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Radiative cooling within illuminated layers of dust on (pre)-planetary surfaces and its effect on dust ejection

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ABSTRACT

Temperature gradients in dust beds embedded in a low pressure gaseous environment induce a lift of particles under certain conditions. This effect can erode planetesimals and enables entrainment of dust into the martian atmosphere. Here, we consider a numerical model to calculate the temperature profile in a dust bed which is subject to illumination. We consider the situation when the illumination is switched on and heats the dust bed's surface and when it is switched off again after a certain time. The calculations focus on the heat transfer by infrared radiation within the dust layer. We find that radiative transfer within the dust bed modifies the absolute temperatures and temperature gradients significantly. This is important for effects which are sensitive to absolute temperatures, i.e. ice sublimation or melting of solids. For low thermal conductivity dust beds of 0.001 W m^{-1} K^{-1} it determines the temperature structure of the dust. For higher thermal conductivities the modifications are moderate with respect to dust eruptions as the order of magnitude of temperature gradients stays the same.

1. Introduction

Dust is ubiquitous in early circumstellar environments. During planet formation dust is present over millions of years at the surface of protoplanetary disks (Haisch et al., 2001). To understand the evolution of protoplanetary disks and planet formation it is important to describe and quantify all possible dust generating processes. Besides other mechanisms, light induced erosion of bodies composed of dust is one mechanism to generate dust particles (Wurm and Krauss, 2006; Wurm, 2007). The same effect might also initiate or aid the lift of particles from the martian surface (Wurm et al., 2008). Light induced erosion critically depends on temperature gradients within the upper dust layers close to the actual surface.

If illuminated by visible radiation, a temperature profile through the dust bed in general shows a maximum below the surface. This is due to a solid-state greenhouse effect as directed light enters through pore space and by forward scattering but cooling by thermal radiation is dominant at the outermost layers of the dust bed. The temperature decreases from the sub-surface maximum towards the surface but also in the opposite direction deeper into the dust bed. The absolute of the temperature gradient at the surface decreases if the external light source is turned off, i.e. the surface moves out of the sunlight or enters shady regions and if that body is allowed to cool by radiation. However, the temperature maximum moves deeper under the surface which can induce intense particle eruptions as currently studied experimentally (Kelling et al., personal communications).

In a previous paper we considered radiative cooling simplified as boundary condition at the surface (Kocifaj et al., 2010). We neglected the radiation transport within the porous body. As dust ejections are bound to a few dust layers at the surface it is important to know but unclear how radiation transport within the dust sample changes the temperature gradients. We therefore consider radiative transfer within the dust bed here in comparison to no heat transfer by radiation as studied earlier.

2. Theoretical background

On the one hand, the radiative cooling of a layer situated at the depth h below the surface occurs because of thermal emission at the temperature $T(h)$. On the other hand, the radiative warming is a cumulative effect of absorbing the radiation of other layers surrounding the layer at the depth h. Radiation incident on a dusty layer is partially reflected, partially absorbed and partially transferred to the underlying layers. The penetration depth of the radiation beam depends not only on its wavelength λ, but also on the microphysical properties of the dusty layer (Ivanov et al., 1988;

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Davidsson and Skorov, 2002). The absorption and scattering efficiencies rapidly vary with size, shape and material composition of the dust particles, as well as with the packing density (filling factor) of the dusty layer (Mishchenko, 1994). The interplay of all these parameters determines the optical behavior of the dust and different set of dust parameters may result in very different optical behavior. The penetration depth of visible radiation may vary from some micrometers up to millimeters for many astronomically relevant materials (Henning et al., 1999).

The fraction of the radiation that is removed from the original radiative flux contributes to the heating of the irradiated environment. In general, monochromatic radiation is exponentially attenuated depending on the optical thickness τ_λ of the environment. The wavelength-dependent optical thickness of a plan-parallel dust bed is a function of the geometrical depth h within the dust bed (Fig. 1)

$$\tau_\lambda(h) = \int_0^h k_{\lambda,ext}(\xi)d\xi, \tag{1}$$

where $k_{\lambda,ext}(\xi)$ is the spectral volume extinction coefficient at the depth ξ (note that ξ runs over the whole layer whose actual depth is h). In a well-mixed non-stratified dust cover the optical thickness grows linearly with the geometrical depth h

$$\tau_\lambda(h) = hk_{\lambda,ext}. \tag{2}$$

As the optical depth increases, the monochromatic flux density of the direct radiation F_λ (W m^{-2} nm^{-1}) gradually drops in favor of diffuse radiation. However, both – the direct and the diffuse component of the radiation field – quickly disappear at large values of h. The determination of the flux density $F_\lambda(\tau_\lambda)$ (see Fig. 1) is a straightforward procedure

$$F_\lambda(\tau_\lambda) = F_{0,\lambda} \exp\left\{-\frac{\tau_\lambda}{\cos z_0}\right\}, \tag{3}$$

where $F_{0,\lambda} = \pi S_\lambda$ is the wavelength-dependent net flux density of the radiation incident on the surface of the dust bed and z_0 is the zenith angle of incidence. Eq. (3) is known as the Beer–Bouguer–Lambert law (Hovenier et al., 2004). The diffuse radiation occurs due to scattering of the radiation beams in any arbitrary elementary volume of a dusty layer. The scattered radiation propagates into all directions, thus the flux density of the downward diffuse radiation needs to be calculated as a cosine-weighted integral of the spectral radiance I_λ over the upper hemisphere. The upward diffuse radiation is obtained correspondingly (integrating the spectral radiance over the bottom hemisphere). The product of cos ζ and $I_\lambda d\Omega$ translates the directional radiances to the flux densities on a horizontal plane. To calculate the spectral radiances I_λ (W m^{-2} nm^{-1} sr^{-1}) at the discrete depth h, the complex integro-differential equation must be solved:

$$\frac{\cos\zeta}{k_{\lambda,ext}} \frac{dI_\lambda(h,\vec{\Omega})}{dh} = I_\lambda(h,\vec{\Omega}) - J_\lambda(h,\vec{\Omega}), \tag{4}$$

where $J_\lambda(h,\vec{\Omega})$ is the wavelength-dependent source function for a beam propagating in the direction $\vec{\Omega}$. The function $J_\lambda(h,\vec{\Omega})$ depends on I_λ as shown in Kocifaj et al. (2010). In that article we have presented the solution of the Eq. (4) for shortwave radiation.

Thermal effects of the monochromatic radiation flux can be evaluated from the radiative balance $q_{r,\lambda}(h)$, which characterizes energy losses in an infinitesimally thin layer situated at the depth h. In general, the radiative balance is a difference of downward and upward radiative fluxes (Brasseur and Solomon, 2005; Rutily et al., 2008). Omitting the thermal radiation and assuming constant flux density of the incident radiation, the $q_{r,\lambda}(h)$ will be a time-independent function. But if the thermal emission is taken into consideration, the $q_{r,\lambda}(h)$ may change with time t.

The absorbed energy in an elementary volume of the dusty layer will contribute to its heating. As the temperature grows, the elementary volume becomes a non-negligible source of thermal radiation. The emission of radiation causes a cooling of the elementary volume. These effects are coupled and determine the energy balance and hence the energy balance is time and depth dependent.

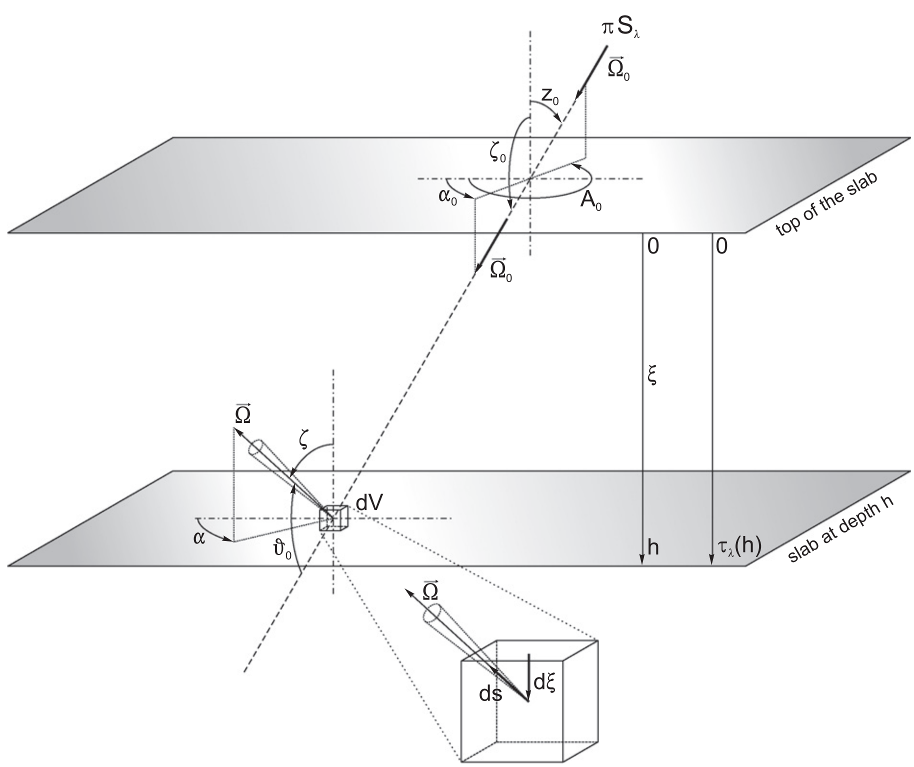

Fig. 1. Geometry of the radiative transfer in plan-parallel dusty environment.