Research Article

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A mathematical conjecture associates Martian TARs with sand ripples

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Abstract: Considering that aeolian sand ripples are formed primarily by creeping particles caused by wind-driven saltation sand particles, we obtain a formulation for determining the height of saturated aeolian sand ripples by incorporating the reptation fluxes with previous experimental results on migration velocities of sand ripples. Based on existing observational results of terrestrial sand ripples on Earth's surface, it estimates that the wavelength of aeolian sand ripples on Mars is generally up to several meters. This implies a possibility that there is another sand ripple on Mars similar in scale to Transverse Aeolian Ridges (TARs) at some time when surface saltation was prevalent. Moreover, perhaps part of the widely observed TARs is the degradation of saltation sand ripples, whose formation is intimately related to saltation and reptation of sand particles. While the other two types of ripple-like morphologies (plain ripples and crater ripples) found by Opportunity Rover are essentially not. Further, we propose that the main factor controlling the scale feature of Martian sand ripples is the intense particle-bed collision process.

Keywords: TARs, sand ripple, reptation, Martian Rover

1 Introduction

The surprising discovery of aeolian features on Mars provides an opportunity and a challenge for geologists and planetary physicists to figure out the evolution process and present status of the Martian atmosphere and climate

[1]. Except for the various aeolian features with similar patterns to terrestrial dunes, such as barchans, transverse dunes, longitudinal dunes, and star dunes [2,3], a large number of ripple-like aeolian bedforms have also been revealed to exist on the Martian surface by the Mars Orbiter Camera (MOC) installed on the Mars Global Surveyor (MGS) and the Mars Exploration Rovers, and recently by the Opportunity Rover at Cape St. Mary, Victoria crater [4] and the High-Resolution Imaging Science Experiment (HiRISE) camera in the orbit around Mars [5]. These ripple-like bedforms can be classified into at least three types: crater ripples, plain ripples, and large-scale ripples (TARs and large dark ripples). Among them, crater ripples composed almost entirely of basaltic 50–125 μm sand are generally found within craters; plain ripples exist mainly on the plains of Meridiani Planum, for which the inter-ripple areas (ripple troughs) are dominated by 50–125 μm basaltic grains while the crests are armored with a monolayer of 1–2 mm fragments of concretions [6], demonstrating a segregation structure of poorly sorted sand particles, that is, a bimodal distribution of grain size. The wavelength of the two types mentioned above is typically ~ 0.1 m, which seems akin to terrestrial aeolian ripples on Earth in length scale. In addition to these small ripples, another population of larger bedforms, which are with a wavelength magnitude of about 10 m [7], has been noted and named as TARs. The composition and particle size of TARs are not always the same, some of them have the same armoring monolayer of granules as the plain ripples [8], while the others are armored with smaller fragments of concretions [9]. The bedforms on the Martian surface are complex due to the surface environment [10]. For all the three types of ripple-like bedforms, their origin and classification have been discussed in recent years, yet not resolved so far.

For the crater and plains ripples, there is a supposition that both of them show characteristics similar to those of terrestrial ripples [6]. Considering the strength of modern winds on Mars, some researchers further concluded that crater ripples were formulated by particulate matter, which are suspended by wind turbulence, and probably currently mobilized by recent winds. While

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plain ripples have not been active recently because the armoring monolayer of granules is hard to be displaced by the current wind regime, therefore, they may be formed a long time ago when winds were relatively stronger [6,11]. However, it makes no difference that Martian dunes are about ten times larger than their terrestrial analogs [12]. The wavelength scale of crater and plain ripples thus appears relatively small with the same scale similarity.

For the third type of bedforms, known as TARs, their sediment source, age, superposition relationships and degree of migration activity are largely unknown. Early views of the Martian surface from the MOC suggested that TARs might be formed from small transverse dunes [13], however, more and more recent observations achieved consistently show that most of them have the wavelength smaller than the Martian dune's wavelength by one order of magnitude [14,15]. In addition, these ripple-like bedforms have no obvious slip face [8], which distinguishes them from dunes, therefore, it is suspicious to conclude TARs to be dunes. Williams et al. suggested these bedforms might be analogous to large terrestrial ripples or ridges [16], while Bourke et al. named these ripple-like bedforms as "Transverse Aeolian Ridges" (TARs) [7], implying these aeolian features on Mars might be the same topographic structures as terrestrial ridges. Blame et al. approved the above results and considered these bedforms to be inactive [8].

Until recent years, the above viewpoints were still debated by researchers. First, new results show that TARs are still active, for example, Silvestro et al. demonstrated that the ripples moved an average distance of 1.7 m in less than 4 Earth months in the dune edges through analyzing HiRISE images [17]. Silvestro et al. pointed out that wind ripples on the Martian surface have a minimum ripple migration rate of 0.66 m per Earth year [18]. Besides, Chojnacki et al. also showed that the sub-metar-tall ripples exhibit similar rates with dunes (~ 0.5 m/year) [19]. Second, many TARs have different shapes compared with the ripples on Earth, that is, they have asymmetric profiles with angle-of-repose lee slopes and sinuous crest lines [4]. Based on these observations, new viewpoints about TARs are proposed recently, for example, the paper of Geissler suggests that TARs are primary depositional bedforms that accumulated in place with the dust carried by the winds in suspension millions of years ago, perhaps in a manner comparable to antidunes on Earth, and were subsequently indurated and eroded to their current states by eons of sandblasting [20]. Foroutan et al. observed that the megaripples and TARs exhibit similar features, and considered that the formation

mechanism of TARs is similar to that of megaripples [21]. While Zimbelman discusses these megaripples were probably transformed from sand ripples [22].

Remote sensing data show that some of the TARs should be composed of smaller sand particles than Large Dark Dunes [23]. On the other hand, *in situ* observations also illustrate that some TARs are not obviously armored by a layer of coarse-sized fragments, suggesting that these bedforms are composed of relatively well-sorted sand particles [8]. Thus, the TARs on the Martian surface contain several kinds of landforms, some are similar to the terrestrial ridges on Earth, while others are similar to the unformed transverse dunes [24], see Figure 1. And the authors of this paper suppose that TARs are actually reptation ripples. To confirm this hypothesis, it is necessary to predict that the reptation ripples exist on Mars, which is not yet found.

Identifying the geomorphic types of TARs is of great significance for understanding the topographic characteristics and the formation process of Martian aeolian features, especially for recognizing the landforms near the landing sites of the Mars Exploration Rovers (MERs). Hence, following the basic concept that aeolian sand ripples are mainly formed by reptating/creeping particles, this paper proposes an expression to predict the ripple height under the assumption of the formation mechanism of aeolian sand ripples. Then, by calculating the range of the wavelengths of sand ripples and snow ripples on earth, it is shown that the predicted results are consistent with the measurement results of these two kinds of ripples. Furthermore, what is surprising is that the predicted

Figure 1: Transverse Aeolian Ridges (TARs) on the floor of Nirgal Vallis, Mars, with wavelengths of TARs from 30 to 100 m. Portion of MOC image E02-02651, 27.8°S, 316.7°E, 2.8 m/pixel, NASA/JPL/MSSS [24].

length of the aeolian sand ripples on Mars can be in the order of several meters, which is comparable with that of TARs. Therefore, it can be concluded that there is a possibility that some of the TARs on Mars were aeolian ripples or transformed by terrestrial sand ripples, which is in accordance with the view of Zimbelman [22].

2 Methods

2.1 Reptation flux on a flat surface

The entrainment rate of reptating/creeping particles in saturated wind-blown sand flux can be analyzed as follows. Considering a flat and loose sand bed, when the inflow friction velocity u_* exceeds the threshold value u_{*t} , large quantities of sand particles will be lifted off and hop along the ground surface under the aerodynamic forces, here u_{*t} is the threshold friction velocity of sand particles with diameter d . When the hopping particles collide with the sand bed due to the force of gravity, they will eject other particles. Some ejected ones with lift-off velocities large enough, called *saltons*, will be accelerated by wind, and splash other particles when they impact sand bed. The grains jump and roll for small distances under the action of small lift-off velocities, which are termed *reptons*. The two-specie model [25] explored the quantity relationship of the above two kinds of particles generated from bed collisions per unit area per unit time when the wind-sand flow is saturated, and give

$$N_{\text{eje}}\phi_{\text{sal}} = p_{\text{sal}}\phi_{\text{sal}} + p_{\text{rep}}\phi_{\text{rep}}, \quad (1)$$

where N_{eje} refers to the number of ejected particles produced by a single impacting *salton*, ϕ_{sal} , ϕ_{rep} represent the vertical number fluxes of *saltons* and *reptons*, respectively, p_{sal} , p_{rep} are the trap probability of *saltons* and *reptons* when they collide the soil. In equation (1), the left side represents the total number of ejecta particles produced from bed collisions, while the right side, respectively, represents the number of *saltons* and *reptons* captured by the sand bed. The above formulation can be rewritten as follows:

$$n_{\text{eje}} = n_{\text{sal}} + n_{\text{rep}}, \quad (2)$$

where n_{sal} refers to the number of particles becoming saltating population (including the rebound one if exit) and n_{rep} represents the number of particles becoming reptating/creeping population.

The numerical simulation results of Anderson and Haff [26] showed that, with the development of wind-blown sand flux from zero to its saturation, the wind friction stress τ approached τ_t . Here, $\tau = \rho_{\text{air}}u_*^2$ is the friction stress of incoming wind flow and ρ_{air} refers to the air density, while $\tau_t = \rho_{\text{air}}u_{*t}^2$ is the threshold friction stress for sand particles. Based on the two-specie model, most *saltons* must experience a sequence of collisions with the bed surface and re-suspensions before reaching the final stable saltation motion. Take the threshold velocity for *reptons* to escape from trapping at the sand bed and become *saltons* as a constant, i.e., $v_{\text{th}} \approx a(gd)^{1/2}$, in which g refers to the gravity acceleration and $a \approx 5$ refers to the proportional coefficient [25]. Then, Anderotti showed that the total number of particles generated from a single collision in saturated wind-sand flow could be evaluated by means of the following expression [25]:

$$N_{\text{eje}} = v_{\text{imp}}/a\sqrt{gd} - 1. \quad (3)$$

The saltation particles move along a distance $L_{\text{drag}} = \rho_{\text{sand}}d/\rho_{\text{air}}$ after a time of $T_{\text{drag}} \propto u_*/g$, that is, the relaxation length and the relaxation time after which the grain has been accelerated by the drag force up to the wind velocity. The final impact velocity v_{imp} is proportional to the final saltation velocity, that is

$$v_{\text{imp}} \propto \frac{L_{\text{drag}}}{T_{\text{drag}}} = \frac{\rho_{\text{sand}}d}{\rho_{\text{air}}} \frac{u_*}{g} = \frac{\rho_{\text{sand}}gd}{u_*\rho_{\text{air}}}.$$

Here, we assume that the proportional coefficient is around 0.2 [27], and ignore number one for some tolerable error, then it is obtained from expression (3) that

$$N_{\text{eje}} = 0.2 \frac{\rho_{\text{sand}}\sqrt{gd}}{\rho_{\text{air}}au_*}. \quad (4)$$

It means about 7 ejection particles for $d = 250 \mu\text{m}$ and $u_* = 0.5 \text{ m/s}$ on Earth. Due to the fact that the *reptons* are produced by the sand-bed collisions of *saltons*, in the first approximation, Andreotti et al. [27] gave

$$\phi_{\text{rep}} = N_{\text{eje}}\phi_{\text{sal}}$$

The relation between the vertical flux ϕ and the integrated horizontal flux q is determined by the grain typical hop length l , that is, $q = \phi l$, then the relation between fluxes of saltation and reptation can be expressed as follows:

$$q_{\text{rep}} = \frac{l_{\text{rep}}}{l_{\text{sal}}} N_{\text{eje}} q_{\text{sal}}. \quad (5)$$

According to Andreotti et al. [27] and Bagnold [28], $q_{\text{sal}} = c\rho_{\text{air}}u_*^3/g$, $c = 1.5$; $l_{\text{rep}}/l_{\text{sal}} \approx gd/u_*^2$, the above expression can be rewritten as follows:

Table 1: Important parameters used in this model

Variable	Parameter
u_*	Friction velocity
u_{*t}	Threshold friction velocity
N_{eje}	Ejecta particles produced by one impacting <i>salton</i>
ϕ_{sal}, ϕ_{rep}	Vertical number fluxes of <i>saltons</i> and <i>reptons</i>
a	<i>Reptons</i> velocity proportional coefficient
d	Sand particle diameter
ρ_{air}	Atmospheric density
ρ_{sand}	Sand particle density
q_{rep}	Saturate reptation flux
V_{imp}	<i>Saltons'</i> impact velocity with surface
L_{drag}	Drag length

$$q_{rep} = 0.2 \frac{c \rho_{air} \sqrt{gd}}{a} \cdot L_{drag}. \quad (6)$$

The symbols used above are listed in Table 1.

2.2 The migration velocity of saturated sand ripples

In this section, the migration velocity of saturated ripples is analyzed. As per the illustrations of previous wind tunnel experiments [29] and field observations [30], for the three phases of the formation of sand ripples, what can be identified from an initial flat bed configuration includes appearance of an initial wavelength, coarsening of the initial sand surface pattern, and finally saturation of the ripples. After saturation, the ripple index $s = l_r/h_r$, in which h_r, l_r refer to the height and wavelength of a saturated ripple, respectively. Though the migration velocities of ripples do not change with time, they are subject to the impact of the properties of blown wind-sand flow only, i.e., the inflow friction speed u_* , the air density ρ_{air} , the particle density ρ_{sand} , the grain size of the sand bed d , etc. Through wind tunnel experiments, Andreotti et al. suggested that the migration velocity of the saturated ripples v_r was related to the wind velocity and the particle size [29], which can be expressed as follows:

$$v_r = \eta \frac{\rho_{air}}{\rho_{sand}} \left(\frac{u_*}{u_{*t}} - 1 \right) \sqrt{gd}, \quad (7)$$

where $\eta \approx 13.4$ refers to a universal constant that can perfectly fit the experimental data in ref. [29].

Introducing the parameters listed in Table 2 in the above equation, the ripple migration velocity on Mars obtained can be 1.38–3.70 m/year, which is bigger than the results of Bridges et al. [31], Silvestro et al. [18],

Table 2: Values of the quantities used in the prediction model

Variable	Parameter	Values
η	Universal constant in equation (7) [29]	13.4
a	<i>Reptons</i> velocity proportional coefficient [25]	5.0
c	Saltation transport rate proportional coefficient [28]	1.5
β	The porosity of the surface material [36]	0.35
p_E	The ratio of u_* with u_{*t} on Earth	1.5–2.0
p_M	The ratio of u_* with u_{*t} on Mars [12]	1.45–2.2
g_E	Gravitational acceleration on Earth	9.8 m/s ²
g_M	Gravitational acceleration on Mars [12]	3.7 m/s ²
d_E	Typical sand particle diameter on Earth	250 μ m
d_M	Typical sand particle diameter on Mars [12]	500 μ m
K	Coefficient in equation (11)	6.8×10^{-3}

Cardinale et al. [32], and Chojnacki et al. [19], i.e., about 0.27, 0.66, 0.297, and 0.5 m/year, respectively, but smaller than the value given by Silvestro et al. [17], i.e., about 5.1 m/year. However, the errors are in the same magnitude as the observed results and the predicted value; therefore, it is acceptable to use formula (7) to predict the sand ripple migration velocity.

2.3 Sand ripples on Mars

In the last few years, the relationship between sand transport and bedforms was explored by many researchers [33,34]. It is noted that the saturated sand ripple formed in steady-state wind sand flow should satisfy the mass conservation equation [35], also known as the Exner equation:

$$\frac{\partial h_x}{\partial t} = -\frac{1}{\rho_r} \frac{\partial q_{rep}}{\partial x}, \quad (8)$$

where $\rho_r = (1 - \beta)\rho_{sand}$ refers to the bulk density of the sediment in the bed, in which β represents the porosity of the surface material and is taken as 0.35 by Anderson [36].

It is assumed that all sand ripples are at the same velocity and in the same shape, and we only consider the motion of a single ripple. The migration speed of the steadily moving ripple is expressed as follows:

$$\frac{\partial h_x}{\partial t} = -v_r \frac{\partial h_x}{\partial x}, \quad (9)$$

where h_x represents the height function of the ripple at a position x , whose origin is placed at the root of the sand

ripple, that is, at a ripple trough. Introducing (8) into (9) leads to

$$\frac{\partial q_{\text{rep}}/\partial x}{\partial h_x/\partial x} \approx \frac{q_{\text{rep}}(x_T) - q_{\text{rep}}(0)}{h_r} = \rho_r v_r, \quad (10)$$

where x_T refers to the streamwise coordinates of the point of the ripple crest. Noting that the spatial continuity of aeolian sand ripples, that is, the leeward slope of one sand ripple generally connects with the foot of the next ripple, the sheltering effect caused by the leeward slope of the upwind ripple will reduce the saltation flux at the foot of the downwind ripple, that is, $q_{\text{sal}}(0) = 0$, and $q_{\text{rep}}(0) = 0$. It is worth mentioning that as the height of the sand ripple increases, the sheltering effects of the upwind ripple will be weakened. Therefore, saltation transport rate changes with x and gradually increases to its maximum on the crest, that is, $q_{\text{sal}}(x_T) = q_{\text{sat}}$ at $x = x_T$, where q_{sat} refers to the saturated vertical flux, that is, $q_{\text{rep}}(x_T) = q_{\text{rep}}$. Introducing (6) into (10), and the height of a saturated ripple h_r can be written as follows:

$$h_r = \frac{q_{\text{rep}}(x_T)}{\rho_r v_r} = K \cdot \frac{u_*}{u_* - u_{*t}} \cdot L_{\text{drag}}, \quad (11)$$

where $K = \frac{0.2c}{a(1 - \beta)\eta}$

Define $p = u_*/u_{*t}$, the above expression can be rewritten as follows:

$$h_r = K \cdot \frac{p}{p - 1} \cdot L_{\text{drag}}. \quad (12)$$

Equation (12) shows that the height of sand ripples is proportional to L_{drag} , suggesting that L_{drag} is a key parameter in the aeolian ripple landform [14].

3 Data and results

On the Earth, $\rho_{\text{sand}} \approx 2,650 \text{ kg/m}^3$, $\rho_{\text{air}} \approx 1.25 \text{ kg/m}^3$, based on equation (12) and the parameter values given in Table 2, the ripple height on the Earth can be obtained from (12), that is, $h_r^E = 0.72 - 1.08 \text{ cm}$. This is consistent with the field observations of refs [28,30], which show that the height of terrestrial ripples is about 0.5–1 cm.

The ripple length on Mars is further predicted, suppose the air density is about [12], and based on equation (12) as well as other parameter values in Table 2, the ripple height on Mars is obtained, $h^M = 1.2 - 1.7 \text{ m}$. Assuming that the ripple index on Mars is similar to that on the Earth, that is, $s = 13 - 30$ [30], it can be estimated that the wavelength of aeolian ripples on Mars l^M is about 15.6 – 51 m. Using photometric methods and new MRO HiRISE data, Zimbelman and Williams [37] suggested the index of TARs be only about 8, that is, $s^{\text{TARs}} = 8$. Considering this value, we conclude that the sand ripple wavelength on Mars is about $l^M = h^M \cdot s^{\text{TARs}} = 9.6 - 13.6 \text{ m}$. These values of the ripple wavelength are basically consistent with the typical height (1.3 m) and the wavelength (25.8 m) of the observed TARs [38]. For example, Wilson and Zimbelman reported that most TARs with wavelengths ranging from 20 to 60 m at equatorward of $\sim 60^\circ$ are at the region where TARs are abundant [39]. Figure 2 shows the comparison between the predicted results of our model using a ripple index from 13 to 30 with the dimensions of individual TARs in Ius Chasma and Terra Sirenum provided by Zimbelman [37] and the data used by Hugenholtz *et al.* [38]. It can be seen from Figure 1 that the predicted ripple length is comparable with the observation of TARs, but only a part of TARs is consistent with the predicted Martian aeolian

Figure 2: Comparison of the ripple wavelength and height predicted using expression (12) and ripple index 13–30 with the observed TARs data (left, data from Zimbelman [37]; right, data from Hugenholtz *et al.* [38]).

ripples, while other TARs are far away from the forecast data. The reason may lie in the fact that the observed TARs were formed in complex environment, for example, in uneven terrain or in complex wind currents.

Therefore, it is reasonable to conclude that Martian TARs (especially those in the region with unidirectional airflow, flat surface and abundant movable sand) are analogous to aeolian sand ripples rather than ridges. Consequently, the other two types of ripple-like bedforms (crater ripples or plain ripples) might not be reptation ripples induced by particle-bed collisions with saltating particles due to their small length scale.

Why the wavelength of the aeolian sand ripples on Mars gets so large? This can be partly explained by the large number of reptating sand particles generated by particle-bed collisions. It can be seen from expression (4) that the number of ejected particles N_{eje} generated by a single collision mainly depends on the ratio $\rho_{\text{sand}}/\rho_{\text{air}}$ which is much larger on Mars than that on the Earth. There, the drag length $L_{\text{drag}} = \rho_{\text{sand}}d/\rho_{\text{air}}$ is also much larger on Mars, which results in a very large ripple height on Mars based on equation (12).

4 Discussion

In this manuscript, an expression used to calculate the height of saturated ripples formed by wind-driven reptating sand particles is derived, which is available for the prediction of the height of ripples produced by the particle-bed splash process based on a series of physical parameters. The predictions of the aeolian sand ripples on the Earth are consistent with the field measurements. While the predictions of the ripple wavelength on Mars show that they are consistent with the ‘ripple-like’ morphologies (i.e., TARs) on the Martian surface, suggesting that the TARs on Mars, especially the ones formed by uniform particles were probably active sand-impact ripples now or ever. The above results also suggest that the other two types of ‘ripple-like’ bedforms (i.e., plain ripples and crater ripples) might not be sand-impact ripples. Based on the observed height and the abundance of TARs on the Martian surface, it can be estimated that much more intense particle-bed collision processes occur on Mars than on Earth.

Finally, the origin or formation mechanism of TARs is still not clear due to several problems. First, only a few observations can prove the activities of TARs, while other TARs seem to be static [40]. Second, many TARs are in different shapes compared to the reptation ripples on the

Earth, that is, they have asymmetric profiles with angle-of-repose lee slopes and sinuous crest lines [20], indicating that the TARs may be subjected to the winds from different directions frequently. Third, the scales of TARs are very discrete [38], which makes the model prediction limited. The work of the manuscript is only an attempt to predict the reptation ripples on Mars, and the conclusion that TARs may probably be reptation ripples still needs to be tested.

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