Light Induced Erosion of Dusty Planetesimals and Mars: $\mu g$ Experiments

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Abstract. In a number of recent experiments it was found that dust beds continuously eject small, micron sized particles under illumination at low ambient pressure. The ejection is caused by temperature gradients within the illuminated dust bed, which induce lifting forces based on thermal creep or photophoresis. In microgravity experiments we observed that the ejection rate depends inversely on the gravity level. Therefore, the effect is much more efficient in low gravity environments. This mechanism can help to understand processing of dust in protoplanetary disks, where it leads to the ejection of particles from an inward drifting body which would be lost to the star otherwise. The mechanism also supports entrainment of dust into the martian atmosphere. Windspeeds are in general too low to pick up dust from the surface by gas drag alone. In contrast to gas drag light induced drag increases in strength at low ambient pressure and has a maximum in the mbar range prevailing on Mars. The interplay of gas drag and light induced lift might explain the existence of dust devils and dust storms on Mars.

1. Introduction
Dust particles composed of $\mu$m sizes are frequently observed in the martian atmosphere and often related to dust devils and (global) dust storms [1]. To date, it is not fully understood how adhering dust particles can be lifted from the martian surface into the atmosphere at the low atmospheric pressures (mbar) on Mars. Particle pick up by gas drag would be the classical mechanism but the mean wind speeds on Mars are in general too low to lift particle by gas drag alone [2–4]. The need for additional lift finds special emphasis by the fact that even at high elevations of several km like e.g. inactive volcanoes active dust devils were found [5]. Here, the ambient pressure is only 1 to 2 mbar. Additional lifting support has to be present, one suggestion, e.g. being a pressure decrease in the center of active dust devils [6]. However, Wurm and Krauss (2006) found a lift of dust particles which are illuminated at low ambient pressure of a few mbar [7]. Applying the experimental findings it was shown that the interplay of atmospheric gas drag and photophoresis might lead to dust particle eruptions from the martian surface [8]. The physical mechanisms are photophoresis and sub-surface pressure increase by thermal creep which obviously can efficiently pull on particles from dusty surfaces [7, 9]. Photophoresis is strongest if the particle size is comparable to the mean free path of the gas molecules [10] – which are just the conditions on Mars: mbar pressure and dust aggregates composed of $\mu$m sized particles.

The threshold for dust entrainment depends on gravity which has to be overcome. This is also true for photophoretic particle ejections which was verified in earlier microgravity experiments [8]. While these experiments determined the threshold intensity of the light flux needed to eject
particles at all, the reduced martian gravity should also enhance the mass rate (ejected particles per time) of the photophoretic ejections. To study this is subject of the experiments reported here.

Before doing so, it might be noted that Mars is not the only environment where the light induced ejection mechanism is of importance. Dust particles of $\mu$m size also play an important role in planet formation processes in protoplanetary disks [11]. Collisions of dust particles in the early phase of planet formation lead to particle growth [12–14]. At a certain size (decimeter to meter regime) bodies rapidly drift inward by gas drag (1 AU in hundred years) and might be accreted by their host star [15]. However, Kelling et al. (2011) showed that dusty bodies might lose up to kg/s by photophoretic and thermal creep ejections at a light flux of several $10^4$ W/m$^2$ [9]. Also here the pressure is in the ideal range for dust ejections with mbar or less, noting that strong variations might be possible [16]. Inward drifting planetesimals are therefore not lost by accretion but are (partially) eroded by the light induced ejection mechanisms. The ejected particles are transpoited, e.g. by photophoresis upwards or outwards in the disk and are hence reintroduced into the planet formation process [17]. In addition, Kelling and Wurm (2011) showed that small particles are produced by the photophoretic ejections which might be transported by turbulence to the surface of the protoplanetary disk [18]. Hence, the light induced ejection mechanisms might also explain why dust can be observed over the whole lifetime of a protoplanetary disk.

In this article we present $\mu$g experiments carried out on a parabolic flight addressing the efficency of the light induced erosion mechanism to complement the earth bound experiments and to estimate the efficiency of the erosion mechanism on bodies with reduced gravity (0.38$g$ on Mars and $\mu$g on planetesimals, $g = 9.81$ ms$^{-2}$).

2. Experiment

The setup of the experiment is shown in Fig.1. Basalt powder ($< 100\mu$m grain size) is placed within a vacuum chamber. The dust bed is illuminated by a red laser (light intensity is $\sim 20$ kW/m$^2$) at ambient pressure of $\sim 5$ mbar. The number of ejected particles over time is observed – Fig.2 shows an example of the ejected dust particles at the different g-phases and Fig.3 depicts the normalized average values of the released particles.

It is observed that the number of released particles increases with decreasing g-level.

3. Model

Similar to Kelling et al. (2011) we attribute the continuous ejections to a photophoretic force [9]. Photophoresis is a result of an interplay between the gas molecules and an inhomogeneously heated surface of a particle suspended in the gas (Fig.4). Gas molecules accommodating to the cold side of the suspended particle leave the particles surface with a smaller momentum than the gas molecules on the warm side. Hence, a force accelerates the particle in general in the direction from warm to cold. The temperature gradient over the particle’s surface is often established by illumination, therefore the name photophoresis. The photophoretic force strongly depends on the pressure and has its maximum if the mean free path of the gas molecules is comparable to the size of the particle [10]. For dust particles of $\mu$m size this corresponds to mbar pressures. The photophoretic force is [10]

$$F_{ph} = \frac{2F_{max}}{p} + \frac{p}{p_{max}},$$

where $p$ is the pressure and $F_{max}$ is the maximal photophoretic force, which appears at the pressure $p_{max}$. The coefficients $F_{max}$ and $p_{max}$ are discussed in [10] and depend on gas and
Figure 1. Experimental setup: Basalt powder (<100 µm) illuminated by a laser (~20 kW/m²) from the top at 5 mbar pressure. The number of ejected particles over time were observed.

Figure 2. Dust eruptions at different g-phases; 5 mbar ambient pressure; ~20 kW/m² light intensity on the dust bed; Basalt powder of <100 µm size.

particle properties.
Kocifaj et al. (2000) showed that illuminated dust beds develop an inverse temperature gradient pointing from a sub-surface temperature maximum towards the cooler surface [19]. The light heats the upper dust layers due to absorption. Only the upper most particle layers (the surface) of the dust bed cools by thermal radiation while the deeper layers transport the heat mainly through conduction. Consequently a sub-surface temperature maximum of several Kelvin at typical depth’s of some 100µm below the surface is established. Fig.5 shows an example of the temperature distribution within an illuminated dust bed [19]. Due to the reversed temperature gradient the surface aggregates in our experiments are effected by a photophoretic force pointing
Figure 3. Normalized number of ejected particles over time. Blue line (trend for normalized number of ejected particles), red line (value of the maximum in the 0g phase), orange line (average of the 1g phase), green line (average of the 2g phase). 0g, 1g and 2g mark the different g-phases.

Figure 4. Photophoresis: Gas molecules accommodating to the cold side of the suspended particle with a temperature gradient over its surface leave the surface with a smaller momentum than the gas molecules on the warm side. As a result, a force accelerates the particle in the direction from warm to cold.
Figure 5. Evolution of the temperature within an illuminated dust bed after a light source of $I = 10 \text{ kW m}^{-2}$ is switched on. Times in seconds are (lines from bottom to top): 0.1, 1.0, 5.0, 10.0, 30.0, 100.0, 500.0 and 3600.0 [19].

Figure 6. Principle of the photophoretic ejections: The continuous ejections of single particle agglomerates are caused by photophoresis. If the induced photophoretic force overcomes gravity and the cohesion forces at the weakest connection, a surface agglomerate is released into the surroundings [9].

In the direction from warm to cold and hence away from the surface (Fig.6). If the photophoretic force $F_{ph}$ overcomes the cohesion between the aggregates $F_c$ and gravity $F_G$

$$F_{ph} > F_c + F_G,$$ (2)

dust particles are continuously ejected from the surface into the surroundings.

In contrast to the linear gravity dependency of the threshold of the particle ejections found by Wurm et al. [8] the analysis of the experimental data of the efficiency (particles per time at the different g-levels, see also Fig.3) of the particle ejections revealed an $1/g$ dependence on the gravity level (Fig.7).
Figure 7. Averaged and normalized number of ejected particles over gravity with standard deviation. The fitted function is of the form \( N = \frac{1}{1 + \xi \cdot g} \), where \( g \) is the gravity and \( \xi = 21.2507 \) s/m\(^2\) the fitted parameter.

For a given dust sample the dependency of the number of ejected particles (mass loss rate) \( N \) can be written as

\[
N \propto \frac{1}{1 + \xi \cdot g},
\]

(3)

where \( g \) is the gravitational acceleration and \( \xi \) is a factor containing all other parameters like e.g. gas parameters. Due to the complexity of the process which depends on particle size, porosity, optical constants, adhesion, thermal conductivity etc. we do not argue in more detail on the fitting parameter \( \xi \) here and leave this to future studies.

The size dependence of the effect is still unclear. While the adhesion of a small particles might dominate over gravity large aggregates only bound by few contacts might be lifted more easily.

4. Applications and Conclusion

In common planet formation scenarios inward drifting bodies are rapidly lost by accretion (meter-size barrier, [15]). As Kelling et al. (2011) and Kelling and Wurm (2011) showed, inward drifting bodies are (partially) eroded by the discussed erosion mechanism [9, 18]. The produced small particles are reintroduced into the planet formation process as they are transported radially outwards (by e.g. photophoresis) in the disk where they can take part in a re-aggregation process (Fig.8). With the help of the light induced particle ejections the problem of the meter-size barrier is somewhat eased. Small ejected particles might also be transpoted upwards (by e.g. turbulence) to the disks surface which gives an explanation why dust is observed over the whole lifetime fo a protoplanetary disk. The results of the \( \mu g \) experiments show that the erosion mechanism is strongly enhanced towards lower g-levels. Hence, the efficiency of the erosion of inward drifting bodies must be corrected towards a faster, more effective erosion. Wurm et al. (2008) showed that dust particles on Mars can be ejected from the surface by photophoresis – if the cohesion is reduced [8]. With the results of our \( \mu g \) experiments one can draw the conclusion that also here the mass rate of ejection benefits from the reduced gravity and might explain how dust gets entrained into the Martian atmosphere with sufficient rate though details are subject to future analysis and work.
Figure 8. Principle of re-aggregation process in protoplanetary disks. An inward drifting body ejects small particles, which can be transported outwards again by e.g. photophoresis.

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