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Ephemeral liquid water at the surface of the martian North Polar Residual Cap: Results of numerical modelling

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ABSTRACT

Gypsum, a mineral that requires water to form, is common on the surface of Mars. Most of it originated before 3.5 Gyr when the Red Planet was more humid than now. However, occurrences of gypsum dune deposits around the North Polar Residual Cap (NPRC) seem to be surprisingly young: late Amazonian in age. This shows that liquid water was present on Mars even at times when surface conditions were as cold and dry as the present-day. A recently proposed mechanism for gypsum formation involves weathering of dust within ice (e.g., Niles, P.B., Michalski, J. [2009]. Nat. Geosci. 2, 215–220.). However, none of the previous studies have determined if this process is possible under current martian conditions. Here, we use numerical modelling of heat transfer to show that during the warmest days of the summer, solar irradiation may be sufficient to melt pure water ice located below a layer of dark dust particles (albedo $\leqslant 0.13$) lying on the steepest sections of the equator-facing slopes of the spiral troughs within martian NPRC. During the times of high irradiance at the north pole (every 51 ka; caused by variation of orbital and rotational parameters of Mars e.g., Laskar, J. et al. [2002]. Nature 419, 375–377.) this process could have taken place over larger parts of the spiral troughs. The existence of small amounts of liquid water close to the surface, even under current martian conditions, fulfils one of the main requirements necessary to explain the formation of the extensive gypsum deposits around the NPRC. It also changes our understanding of the degree of current geological activity on Mars and has important implications for estimating the astrobiological potential of Mars.

1. Introduction

The formation of large, young (Tanaka et al., 2008) gypsum deposits within the Olympia Planum region (Fig. 1), surrounding the North Polar Residual Cap NPRC, (Titus et al., 2008) has been an unsolved riddle since their discovery (Langevin et al., 2005). It was proposed that gypsum was formed by precipitation from water emanating from polar layered deposits (Fishbaugh et al., 2007). However, it is improbable that a large amount of bulk water could exist under current martian low atmospheric pressure sufficiently long to form the observed deposits (Niles and Michalski, 2009). To overcome this problem, a model of gypsum formation due to weathering in the ice was proposed (Catling et al., 2006; Zolotov and Mironenko, 2007; Niles and Michalski, 2009; Massé et al., 2010). In this model silicate particles weather due to a small amount of water formed in the contact with ice. The amount of gypsum (along with other weathering minerals in assemblage similar to those found in basaltic rocks and meteorites on Antarctica: Hallis, 2013) formed beneath a single particle is very small, but because there are many such particles, this process can produce gypsum deposits visible on a planetary scale (Langevin et al., 2005; Massé et al., 2010), especially over long time scales. Until now, none of the papers (Catling et al., 2006; Zolotov and Mironenko, 2007; Niles and Michalski, 2009; Massé et al., 2010) have produced a convincing model testing whether this process is possible under current martian conditions.

The aim of this paper is to determine if solar irradiation available currently (and during periods within the last few Ma when it was higher; Laskar et al., 2002) at the NPRC is sufficient to heat a layer of basaltic dust grains (2, 20 and 200 μm in thickness) enough to melt a thin layer of dusty glacial ice (10% basalt 75% ice, 15% pore space) located directly beneath it. The model is applicable (1) for the areas within south-facing side of the NPRC spiral troughs that are covered with a thin layer of basaltic dust eroded out from ice (Fig. 1) and (2) only during the warmest days of the year or tens of years (with average or low amount of dust in the

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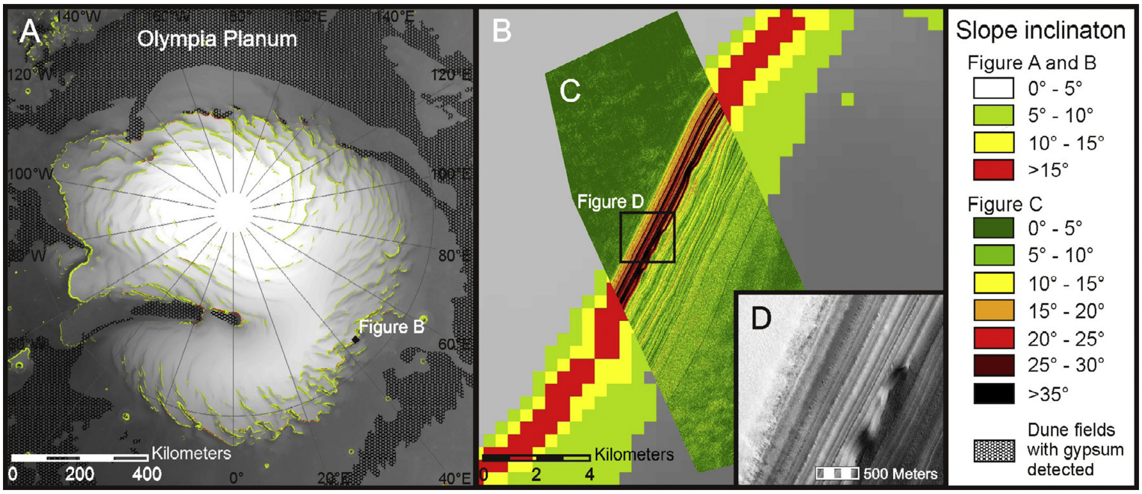

Fig. 1. Location of steep, south facing slopes within NPRC, where ice melting due to radiant heating of a dust layer on its surface may be taking place. (A) Slope inclination based on MOLA data with spatial resolution of 463 m, dune fields with detected signal of gypsum (based on Massé et al., 2012) and grey scale MOLA elevation in the background. The average slope inclination is ~10°, but in some sections it is above 40°. (B and C) Example of how surfaces marked with colour on (A) look up close. Close up image is derived from the HiRISE digital elevation model (DTEPC_001472_2785_001710_2785_U01) characterised by resolution of 1 m, overlaid on MOLA-derived map. Significant parts of the slope have inclinations greater than 20°, and up to 90°. (D) HiRISE image (PSP_001472_2785) displaying close up of the steepest part of the slope where inclination locally exceeds 35°. This image shows that surface roughness on scales <1 m is significant which means that on a sub-metre scale slope inclination can vary from 0° up to 90°. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

atmosphere and no clouds blocking sunlight: Inada et al., 2007), when surface temperature reaches 215 K and solar irradiation delivers >260 W m^{-2} (on the inclined surface). Below we discuss the main outcomes of the model in terms of its most important parameters: S [W m^{-2}] – power of the solar radiation close to the martian surface per 1 m^2 perpendicular to the radiation during local solar noon, A – albedo (for visible wavelengths), E – emissivity (for infrared) and k [W m^{-1} K^{-1}] – the coefficient of thermal conductivity of porous-dusty firn under dust layer.

2. Methods

2.1. The model

The numerical model used here is based on a one dimensional, time-dependent equation of heat transfer (Czechowski, 2012, 2014), that allows to determine the temperature distribution, conduction of heat and possible melting. We consider the 1D, time dependent equation:

$$\rho\ c_p \frac{\partial T(x,t)}{\partial t} = \frac{\partial}{\partial x} k(x,t)\ \frac{\partial}{\partial x} T(x,t) + Q(x,T,t) \quad (1)$$

where ρ, c_p, T, t, k, and Q are density, specific heat, temperature, time, thermal conductivity and efficiency of heat source/sink, respectively. The heat source/sink results from solidification/melting, $Q > 0$ for solidification and $Q < 0$ for melting – Table 1. Of course, Q depends also on content of volatiles in the porous-dusty firn. In our model the water ice is the only component of the firn that could be melted, so latent heat of water ice c_m is a parameter of the model. The equation is considered for $t > 0$, and for $x = [0, D]$ with the following boundary conditions:

$$-k\frac{\partial T(0,t)}{\partial x} = A\,S\cos(\alpha(t)) - E\,C\,T(0,t)^4 \quad \text{for } x = 0 \text{ (at the surface)}, \quad (2)$$

$$T(D,t) = T_{\text{low}}, \quad \text{for } x = D \text{ (at the lower boundary)}. \quad (3)$$

The S, A, E, D, and C, are solar irradiation, albedo, emissivity, thickness of considered layer, and Stefan–Boltzmann constant ($C = 5.67 \cdot 10^{-8}$ W m^{-2} K^{-4}), respectively. For $x < d_d$ physical properties of the medium correspond to properties of basalt, for $x > d_d$ the properties are of porous dusty firn.

The $\alpha(t)$ is the angle between the solar radiation and normal to the surface. The $\alpha(t)$ changes during motion of the Sun on the martian sky. Initial temperature changes linearly from T_{ini} to T_{low} according to the formula:

$$T(x,0) = T_{ini} - (T_{ini} - T_{low})x/D. \quad (4)$$

More details of the parameters are discussed below and in Table 1. The geometry of the problem is given in Fig. 2A. We considered a thin layer of dust grains (of thickness: 2 μm, 20 μm or 200 μm) resting on a porous-dusty firn (10% basaltic dust, 75% water ice and 15% pore space). The surface of the layer is exposed on an inclined south facing slope. The angle of inclination δ is equal to:

$$\delta = \text{latitude} - 25.15^{\circ}. \quad (5)$$

Such choice of δ guarantees that during local summer noon the angle $\alpha = 90°$ (perpendicular incidence of solar radiation) is reached. The angle 25.15° is the inclination of martian axis of rotation with respect to the normal vector to the orbital plane.

To solve the system (1)–(3) the numerical program developed for a similar problem (see e.g. Czechowski 2012) was used with some modifications. The program uses an explicit-finite difference method. The most important modification is the introduction of the non-uniform grid with the resolution of the order O(10^{-7} m) in the top-most part of the model (within the dust layer and directly beneath it). The modified program includes also some Matlab functions, e.g. the solver used in function pdepe().

Note, that in the present study we are interested in the maximal possible duration of melt existence at the near-surface and the maximal amount of liquid water produced, not average surface or interior conditions (mainly the temperature) of the NPRC that were the topic of several previous studies (Kieffer et al., 1976; Larsen and Dahl-Jensen, 2000). Thus values of parameters have been used which correspond to the warmest part of the considered period. The period could include several martian years.

In the current study various effects of atmosphere (and the dust) are partially accounted for by assuming solar irradiation below its value outside the atmosphere. The direct heat transfer from regolith to atmosphere is usually low because of the low