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Amplification of dust loading in Martian dust devils by self-shadowing

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ABSTRACT

Insolation of the Martian soil leads to a sub-surface overpressure due to thermal creep gas flow. This could support particle entrainment into the atmosphere. Short time shadowing e.g. by the traverse of a larger dust devil would enhance this effect. We find in microgravity experiments that mass ejection rates are increased by a factor of 10 for several seconds if a light source of 12.6 kW/m^2 is turned off. Scaled to Mars this implies that self-shadowing of a partially opaque dust devil might lead to a strongly amplified flux of lifted material. We therefore suggest that self-shadowing might be a mechanism on Mars to increase the total dust loading of a dust devil and keep it self-sustained.

1. Introduction

It is still a challenge to explain dust entrainment within Martian dust devils. A current overview of lifting mechanisms can be found in Neakrase et al.. It includes gas drag (Greeley et al., 1980), pressure differences associated to a dust devils passage (Balme and Greeley, 2006) and thermal creep induced overpressures (de Beule et al., 2014; Küpper and Wurm, 2015). However, it is unclear if the necessary conditions (wind speed, pressure difference) are always met in the low pressure atmosphere on Mars.

This paper is not treating the initial formation of a dust devil in spite of all possible problems but assumes it to be existent. There is no doubt that dust devils can form as they have been observed frequently by now in different locations e.g. by rovers or satellite images (Greeley et al., 2006b; Reiss, Hoekzema and Stenzel, 2014).

While small dust devils might not be totally opaque, observations of larger devils show that they can be optically thick, casting shadows as they move (Greeley et al., 2006b; Reiss, Hoekzema and Stenzel, 2014). Depending on the size of a dust devil and its speed it takes several seconds to cross a spot of Martian soil along the trajectory. This implies that this spot, which is illuminated before the dust devil's arrival is shadowed for several seconds during the devil's passage. This change in illumination might have a severe impact on the dust flux lifted from the ground which is the focus of this work.

2. Illumination and lifting

By insolation the dust is heated. This heat can partly be reradiated from the surface as thermal radiation. The absorption length of infrared radiation is normally much shorter than for visible wavelength – therefore only the surface can cool efficiently, but heat is deposited along several layers at the top of the dustbed. Inside the dustbed thermal conduction and radiation between the single grains have to be considered. This results in a relatively flat temperature profile at the top and a decline to ambient temperature deeper inside the dust bed. If the illumination is switched off, the thermal radiation will quickly cool the surface, leading to a temperature profile with a maximum inside the dust bed.

In rarefied gases temperature gradients have peculiar consequences. The Knudsen effect (Knudsen, 1909) is important here, as it states that in equilibrium the pressures p in two chambers communicating through a capillary smaller than the mean free path of the gas is determined by their temperatures T

$$\frac{p_1}{p_2} = \sqrt{\frac{T_1}{T_2}}. \qquad (1)$$

If not in equilibrium, the associated mass flow rate of the gas $\dot{M}$ can be described for an indefinite capillary with a temperature gradient as (Muntz et al., 2002)

$$\dot{M} = p_{avg} \frac{A}{\sqrt{2\frac{k_B}{m}T_{avg}}} \left(\frac{L_r}{T_{avg}} \frac{\Delta T}{L_x} Q_T - \frac{L_r}{p_{avg}} \frac{\Delta p}{L_x} Q_p \right), \qquad (2)$$

where p_{avg} is the average pressure in the capillary, T_{avg} the average temperature, A is the cross section of the capillary, L_r its radius, L_x its length, k_B is the Boltzmann constant, m the molecular mass of the gas, ΔT is the temperature difference across the capillary, Δp

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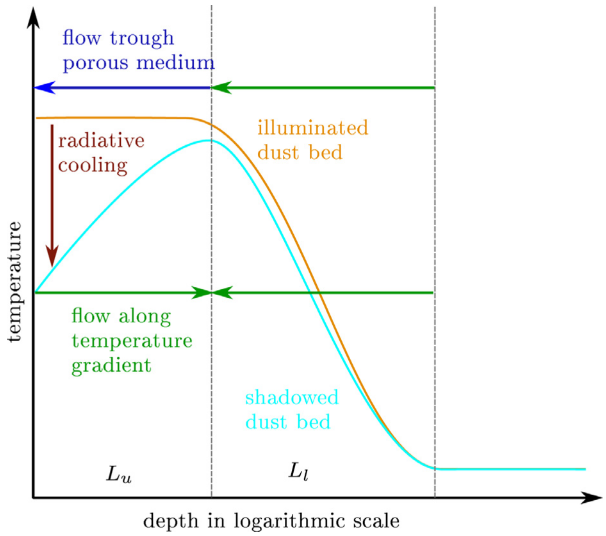

Fig. 1. Sketch of the influence of a shadowed region. A detailed calculation is done in Kocifaj et al. (2011). For the illuminated dust bed the temperature gradient induced thermal creep pumps gas from the deeper layers upwards. The flat temperature profile at the top leads to an overpressure inside the dust bed, as there is only pressure driven flow through the pores here. If the illumination is switched off, the surface cools by thermal radiation. This reversed temperature gradient enhances the sub-surface pressure.

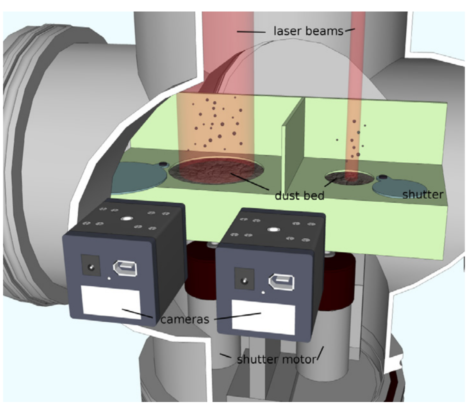

Fig. 2. Sketch of the experiment. Two different dust beds are placed in a vacuum chamber and illuminated with lasers from above. During catapult launch, the dust is protected by a shutter.

the pressure difference, Q_T and Q_p are the coefficients of thermal and pressure driven flow and depend on the Knudsen number (see Sone and Itakura (1990)).

The details will depend in a complex way on particle optical properties, dust bed morphology, time evolution of the ejections themselves, heat transfer and so on. We do not aim to construct a detailed model at this point but just quantify the ratio of ejected particle rates with and without illumination in measurements. Therefore, experiments have been carried out in microgravity at the drop tower in Bremen, where ejected particles can be observed without gravitational bias. Additional experiments using a centrifuge in parabolic flights provided data for low gravity of 0.3 g, close to Martian gravity.

3. Drop tower experiments

The principle of the experiment is straight forward (Fig. 2). The microgravity time for an experiment is about 9s.

A dust bed is sealed during launch of the experiment capsule by a lid. The dust bed is placed within a vacuum chamber which

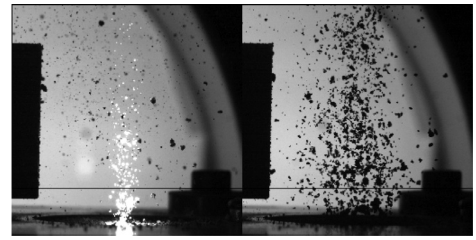

Fig. 3. Sample images of particle ejections with illumination (left) and after the light source is turned off (right) with the small laser spot. The region of interest, where particles are counted, is the whole area above the black line. Each image has a size of 3.4 cm.

is evacuated to 2 mbar pressure. Once microgravity is reached the cover is removed. The dust is then exposed to illumination. Illumination is provided by a diode laser. The laser is coupled into a glass fiber. The exiting light beam is shaped to provide an essentially parallel beam with a certain spot diameter on the dust bed surface. This illumination leads to particle ejections from the dust bed. Particles are observed by a camera from the side. The frame rate varied for the experiments considered between the two values of 1000 fps and 500 fps. The spatial resolution of the optical system is 68 μm/pixel. Illumination for the observations is provided by two means. First, scattered laser light provides imaging for particles ejected. In addition an illuminated background provides dark images of particles not within the laser light. During the course of an individual experiment the laser is turned off. Particles are now still visible in front of the illuminated background. Two slightly different configurations were used, one with a large infrared laserspot (955 nm wavelength, 3.4 cm spot diameter, 7 cm dust bed diameter, 2 cm dust bed depth, radiant flux at the surface of 12.7 kW/m^2) and one with a smaler red laserspot (655 nm wavelength, 5.5 mm spot diameter, 3 cm dust bed diameter, 2 cm dust bed depth, radiant flux at the surface of 12.6 kW/m^2).

The light sources were selected due to availability and limited number of microgravity experiments. Also, the high power available in IR allowed a larger spot diameter. It should be noted that this illumination differs from the solar spectrum. Ground based experiments of dust lifting with green and blue light do not suggest large differences in the relevant wavelength range but those are unpublished (de Beule, personal communication). Therefore, slight changes might have to be expected.

The dust sample was a JSC-1A Mars simulant (palagonite) which was heated for 1 h at 400°K to remove residual volatile components. The samples had a broad size distribution below 1 mm. The average particle size was 306 μm.

4. Data reduction

The light flux used induces particle ejections during illumination and an increased particle ejection once the light source is turned off. Sample images from the video sequence are shown in Fig. 3.

For the different experiments we used the following algorithm to deduce a ration between the ejected mass flux with and without illumination. From the video images with open lid at zero gravity, a median image was calculated. This background was subtracted from every image. The resulting images were binarized by setting a fixed brightness threshold. This outlines the particles illuminated by the laser. A second set of binarized images was generated in the same way to outline particles not illuminated by the laser by inverting the images first. Bright and dark particles were combined. Further image processing then provides the number of particles n and the average size A_P of individual particles. These are determined in a region of interest, which is always placed in the same