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An insolation activated dust layer on Mars

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ABSTRACT

The illuminated dusty surface of Mars acts like a gas pump. It is driven by thermal creep at low pressure within the soil. In the top soil layer this gas flow has to be sustained by a pressure gradient. This is equivalent to a lifting force on the dust grains. The top layer is therefore under tension which reduces the threshold wind speed for saltation. We carried out laboratory experiments to quantify the thickness of this activated layer. We use basalt with an average particle size of 67 μm. We find a depth of the active layer of 100–200 μm. Scaled to Mars the activation will reduce threshold wind speeds for saltation by about 10%.

1. Introduction

It is a long standing problem how to move particles on the martian surface. The most prominent mechanism is wind in analogy to transport of sand on Earth. Numerous work has been carried out on this in the past especially in wind tunnel experiments (Greeley et al., 1980, 1992; White et al., 1997).

Recent images of the HiRISE camera onboard the Mars Reconnaissance Orbiter show that martian sand transport is still active. They find dunes which travel several meters in a few years (Bridges et al., 2012). However, a problem encountered in the explanation of particle lift is that wind alone requires rather large speed to initiate saltation. The pressure on Mars on average is only 6 mbar in contrast to 1000 mbar on Earth. This reduces the dynamic pressure of a gas flow strongly. A speed of 30 m/s is supposed to be necessary to pick up the most susceptible particles of 100 μm in size (Greeley et al., 1980). High tangential wind speeds in vortices might also mobilize particles. Obviously, dust devils bear witness of dust lifting. Visible dust devils come in a variety of sizes (Lorenz, 2009). The largest ones might easily lift dust. However, Stanzel et al. (2008) and Reiss et al. (2014) find wind speeds (tangential and transversal) which are not always large enough. Also, Reiss et al. (2009) observed dust devil activity on Arsia Mons. This relates to an atmospheric pressure of only 2 mbar which requires still larger wind speeds.

There have been suggestions to support or ease particle lift one way or the other. The choice of particles to be picked up has been varied in wind tunnel experiments. As an example, the rolling of volcanic glass particles might reduce threshold speeds (de Vet et al., 2014). The pressure within dust devils is reduced compared to ambient conditions. It has been proposed that the traverse of such a pressure minimum might be sufficient to lift dust (Balme and Hagermann, 2006). Last not least and connecting to the work presented here, Wurm and Krauss (2006) found that illumination of a dust bed at low pressure provides a lift. This was applied to Mars by Wurm et al. (2008). Especially this latter effect is strongly depending on ambient pressure in a maybe non-intuitive way. Wind or gas drag and dynamic pressure decrease with decreasing pressure. The induced lifting force of an insolated surface can increase to lower pressure by orders of magnitude in strength. The force peaks around Knudsen numbers of $Kn \approx 1$, where Kn is the ratio between the mean free path of the gas molecules and the size of a particle or pore within the dust bed. Hence, for micrometer dust particles insolation supported lift is not important on Earth but maximized on Mars.

The model discussed for this lifting force so far included photophoretic forces, solid state greenhouse effects and gas compression by thermal creep (Kocifaj et al., 2011; Kelling et al., 2011; de Beule et al., 2013). These are important on long timescales (h) as current research is supporting (Koester et al., personal communication). However, here we consider gas flow through the dust bed and related pressure differences which was not included in the earlier models. This provides lift for a sample where illumination changes on short time scales of seconds or even fractions of seconds. The importance of this became obvious in microgravity experiments where de Beule et al. (2014) observed an efficient

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gas flow through an illuminated dust bed directed upwards. The effect is tied to the temperature profile within the illuminated dust bed.

The basic pumping is provided by thermal creep. For a constant temperature gradient pure thermal creep pumping does not require any pressure differences within the soil. However, the temperature profile along the top layer of an illuminated soil is rather flat as radiation is absorbed and thermally emitted. This layer cannot pump by thermal creep but has to keep up the thermal creep gas flow from below nevertheless. A pressure gradient is established close to the surface to do so. In accordance with Darcy's law the pressure increase below the surface transports the gas flow handed over by the Knudsen pump (thermal creep) below. Once set, this overpressure not only moves the gas but also acts on the dust particles. Particles within this top layer are under constant tension and can be ejected if cohesion and gravity can be overcome by any means. We call this an *insolation activated layer*.

We quantify the thickness of this layer here based on laboratory experiments. We illuminate a dust sample with sufficient light flux to compensate gravity. We then remove cohesion by short vibrations. This leads to a removal of the tension activated layer down to the pressure maximum and allows its thickness to be determined.

2. Sub-surface pumping

We detail the light induced sub-surface pumping in this section. The principle is shown in Fig. 1.

The light enters the dust bed and is absorbed. The heat is conducted further down into the dust bed. In addition, at the surface the dust bed can cool by thermal radiation. In consequence a temperature gradient is established starting a few particle layers within the dust bed (at depth x_1 in Fig. 1) and is directed to deeper layers. Temperature gradients always lead to a thermal creep gas flow in a porous medium, where gas is transported along the particles' surface from cold to warm. This was first introduced by Maxwell (1879) as thermal transpiration where two gas reservoirs

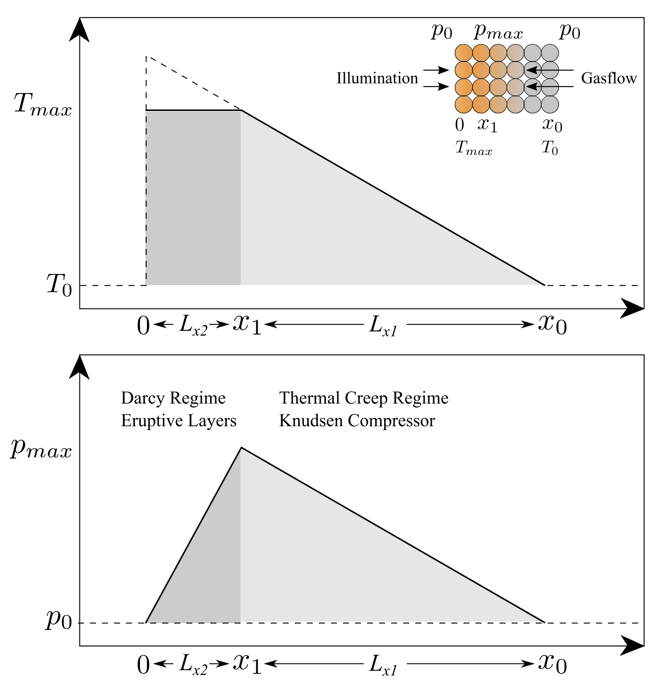

Fig. 1. Principle for pressure distribution for given temperature profile and open geometry (ambient pressure the same on both sides of the dust sample). L_{x2} marks the depth of the dust bed from 0 to x_1 with constant temperature and L_{x1} the part of the dust bed with a temperature gradient from x_1 to x_0.

with different temperatures are connected by a small channel in a low pressure environment. Gas molecules creep along the channel wall from cold to warm. If the diameter of the channel is comparable to the mean free path of the gas molecules the pressure driven back flow can be smaller than the thermal creep flow (Knudsen, 1909). In an illuminated dust bed the gas molecules creep from cool layers deep within the dust bed (x_0 in Fig. 1) upwards until the temperature levels off close to the surface at x_1.

If the temperature increase in Fig. 1 would be linear from x_0 to the surface there would be no pressure differences. Every sub-layer would just transport the same amount of gas by thermal creep. However, if there is a top layer of constant temperature the gas molecules do not creep along these particles all the way to the surface, but only to x_1. The thermal creep gas flow leads to a concentration of molecules and the pressure is locally increased.

The increase of pressure below the surface at x_1 leads to a pressure driven gas flow through the top layer. The pressure adjusts itself to a value where gas flow through the top layer matches the incoming thermal creep gas flow from below. Both aspects, the temperature gradient driven thermal creep gas flow (Knudsen compression) and the pressure driven gas flow (Darcy flow Darcy, 1856) are usually occuring in the same capillary. The mass flow of the gas through capillaries was described by Sone and Itakura (1990) and Muntz et al. (2002) as

$$\dot{M} = p_{avg} \frac{FA}{\sqrt{2 \frac{k_B}{\mu} T_{avg}}} \times \left(\frac{L_r}{L_x} \frac{\Delta T}{T_{avg}} Q_T - \frac{L_r}{L_x} \frac{\Delta p}{p_{avg}} Q_p \right) \tag{1}$$

where p_{avg} and T_{avg} are the average pressure and temperature within the dust bed, F is a factor giving the amount of capillaries within the surface area A, k_B is the Boltzmann constant, μ the molecular mass of the gas, L_r and L_x are the radius and length of the capillaries and ΔT and Δp are the temperature and pressure differences within the dust bed, respectively. The coefficients Q_P and Q_T depend on the Knudsen number and describe the pressure driven (back) flow and the flow by thermal creep, respectively. It has to be noted that the length of the capillaries L_x is different in the thermal driven $(L_{x1}, |x_0 \rightarrow x_1|)$ and the pressure driven $(L_{x2}, |0 \rightarrow x_1|)$ part.

If the dust bed is heated two mass flows develop. The first one $\dot{M}_1$ is dominated by thermal creep (Knudsen pump) due to the temperature gradient

$$\dot{M}_1 = p_{avg} \frac{FA}{\sqrt{2 \frac{k_B}{\mu} T_{avg}}} \times \left(\frac{L_r}{L_{x1}} \frac{\Delta T_{L_{x1}}}{T_{avg}} Q_T - \frac{L_r}{L_{x1}} \frac{\Delta p_{L_{x1}}}{p_{avg}} Q_p \right) \text{ with} \tag{2}$$

$$\frac{\Delta T_{L_{x1}}}{T_{avg}} Q_T > \frac{\Delta p_{L_{x1}}}{p_{avg}} Q_p \tag{3}$$

and the second one is driven by the pressure building up according to

$$\dot{M}_2 = p_{avg} \frac{FA}{\sqrt{2 \frac{k_B}{\mu} T_{avg}}} \times \left(0 - \frac{L_r}{L_{x2}} \frac{\Delta p_{L_{x2}}}{p_{avg}} Q_p \right), \tag{4}$$

as the top layer temperature is flat or $\Delta T_{L_{x2}} = 0$. It might be noted that the latter is also equivalent to a description by Darcy's law. In total, the flow velocity is set by the Knudsen pump within the dust bed and the overpressure which maintains that flow also in the top layer activating it by putting tension on the dust particles. If the force caused by this pressure gradient overcomes gravity and cohesion, particles can be lifted from the dust bed's surface.

To quantify the temperature profile and the resulting flow velocities and pressure differences we modeled the insolation of a dust bed as described in earlier work by Kocifaj et al. (2011). Fig. 2 shows the numerical simulation of a temperature profile in a dust bed consisting of 25 µm (radius) spheres. The calculations