Icarus 234 (2014) 91–98

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Lift-off parameters of saltating particles on Mars

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ARTICLE INFO

Article history:
Received 24 April 2013
Revised 11 January 2014
Accepted 23 February 2014
Available online 4 March 2014

Keywords:
Geophysics
Mars
Mars, climate
Mars, surface

ABSTRACT

The aeolian events are frequent on Mars. However, we have very limited understanding of aeolian process, because we cannot conduct experiments, as we did on Earth, on martian surface directly right now. In this paper, we studied the lift-off parameters of saltating particles in wind-blown sand on Mars systematically through a numerical way. The main findings are shown as follows: (1) the lift-off speeds of martian particles increase linearly with wind shear velocities; (2) the lift-off speeds of particles on Mars have the same order of magnitude as but a little smaller than those on Earth at the same shear velocity; (3) the lift-off angles on Mars are almost equal to those on Earth and have weak dependence on shear velocities; (4) the lift-off parameters (both speeds and angles) are influenced by particle diameters.

1. Introduction

The aeolian features, widely distributing on martian surface (Malin and Edgett, 2001), have been focused and studied since the first images of Mariner 9 (McCauley et al., 1972). Extracting and studying these features, such as sand ripples and dunes, are helpful to understand the change of martian climate in the past (Gardin et al., 2012) and obtain the wind information near the surface in the boundary layer (Silvestro et al., 2010; Bridges et al., 2012b). The obtained wind information provides the possible of studies on the formation and evolution of aeolian features on Mars. These studies thereby could be useful for the selection of mission landing sites (Golombek et al., 2012) and survey routines (Grotzinger et al., 2012) and avoiding the experience of Spirit Mission (Kerr, 2009).

The transport of aeolian sediment is observed frequently on Mars (Sullivan et al., 2005), particularly for dust devils and sand storms (Cantor et al., 2001; Balme and Greeley, 2006). However, because of the low resolution of images, the sand ripples and dunes on martian surface have been considered to be almost immobile (Geissler, 2005). The improvement of exploring techniques, such as the employment of HiRISE, gives us a chance to see the details. It is found that the sand ripples and dunes on Mars indeed migrate under current climate (Bourke et al., 2008; Sullivan et al., 2008; Chojnacki et al., 2011; Hansen et al., 2011; Silvestro et al., 2011). Also, the sand transport rate (Bridges et al., 2012b) and the migration rates of sand ripples and dunes (Bridges et al., 2012a) are found to be comparable to those on Earth. These new findings suggest that the study of aeolian transport on Mars is far from sufficient (Durán et al., 2011; Kok et al., 2012).

The aeolian process plays an important role in the change of landforms on both Mars and Earth (Shao, 2008; Zheng, 2009; Kok, 2010a). Nevertheless, so far, we cannot measure the motion of aeolian sediment particles directly on Mars as we did on Earth. Hence, both qualitative and quantitative measurements of the basic physical process of martian particle transport are absent. For example, the mean lift-off (impact) velocities and angles of saltating particles, as well as their corresponding distributions, near the sand bed are missing. Fortunately, although experimental data is not available, the numerical simulation could be a helpful way to investigate the transport of martian saltating particles.

Here, several previous numerical studies are briefly introduced (For a straightforward look, please see Table A1 in the Supplementary data S1). The early study on the trajectories of martian particles was conducted by White et al. (1976). They found that the speed of saltating particles on Mars is larger than that on Earth, and the ratio of the saltating speed to fluid threshold on Mars is also several times larger than that on Earth. Besides, the incident angle of martian particles was found to be generally smaller than 3°, which is far below the incident angle of terrestrial particles (Fu et al., 2013; Zheng et al., 2013). But, all the particles were released into the air vertically from the surface during their calculations. This treatment is most likely to be inconsistent with the truth. Almeida et al. (2008) employed Fluent to simulate the

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http://dx.doi.org/10.1016/j.icarus.2014.02.023
0019-1035/

saltation of sand by solving the turbulent wind field inside a wind tunnel and the air feedback with the dragged particles. They found that the average incident speed of martian particles was generally 5–10 times higher than that of terrestrial particles, and the average incident angle of martian particles had the same order of magnitude as that of terrestrial particles. However, in their simulations, the particles were set to be rebounded from the surface with a restitution coefficient of 0.6 and a lift-off angle of 36°, instead of fully considering the splash process (Kok, 2010a). Thus, their results may be more suitable for sand-supply limited condition (Ho et al., 2011), but not for the sand transport limited case (Kok, 2010a; Ho et al., 2011). Kok (2010b) parameterized the hysteresis phenomenon (the hysteresis between static and dynamic thresholds) into his numerical model. The modeling results showed that the hysteresis effect causes saltation to occur for a much lower wind speed than previously thought. He pointed out that because the impact threshold is very low, once particles were initiated, saltation could be maintained under the current martian environment. Therefore, the consideration of hysteresis effect provides us an opportunity to improve our understanding of wind-blown sand on Mars. Although a recent publication (Yizhaq et al., 2014) supports his consideration, more studies, like simulations of steady-state saltation on Mars by different models, are required to verify the consideration. Another, the model results showed that the speed of martian particles was a little smaller than that of terrestrial particles, but almost did not change with wind, which is still debatable and challengeable. A discussion about the response of saltating particle speeds to wind was conducted in the work of Zheng et al. (2013), and some new experimental measurements (Fu et al., 2013; Rotnicka, 2013) provide potential evidence against the independence of saltating particle speed on wind. Thus, some results obtained by Kok's model may need to be improved.

Based on the review of literatures above, we find that our understanding of lift-off information of martian particles is limited currently. The lift-off parameters determine the trajectories of saltating particles physically, and are crucial for many aeolian models applied to both terrestrial and extraterrestrial environments (Anderson and Haff, 1988; Werner, 1990; Zheng, 2009; Kok, 2010a). Therefore, the aim of this paper is to numerically investigate the lift-off parameters (velocity and angle) of martian saltating particles, as well as the responses of these parameters to wind shear velocities, following the work of Zheng et al. (2013). The model of Zheng et al. (2013) is briefly introduced in Section 2. The means and distributions of lift-off parameters of martian saltating particles are shown in Section 3. The discussion and conclusions are arranged in Section 4.

2. Methods

Despite a difference in the parameters of physics, the basic process of aeolian sediment transport on Mars is generally similar to that on Earth (Almeida et al., 2008; Kok, 2010a). It is well-known that saltation plays the predominant role in aeolian sediment transport (Bagnold, 1941). Recently, Zheng et al. (2013) established a model to study the movement of martian particles in steady-state saltation. The modeling of sand saltation is usually composed of four sub-processes: aerodynamic entrainment, grain hopping, grain–bed collision and wind field modification (Anderson and Haff, 1988). Because the impact–entrainment is the dominant mechanism in steady-state saltation (Kok et al., 2012), the aerodynamic entrainment was neglected in the model of Zheng et al. (2013). Thus, the remained three processes are included into the model. Since there is little information about the initial speed and angle of saltating particles on Mars, Zheng et al. (2013) assumed that some particles have been initiated with an initial distribution of incident speed. Then, these initiated particles hop in the air and collide with the bed continuously by the drive of wind, with a systematic adjustment of particle velocity (angle) distribution. The continuous hops and collisions would not stop until both speed distributions and angle distributions of particles reach the steady state. These stable distributions are exported as the final results.

The trajectories of saltating particles were calculated by mainly considering the role of gravity and aerodynamic drag (details see Eq. (A1) in Supplementary data S2). Because the sand particles alter the wind profile significantly (Shao, 2008), Zheng et al. (2013) considered the influence of moving particles on the wind profile in the model. For simplification, a wind profile, which is analytically derived from the measurements in the wind tunnel (Feng et al., 2009), was employed (details see Eq. (A2) in Supplementary data S3). For sand-bed collision process, the stochastic particle–bed collision model established by Zheng et al. (2005) was applied. The stochastic model is composed of three parts: the incident particle, the impacted particle on the bed and the remaining particles on the bed (details see Fig. A1 in Supplementary data S4). Based on the collision theory and momentum balance, Zheng et al. (2005) derived the solution of particle speed after collision (details see Eq. (A3) in Supplementary data S4). Therefore, one advantage of the model established by Zheng et al. (2013) is that the lift-off speeds are analytic solutions, in comparison to previous models (Anderson and Haff, 1988; Werner, 1990; Zheng, 2009; Kok, 2010a).

The model of Zheng et al. (2013) proves to be able to predict sand motion in steady-state saltation on Earth well both qualitatively and quantitatively. Thus, it was applied to the study of sand saltation on Mars. In this paper, the model is employed to study the lift-off parameters of martian saltating particles. In the following, we first calculated saltations on both Earth and Mars in the cases of $u_* = u_{*,e} = u_{*,m} = 0.3$, 0.5 and 0.7 $\mathrm{ms^{-1}}$, respectively, and then calculated saltations in the cases of $u_*/u_{*ft} = u_{*,e}/u_{*e,ft} = u_{*,m}/u_{*m,ft} = 1.0$, 1.25, 1.5, 1.75 and 2.0, respectively. Here, e and m represent the quantities on Earth and Mars, respectively. u_{*ft} is the fluid threshold. The expression of Shao and Lu (2000), $u_{*ft} = A_N((\rho_s - \rho_a)gD/\rho_a + \gamma/(\rho_a D))^{0.5}$, includes the influence of inter-particle force and shows good agreement with experimental data (Kok et al., 2012), where D is the particle diameter, $A_N = 0.111$, $\gamma = 2.9 \times 10^{-4}\ \mathrm{N\ m^{-1}}$. So, it is selected here to estimate the fluid threshold on Earth and Mars. Thus, the estimated fluid thresholds of terrestrial particles with $D = 0.25$, 0.35 and 0.5 mm are 0.277, 0.316 and 0.37 $\mathrm{ms^{-1}}$, respectively; and 1.56, 1.71 and 1.95 $\mathrm{ms^{-1}}$ for the corresponding diameter of martian particles, respectively. u_* represents the wind shear velocity and u_*/u_{*ft} is defined as the dimensionless wind shear velocity. The particle diameter is $D = 0.25$ mm when the influences of shear velocities are concerned; while the diameters of $D = 0.25$, 0.35 and 0.5 mm are used when the influences of particle diameters are focused.

The basic planetary parameters of physics involved in this paper are shown in Table 1. Besides, on Earth, the impact threshold is usually considered to be 0.8 times of the fluid threshold (Bagnold, 1941). Experimental studies (Rasmussen et al., 2009; Ho et al., 2011) suggest that the impact threshold of particles with $D = 0.25$ mm on Earth is about 0.2 $\mathrm{ms^{-1}}$. For the martian particles

Table 1
Main physical parameters used in simulations. g, η, ρ_a and ρ_s represent the gravity, dynamic viscosity of air, density of air and density of sand grains, respectively, according to the work of Pähtz et al. (2012).

Planet	g ($\mathrm{ms^{-2}}$)	η ($\mathrm{kg\ m^{-1}\ s^{-1}}$)	ρ_a ($\mathrm{kg\ m^{-3}}$)	ρ_s ($\mathrm{kg\ m^{-3}}$)
Earth	9.81	1.78×10^{-5}	1.225	2650
Mars	3.72	1.30×10^{-5}	0.02	3000