model for dune formation that solves the transport equations at the level of the particles is unreliable. In the next Section we present a different kind of approach which is more suitable for the study of dune formation.

3. Model for dune formation

Our dune model considers the layer of saltating grains as a thin fluid-like sheet moving on the immobile sand bed [12,13]. The model accounts for the exchange of sand between the saltation cloud and the sand bed, and for the saturation transient of the sand flux: due to the multiplicative process of saltation, i.e. the ejection of grains after grain-bed collisions ("splash"), the mass flux q per unit time and length achieves a maximum value q_{s} after a distance called "saturation length", which defines the minimal size of a dune [14].

The model can be summarized as follows:

(i) first, the wind shear stress τ over the topography is calculated by using the model of Weng et al. [15] that solves the turbulent wind over dunes or smooth hills;
(ii) next, the sand flux is calculated using the equation $\boldsymbol{q} = [1/\ell_{\mathrm{s}}](1-|\boldsymbol{q}|/q_{\mathrm{s}})$, where the length scale ℓ_{s} is a complex function of the wind velocity [12];
(iii) the change in the surface height h is computed using mass conservation, $\mathrm{d}h/\mathrm{d}t = -\nabla \cdot \boldsymbol{q}/[0.62\rho_{\mathrm{p}}]$, and
(iv) wherever the local slope exceeds 34° the surface becomes unstable relaxing through avalanches.

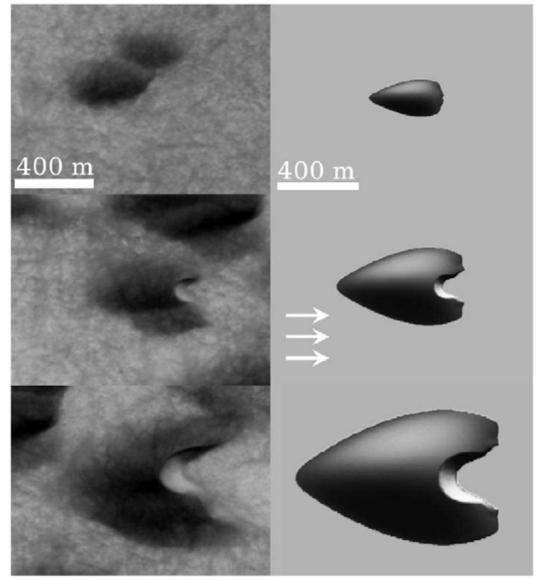

Fig. 2. Images (left) and simulations (right) of the barchan dunes in the Arkhangelsky crater on Mars. The arrows indicate the wind direction. Wind strength is $u_* = 3.0 \pm 0.1$ m/s. Images credit: NASA/JPL/MSSS.

A "separation bubble", connecting the brink with the ground, is then introduced at the dune lee, as defined in Ref. [13]. Inside the bubble the flux is set to zero since the wind is simply too weak to transport sand forwards in the bubble. Open boundaries and a constant sand influx at the inlet are used.

Most of the main parameters of the model, i.e. gravity, grain diameter and density, as well as fluid density and viscosity have been listed in the last Section when we dealt with the microscopic simulations of saltation. One parameter of the dune model is, however, unknown: the entrainment rate γ gives the number n of grains that enter the saltation cloud when the air-borne shear stress $\tau_{\mathrm{a}} = \tau - \tau_{\mathrm{g}}$, where τ_{g} is the grain-borne shear stress due to the grain-bed collisions, deviates from the steady-state value τ_{t}: $\gamma = \mathrm{d}n/\mathrm{d}(\tau/\tau_{\mathrm{t}})$. The terrestrial value $\gamma = 0.2$ has been obtained from comparisons with measurements that are not available for Mars, and thus the Martian γ must be determined from comparisons of the simulations with real dunes. As a first guess, however, we take $\gamma = 0.2$ for Mars as on Earth.

The barchan dunes in the Arkhangelsky crater (Fig. 2) are amongst the largest barchans of Mars. In order to reproduce their shape, we start with a Gaussian hill with volume similar to that of the Arkhangelsky dunes and take a wind of constant direction and strength u_* in the range of maximum Martian wind speeds, i.e. between 2.0 and 4.0 m/s [1–3]. The simulations yield a surprising result: the Martian sand hill does not evolve into a barchan and is completely eroded unless we increase γ by one order of magnitude, i.e. $\gamma = 2.0$. The larger entrainment rate on Mars compared to the Earth is consequence of the larger splash on Mars due to the higher impact velocities of Martian saltating grains [4]. Taking this new insight into account, the shape of the Arkhangelsky dunes is successfully reproduced if we take a wind shear velocity $u_* = 3.0 \pm 0.1$ m/s [14] as seen in Fig. 2. This value coincides with the average shear velocity that occurs during the strongest Mars dust storms [2,3].

Our calculations also explain the shape of exotic Mars dunes as those in Fig. 3. We find that such dunes are formed by a *bimodal* wind, i.e. a wind that oscillates between two directions. The wind lasts at each direction for a time T_{w}, and the oscillations between the two wind directions are simulated through alternate rotation of the field by the divergence angle θ_{w} (Fig. 3). Mars dune shapes are obtained only when T_{w} lies in the range

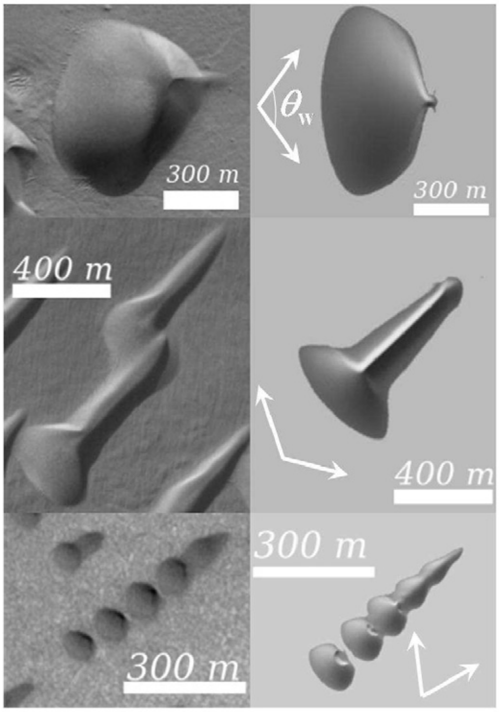

Fig. 3. Images (left) and simulations (right) of Martian bimodal dunes [16]. Arrows indicate the wind directions. A divergence angle $\theta_{\mathrm{W}} = 100°$ leads to "wedge dunes" as those in the Wirtz crater (top), while "drop dunes" are obtained with $\theta_{\mathrm{W}} = 120°$ (center). Drop dunes decay into rounded barchans after a decrease of θ_{W} down to 80° (bottom). Images credit: NASA/JPL/MSSS.

between 1–5 days, whereas the particular dune shape depends on θ_{W} (Fig. 3). The value of T_{W} obtained from the calculations of bimodal dunes means the effective time during which u_* has the value 3.0 m/s on Mars. Taking into account the frequency with which such wind velocities occur on Mars—once a decade during 40 s [1]—the characteristic timescale of the bimodal winds lies, in reality, in the range between 10000 and 50000 years [16]. This timescale is of the order of the half period of the precession of the Martian axis, which is responsible for the most significant changes in the Martian climate and causes changes in directions of the strongest Mars winds by more than 90° [17]—exactly as in our simulations of Martian dunes.

The calculations show that the Martian drop dunes (Fig. 3, center) would need roughly $\Delta T = 40$ months to appear from a Gaussian sand heap under bimodal wind regime. However, taking into account the frequency with which sand-moving winds occur on Mars, this timescale corresponds in reality to $\Delta T = 15$ million years. In the same manner, we find $\Delta T = 65$ million years for the wedge dunes (Fig. 3, top). On the other hand, Mars barchan dunes as those in the Arkhangelsky crater (Fig. 1) need roughly 5000 years in order to move 1 m [8,16]. This explains why Martian dunes look apparently static.

4. Summary

We adopted two approaches in order to study aeolian transport of sand under atmospheric conditions of today's Mars. In the first one, we solved the equations of aeolian transport at the level of the particles, and found that grain trajectories on Mars are giant as compared to their counterparts on Earth. The quantitative assessment of saltation trajectories and particle impact velocities achieved through our simulations represent a valuable contribution for future studies on the geologic evolution of the Martian surface [8]. Furthermore, we have shown, by means of dune simulations, that Mars dunes could have been formed by the thin atmosphere of today's Mars. Mars dunes move slowly because the velocity of Martian winds is seldom above the minimal threshold for saltation [14,16]. Our estimates for the strength of Mars sand moving winds and the time period of bimodal winds on Mars are consistent with values reported by the Missions [1–3]. In the future we intend to adapt our simulations in order to study saltation and dune formation on Venus, Titan and under water.

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