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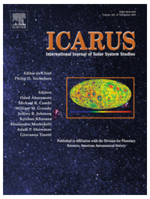

Experimental investigation of insolation-driven dust ejection from Mars' CO_2 ice caps

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ABSTRACT

Mars' polar caps are – depending on hemisphere and season - partially or totally covered with CO_2 ice. Icy surfaces such as the polar caps of Mars behave differently from surfaces covered with rock and soil when they are irradiated by solar light. The latter absorb and reflect incoming solar radiation within a thin layer beneath the surface. In contrast, ices are partially transparent in the visible spectral range and opaque in the infrared. Due to this fact, the solar radiation can penetrate to a certain depth and raise the temperature of the ice or dust below the surface. This may play an important role in the energy balance of icy surfaces in the solar system, as already noted in previous investigations. We investigated the temperature profiles inside CO_2 ice samples including a dust layer under Martian conditions. We have been able to trigger dust eruptions, but also demonstrated that these require a very narrow range of temperature and ambient pressure. We discuss possible implications for the understanding of phenomena such as arachneiform patterns or fan shaped deposits as observed in Mars' southern polar region.

1. Introduction

The Martian polar caps are currently the only assured naturally occurring carbon dioxide ice deposits in the inner solar system and they are one of the most active geological features on the Martian surface. Both polar caps are seasonally covered with CO_2 ice. While at the northern polar cap the CO_2 ice sublimes during the summer season uncovering a base of H_2O ice, there is a perennial and seasonal CO_2 ice deposit at the southern polar cap (Bibring et al., 2004; Langevin et al., 2005). In the areas surrounding the polar caps phenomena that have no terrestrial analogues can be observed. An example is the so-called 'cryptic region', a dark region covered by ice in the southern polar area (Kieffer et al., 2000; Titus et al., 2008). Here, dark surface features can be found that have a low visible albedo, close to that of bare Martian soil, and at the same time a low surface temperature, approximately the sublimation temperature of CO_2 ice - two properties that seem to contradict each other. This 'albedo-temperature paradox' can be explained by the assumption that a large fraction of the solar flux penetrates a layer of CO_2 ice and is absorbed either by the dust underneath or in a dust layer inside the CO_2 ice cover. Another possible explanation for this effect is described by Langevin et al, (2006). They mention that in early spring the CO_2 ice layer is covered by a thin dust layer and that, in case of thermal equilibrium of ice and dust, a similar signature in the temperature and albedo observations would be recorded.

Some of the most dominant features that can be observed in the cryptic region are the so-called arachneiforms, or 'spiders', branching radial troughs or channels diverging from one common centre (e.g. Kieffer et al., 2000; Piqueux et al., 2003; Portyankina et al., 2010, 2012). A possible explanation for the formation of these geomorphic features is the so-called 'solid-state greenhouse effect', further on denoted as SSGE, a phenomenon similar to the atmospheric greenhouse effect (Brown and Matson, 1987; Fanale et al., 1990): sunlight can penetrate the CO_2 ice layer down to a dust deposit at depth where the radiation is absorbed, with the heat increase leading to sublimation of the CO_2 ice on the boundary between the ice layer and the underlying dark material. As gas pressure increases, the overlaying ice fractures where it is weakest, leading to gas ejections that transport entrained dust to the surface. The SSGE was also considered as a possible explanation for geyser–like eruptions observed on Triton by Voyager 2 (see Soderblom et al., 1990).

A number of researchers have explored the theoretical aspects of this topic (e.g. Matson and Brown, 1989; Fanale et al. 1990; Portyankina et al., 2010). However, only few results of laboratory measurements of sub-surface heating caused by irradiation could be found in literature (see e.g. Dissly et al., 1990; Kaufmann et al., 2006).

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In a series of experiments, de Villiers et al. (2012) showed that a pressure-gradient-driven gas flow inside granular media can lead to erosion that produces patterns similar to the spider-like structures observed on Mars. This supports the theory that spiders are the results of venting of CO_2 gas. Further laboratory experiments concerning the influence of solar radiation on CO_2 ice and dust have been performed recently by Philippe et al., 2015, but, as far as it is known to the authors, no results from experiments showing the formation and influence of pressure gradients inside CO_2 ice under Martian conditions have been published so far.

Based on work by Kaufmann et al. (2006), who investigated the solid state greenhouse effect on various materials such as clear compact H_2O ice and glass beads with and without absorbing layers, we investigated the behaviour of CO_2 ice under Martian conditions in a series of experiments. These experiments may contribute to our understanding of the phenomena observed on Mars. Note that our aim is not to advance the underlying theory, nor give any quantitative explanation for this phenomenon, which (after careful laboratory simulations) turns out to be a remarkably complex process. However, by presenting the results of a long series of resource-intensive experiments and our interpretation of the phenomena observed, we are hoping to elucidate some of the open questions surrounding the processes taking place in Mars' cryptic region.

2. Laboratory experiments

We have observed the behaviour of CO_2 ice slabs containing a dust layer under insolation in Martian conditions. The measurements were intended to improve our understanding of the phenomena observed in the cryptic regions on Mars, although the CO_2 ice samples were not produced under Martian conditions. Nevertheless, our ice slabs were produced directly from the gas phase. For this purpose, a pressure vessel was continuously flooded with CO_2 gas at a pressure of about 1.5 to 2 bar. The base of the vessel was cooled by immersing it in a bath of liquid nitrogen while the top of the vessel was kept at a temperature above 193 K, i.e. although the partial pressure of the gas is higher than on Mars the temperature during ice deposition is in a similar range. The gas froze from the base upwards, which resulted in blocks of translucent CO_2 ice. This method is based on Behn (1900).

The ice samples are of polycrystalline structure and have an average density of $1570\,\mathrm{kg/m^3} \pm 110\,\mathrm{kg/m^3}$. They were almost perfectly transparent on mm to cm scales. The large number of cracks and fissures in the ice reduced the transparency but, although the final sample was only translucent, the dust layer inside could clearly be seen, i.e. the light could penetrate down to the dust layer with only very little scattering. The white-ish appearance of our samples in the images is mainly caused by H_2O frost forming on the samples immediately as they were taken out of the chamber. Especially in Fig. 3 the H_2O ice crystals settled can clearly be seen.

Although the pressure during the ice growing process was much higher than on Mars, the samples are still an appropriate starting point for investigations of the solar influence on CO_2 ice layers at the Martian polar caps. The absorbing layers were obtained by adding Mars analogue material (JSC Mars-1A) in different grain size ranges to the samples by pouring a certain amount of dust on the surface of one ice block and putting a second ice block on top of it. The crack between the two blocks was then sealed with ice before the experiment was started.

The basic set-up for all the experiments was the same: a cylindrical block of CO_2 ice, with an initial diameter d_s of 12.5 cm and a height h_s between 6 and 10 cm, including a layer of dust, was put on a cooled base plate in a vacuum chamber. The temperature profile inside the sample during the experiment was measured using RTD temperature sensors (PT100). During the experiments the environmental chamber was cooled down by using liquid nitrogen and a temperature control system to temperatures of 150 K or below and depressurised to values below 10 mbar. The samples were irradiated using a solar simulator[1] and the temperature profile inside the sample was measured whilst ambient pressure was monitored. Additionally, a time lapse record of the morphology of the sample during the irradiation phase was obtained using a set of commercial off-the-shelf webcams. A sketch of the sample preparation and the measurement set-up is given in Fig. 1.

2.1. Measurements using unsorted dust

Samples were prepared by stacking two slabs of CO_2 ice, with approximately 1 g of JSC Mars-1A dust (grain size $d \leq 1$ mm, randomly distributed) centred on the surface of the lower slab. The dust was concentrated within a circle approximately 8 cm in diameter. The two slabs were re-introduced into the pressure vessel, which was then flooded with CO_2 gas whilst being cooled from the base and heated at the top, as outlined above. This procedure leads to a sealing of the gap between the two slabs by resubliming CO_2 gas. The result is a compact sample with a dust layer inside. PT100-sensors were inserted into holes drilled into the ice block with a vertical spacing of 1 cm. It has to be noted that simply inserting sensors into drill holes led to non-optimal thermal contact between the sensors and the sample.

The fundamental conditions for these experiments were identical: the copper base plate was pre-cooled to $T_0 \sim 150$ K. In the following, we will refer to the temperature T_0 of the base plate as 'base temperature'. The pressure inside the environmental chamber was kept at approximately 5.3 mbar and the samples were irradiated with an intensity of 650 $\mathrm{Wm^{-2}}$, an intensity that is higher than at the Martian polar caps, since these experiments were meant to prove the concept that a pressure increase inside CO_2 ice can lead to observable dust eruptions. This leads to a higher energy input within a short time period and therefore reduces the experiment's run time which is constrained by the supply of liquid nitrogen for cooling.

However, the duration of the irradiation phase and the height of the samples varied (see Table 1 for details). During the experiments no additional CO_2 was introduced into the chamber which means that any additional deposition of CO_2 ice on the sample was avoided. The change of the sample was captured from two different angles during the experiment (top view and side view). No signs of dust ejection could be found in the time lapse footage or in the environmental chamber. Neither did careful examination of the samples after insolation suggest that dust had erupted from the slab.

With regard to the SSGE, no definite temperature maximum below the surface could be detected unambiguously and quantitative reproducibility of the temperature recordings was rather poor. This is partly owed to the fact that the *p-T* regime is largely influenced by the sublimation and deposition of CO_2 and the associated exchange of latent heat which affects temperature measurements. Nevertheless, careful examination of the sample after irradiation showed clear evidence of the influence of solar radiation on the temperature of the dust layer. The radiative energy absorbed by the dust had caused the surrounding ice to sublime, with the dust sinking through the ice, leaving a cavity in its wake, as shown in Fig. 2. Ice channels created by the dust particles, or needle-like ice features that remained around those channels were what defined these experiments with a random mix of dust grain sizes. These features could clearly be seen when the sample was cut in half. For dust particles towards the large end of the grain size range, a

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[1] LS1000R3 Solar Simulator, Solar Light Company, Inc. including AM0 filter

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