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Soil Evaporation on Mars by Magnetic Dipole-Dipole Interactions between Magnetic Clusters

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Magnetic dipole-dipole interaction on the surface of Mars and its significance with regard to saltation is discussed. It is shown that dipolar magnetic collisions between magnetized clusters o aggregates on Mars could potentially eject soil particles from the surface with heights around of 1 cm or thereabouts depending of the size of the soil particle and with a maximum effectiveness around of 100 ?m diameter. The magnetic dipolar mechanism could operate in concert with the wind to trigger dust storms specially when the stress forces exerted by the air are only enough to roll soil particles (reptation) but high enough to induce the approaching of magnetic clusters to a critical distance where attractive interaction between dipoles can overcome the frictional forces opposing the motion and then igniting saltation. Utilizing a simplified physical model, analytical expressions for the maximum height as function of the diameter of the soil particle was derived. .

Keywords. *Aeolian transport, Saltation, Loss of river deltas,Martian dust cycle*

I. INTRODUCTION

The object of this work was a first assessment on a new mechanism for aeolian transport on the surface of Mars which can contribute to the ejection of grain and dust particles. The proposed mechanism is driven by magnetic dipole-dipole collisions between magnetized grains of the Martial soil enabling dust and grains to hop erratically over the surface with ballistic trajectories where can emigrate transported by the Martian winds or igniting saltation. Dipole-dipole magnetic collisions seems an unavoidable consequence on the surface of Mars. In fact, since the early times of the Viking missions to Mars (1976) and the Mars pathfinder mission (1977) it was well established that the martian soil and dust is magnetic. More recently, according with the NASA´s Mars Exploration Rover Spirit, almost all dust particles in the Martian atmosphere are magnetic and containing the strong magnetic mineral magnetite (Fe_3O_4), [1]. As a result, magnetic dipole-dipole interactions with the formation of magnetic aggregates and clusters is an unavoidable phenomena, in fact, there is a great deal to try to avoid such an interactions, [2].

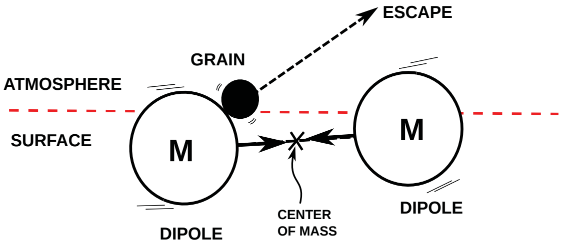

FIG. 1: Saltation induced process by magnetic interaction between two dipoles

II. METHODS

A. assumptions

The difficult which arose when attempting to analyze the proposed mechanism, lie in the complexity of the dynamic problem which in addition with the substantial uncertainties in the magnitude of several parameters not known with high precision today allows only a first theoretical assessment. The simplifying assumptions utilized in the analysis and a short discussion of their validity follows:

(a) Only a single knock-on collision is considered. Therefore, neither multiple dipole collisions with a given grain particle or slowing dow with media is considered. Calculation using elastic scattering laws shows this to be an reasoned assumption.

(b) Both dipoles have the same magnetization with the

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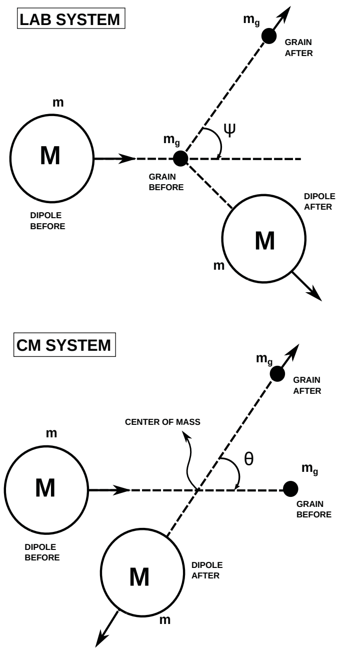

FIG. 2: Grain particle elastic scattering in laboratory (LAB) and center of mass (CM) systems.

same diameters. Due to the multiplicity of possibilities, it seems that the most representative would be to assume that magnetic agglomeration and growth of magnetic clusters is more or less homogeneous and then in average each magnetic aggregate has the same magnetization and the same size.

B. analysis

The actual situation from our generalized model is shown in Fig. 1. In this, two dipoles located at the surface are being accelerated each other to their center of mass located in between. This situation occurs when both dipoles are close enough to overcome the rolling drag force opposing the motion, and this may be ignited by the action of typical Martian winds which although insufficient for direct entrainment of grains into the atmosphere by air shear, however strong enough for moving sands and then renewing the soil from consolidate magnetic big clusters and promoting the formation of new ones and grain pilling up. Now, during its accelerated travel to the center of mass, the dipole can eventually hit some grain and the exchanging momentum as depicted in Fig. 1. The energized grain can then escape the surface.

With this rather simple picture we can infer some theoretical estimations of the proposed mechanism.

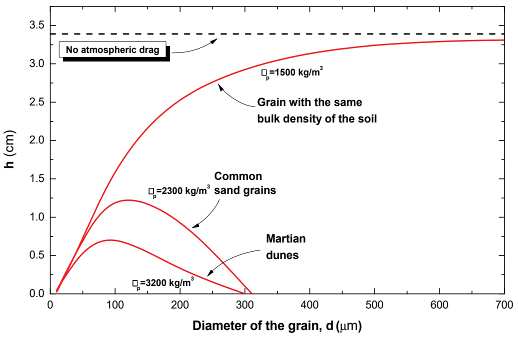

FIG. 3: The maximum height attained by a grain ejected from the surface by collision with a dipole as function of the diameter of the grain

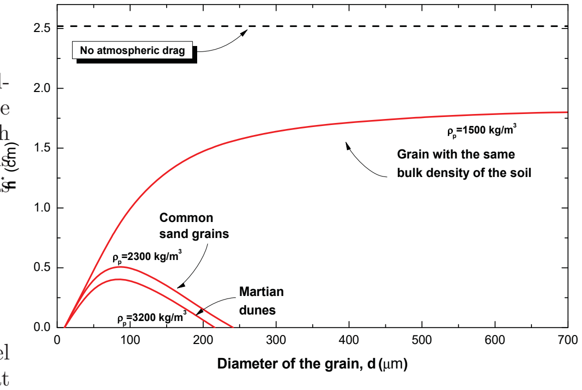

FIG. 4: The most probable height attained by a grain ejected from the surface by collision with a dipole as function of the diameter of the grain

To begin with, let us analyze the minimum density of dipoles required to develop a continuous dipole-dipole interaction on the surface of Mars. This can be made as follows:

First, the magnetic force between two aligned dipoles with the same magnetization M and the same diameter d_p (according with our simplifying assumptions) and separated by a distance r is given by, [2],

$$F_m = \frac{\mu_o \pi M^2}{24} \frac{d_p^6}{r^4} \tag{1}$$

On the other hand, if the dipoles are separated by a distance r, then the density of particles per unit of area N may be roughly calculated as $N \approx \frac{1}{r^2}$ particles per unit of area, and then, Eq.(1) may be rewritten as

$$F_m \approx \frac{\mu_o \pi M^2 d_p^6 N^2}{24} \tag{2}$$

On the surface this force must be balanced by the rolling friction force given by

$$F_f = \frac{\rho_p \pi d_p^3 g c_d}{6} \tag{3}$$

where ρ_p is the density of the dipole (mass per unit of volume), g is gravity, and c_d the rolling friction factor. By equating Eq.(5) and Eq.(3) we obtain that the critical density required for magnetic agglomeration yields

$$N_c = \frac{2}{M} \sqrt{\frac{\rho_p g c_d}{\pi \mu_o d_p^3}} \tag{4}$$

Likewise, the critical distance r_c in which magnetic dipolar interaction overcomes frictional opposing forces is given by $N_c \approx \frac{1}{r_c^2}$ which yields

$$r_c = \left[\frac{\mu_o M^2 d_p^3}{4 \rho_p g c_d} \right]^{\frac{1}{4}} \tag{5}$$

- **Discussion**

Although the magnetization of particles on Mars is not known with high precision, nevertheless it has been estimated around $\approx 3 \times 10^4$A/m [3]; the density of the grain of soil around 3.2×10^3 kg/m^3 and Martian particles with diameters 600 μm , [4]; $g = 3.711$ m/s^2; $\mu_o = 4\pi \times 10^{-7}$ H·m, assuming a conservative large rolling drag factor around $c_d = 1.0$, with these values one obtains $N_c \approx 25$ particles per cm^2. This represent a critical distance around of $\approx 2000\mu$m for particles with diameter 600 μm.

C. momentum considerations

In previous section it was assessed if the conditions for magnetic clustering and growth were satisfied in terms of the minimum critical density required. It was found that at the surface the dipole-dipole activity is a process highly probably.

In this section we will analyze what will be the fate of the particle of dust wince is knocked out by the dipole up to finally "escape" or is absorbed by the media.

To begin with, the kinetic energy E_g which can gain the grain after the collision with a dipole with kinetic energy E_m is given in the LAB system by, [5]

$$\frac{E_g}{E_m} = \frac{4 m_g m}{(m_g + m)^2} \cos^2 \psi \tag{6}$$

where m_g and m are the mass of the target grain and the dipole, respectively; ψ is the angle through which m_g is deflected in the LAB system. The mass of the dipole could be more or less the same than the grain, however, a more conservative assumption (reducing the kinetic energy of the ejected grain) is to assume that because the magnetic agglomeration, dipoles they growth forming clusters heavier than grains, i.e., $m \gg m_g$ and then Eq.(6) simplifies as

$$\frac{E_g}{E_m} \approx 4 \cos^2 \psi \frac{m_g}{m} \tag{7}$$

The energy of the dipole E_m can be calculated taking into account that each dipole is approaching each other towards their center of mass. Because both dipoles were initially at rest, then the center of mass is always at rest and then the maximum kinetic energy which can be transported by a dipole will be a half of the total kinetic energy of the two dipole system (approaching each other with the same velocity towards their center of mass). Therefore, the kinetic energy of a single dipole is given by

$$E_m = \frac{\mu_o \pi M^2}{144} \frac{d_p^6}{r^3} \tag{8}$$

and the maximum energy of the dipole at the moment of collision with the dust particle will occur when when $r \to d_p$, i.e., just before the collision with the other dipole at the center of mass, therefore, Eq.(9) simplifies as

$$E_m \approx \frac{\mu_o \pi M^2 d_p^3}{144} \tag{9}$$

Inserting the above equation into Eq.(10), the maximum kinetic energy E_{max} gained by the grain target with $\cos^2 \psi = 1$, yields

$$E_{max} = \frac{\mu_o \pi M^2 d_p^3}{36} \frac{m_g}{m} \tag{10}$$

Taking into account that $m = \frac{\rho_p \pi d_p^3}{6}$, Eq.(10) becomes

$$E_{max} = \frac{\mu_o M^2 m_g}{6 \rho_p} \tag{11}$$

D. The maximum height

Once the grain is ejected from the surface after the collision with the dipole, the maximum altitude attained if atmospheric drag is neglected is given by the total conversion of the initial kinetic energy of the grain i.e., E_{max} into gravitational potential energy, $m_g g h$, yielding

$$h = \frac{\mu_o M^2}{6\rho_p g} \tag{12}$$

A more accurate calculation implies considering the atmospheric drag force. This force may be approximated by using the Stokes law assuming a viscous uniform drag, and creeping motion in the vertical-direction. This is justified if we consider that Reynolds number are expected to be no higher than 100 or thereabouts, Almeida et al. (2008). Therefore, the momentum equation is given by

$$m_g \ddot{h} = -m_g g - 3\pi\eta d\dot{h} \tag{13}$$

where $\ddot{h}$ and $\dot{h}$ are the vertical acceleration and velocity of the grain at time t, respectively; η is the dynamic viscosity of the atmosphere; and d the diameter of the grain. Considering the initial condition $\dot{h}(t=0) = \sqrt{\frac{2E_{max}}{m_g}}$, Eq.(13) is easily solved and yields

$$h(t) = -\frac{m_g g t}{3\pi\eta d} + \frac{m_g}{3\pi\eta d}\left[\sqrt{\frac{2E_{max}}{m_g}} + \frac{m_g g}{3\pi\eta d}\right]\left[1 - e^{-\frac{3\pi\eta d t}{m_g}}\right] \tag{14}$$

and considering Eq.(11) and $m_d = \frac{\pi\rho_d d_d^3}{6}$ where ρ is the density of the grain which may be assumed equal than the dipole, i.e., $\rho \approx \rho_p$, Eq.(14) becomes

$$h(t) = -\frac{\rho_p g d^2 t}{18\eta} + \frac{\rho_p d^2}{18\eta}\left[\sqrt{\frac{\mu_o M^2}{3\rho_p}} + \frac{\rho_p g d^2}{18\eta}\right]\left[1 - e^{-\frac{18\eta t}{\rho_p d^2}}\right] \tag{15}$$

E. The most probable height

Eq.(15) was a derivation for the maximum height attained by a grain ejected after collision with a dipole, and in doing so, it was assumed that the grain is ejected in a straight vertical angle and then without horizontal compound. Nevertheless, the most probably situation is that dipole-dipole collisions occur in the horizontal plane, and then the grain must be ejected with a certain probabilistic angle following the mechanics of elastic scattering. To begin with, let us consider the collision of the grain with the dipole in the Lab system as well as the Center of Mass system as depicted in Fig. 2. Experiments indicate that the scattering between particles with energies lower than MeV, are spherically symmetric, i.e. isotropic, in the center of mass (**CM**) system, [6]. In other words, it appears from experiments that all values of $\cos\theta$ from -1 to $+1$ are equally probably.

The relationship between θ i.e., the angle through which m and m_g is deflected in the **CM** system and the angle ψ though which m_g is deflected in the **LAB** system, is given by [5]

$$\psi = \frac{\pi}{2} - \frac{\theta}{2} \tag{16}$$

Therefore, if scattering is spherically symmetric in θ, it will also be so in ψ.

The average cosine of the scattering angle ψ -in the **Lab** system, is given by

$$\bar{\beta} = \frac{\int_0^\pi \cos\psi d\Omega}{\int_0^\pi d\Omega} \tag{17}$$

where $d\Omega$ is an element of solid angle. Taking into account that $d\Omega = 2\pi\sin\theta d\theta$ and the relationship between angles at the Lab and Cm systems given by Eq.(16) it is found that

$$\bar{\beta} = \frac{2}{3} \tag{18}$$

and then the most probably height $h^*(t)$ is given by

$$h^*(t) = -\frac{\rho_p g d^2 t}{18\eta} + \frac{\rho_p d^2}{18\eta}\left[\sqrt{\frac{\mu_o M^2(1-\bar{\beta}^2)}{3\rho_p}} + \frac{\rho_p g d^2}{18\eta}\right] \times$$

$$\left[1 - e^{-\frac{18\eta t}{\rho_p d^2}}\right] \tag{19}$$

and considering Eq.(18) becomes

$$h^*(t) = -\frac{\rho_p g d^2 t}{18\eta} + \frac{\rho_p d^2}{18\eta}\left[\sqrt{\frac{5\mu_o M^2}{27\rho_p}} + \frac{\rho_p g d^2}{18\eta}\right]\left[1 - e^{-\frac{18\eta t}{\rho_p d^2}}\right] \tag{20}$$

III. RESULTS

A. Analysis

In order to obtain some idea of the shape of the curve predicted by Eq.(15) and Eq.(20) for the maximum and the most probably height, respectively, we assume some values of the parameters: The magnetization of particles on Mars is not known with high precision, but has been estimated up to a $\approx 3 \times 10^4$A/m [3]; $g = 3.711$ m/s^2; $\mu_o = 4\pi \times 10^{-7}$ H·m; particle densities can be found as low as $\rho_p = 2300$ kg/m^3 for common sands White (1979) up to $\rho_p = 3200$ kg/m^3 for typical Martian dunes [4]. The dynamic viscosity of the Martian atmosphere can be calculated as function of temperature T, using the Suterland´s formula, [7]

$$\eta = \eta_o \left[\frac{T_o + C}{T + C}\right] \left(\frac{T}{T_o}\right)^{\frac{3}{2}} \tag{21}$$

where for CO$_2$ we have $\eta_o = 1.48 \times 10^{-5}$ kg/ms, $C = 240$, and $T_o = 293.15$ K. Therefore for the range of temperatures on the surface of Mars a representative $\eta_o = 1.0 \times 10^{-5}$ kg/ms is assumed. The resulting curves are shown in Fig. 3 and Fig. 4 for the maximum and most probably height, respectively., and considering typical densities for sands of Mars. Also the possibility that some grains share the same density than the bulk density of the soil -which can be as low as $\rho_p = 1500$ kg/m^3 or less, [8] is plotted. It is seen that for typical sands the attainable height could be around 0.5-to.1.5 cm and with a maximum efficiency fo grains with diameters $\approx 100\mu$ m. The case for grain with densities close to the bulk density of the soil (which implies porosities around 60% ,[8] shows that an asymptotic height ≈ 3.3 cm is attained.

IV. DISCUSSION AND CONCLUSIONS

A new type of particle ejection mechanism driven by magnetic dipole-dipole collisions on the surface of Mars was investigated. The preliminary results are showing that grain of soil could be ejected after the collision with energetic dipoles up to a maximum height between ≈ 0.7 cm to ≈ 1.2 cm for Martian dunes and common sands, respectively, and with the most probable height around 0.5 cm and with a diameter of the grain around 100 μm. The mechanism can works in a cooperative way with the wind to trigger dust storms. In fact, even when the stress forces exerted by the air are only enough to roll the particle around the point of contact with the surface (reptation), however, this soft wind can induce the approaching of dipoles and then promoting dipole-dipole collisions which by the mentioned momentum exchange with the surrounding grains can ignite saltation.

NOMENCLATURE

c = rolling drag coefficient
d = diameter of the particle
E = energy
F = force
g = gravity
h = height
m = mass
M = magnetization
N = number of particles per unit of area
r = distance between dipoles
T = temperature
z = altitude

Greek symbols

$\bar{\beta}$ average cosine of the angle ψ
μ_o permittivity of free-space
η dynamic viscosity
ρ density of the particle
ψ angle of deflection in the LAB system
θ angle of deflection in the CM system
Ω solid angle

subscripts symbols

c critical
f friction
g grain
m magnetic
p particle
1 before collision
2 after collision

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V. REFERENCES

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