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The Effect of a Non-Volatile Dust Mantle on the Energy Balance of Cometary Surface Layers

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Abstract

It is likely that large parts of a cometary surface layer consist of porous ices, which are covered by a thin layer of non-volatile debris, whose structure is also fluffy and porous. In this paper the results of model calculations are presented, which show the effect of ice and dust pore sizes, and of the dust mantle thickness upon the thermal behavior of such a dust-ice system, when it is irradiated by the sun. In particular, it is found that the average pore size of the ice and the dust material has a large influence both on the dust surface temperature and on the temperature at the dust-ice interface.

INTRODUCTION

Several lines of evidence make the existence of dust mantles on the surface of cometary nuclei (at least temporarily) probable. One argument comes from the fact that during the close-up observations of comet Halley by the spacecraft Giotto and VEGA only a small part of the nucleus showed 'activity' in the form of dust particle emission (Keller, 1990). The rest of the surface appeared inactive, which might be caused by a dust mantle overlying the cometary ice. The build-up and removal of dust mantles in response to varying solar irradiation conditions may be responsible for many features of cometary light curves (Jewitt, 1991). Recently, the build-up of dust mantles during irradiation of ice-dust mixtures could even be directly observed in the laboratory, although under terrestrial gravity conditions (Grün et al., 1991). In the following we present some results of model calculations, which demonstrate the influence of a dust mantle on the thermal behavior of a dust-ice system. Hereby it is assumed that both the dust mantle and the underlying ice have a porous, grainy structure, which can be characterized by an average pore size and a volume porosity. It is investigated in detail how the variation of these pore sizes and the variation of the dust mantle thickness affect dust and ice temperature and the heat flow to the interior.

GOVERNING EQUATIONS

Before presenting the results, we give a short survey of the basic equations used in our model and the geometry assumed. As we are only interested in surface layers, a one-dimensional geometry is chosen, where all variables depend only on the depth coordinate x and on time t. The total thickness of the dust-ice layer is chosen as 8 cm. It is assumed that the system is heated up at the upper end by absorption of solar radiation and kept at a constant low temperature at the lower end. The thermal equation for the dust mantle is given by

$$(1-\psi_d)\varrho_d c_d \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left[\lambda_d(T)\frac{\partial T}{\partial x}\right] - f_g c_g \frac{\partial T}{\partial x} \tag{1}$$

where the thermal conductivity of the mantle

$$\lambda_d = \lambda_d' + 4 r_d \varepsilon \sigma T^3 \tag{2}$$

consists of a contribution λ_d' caused by conduction via contact points and a radiative term proportional to the average pore radius r_d of the mantle material. The gas mass flux through the mantle (f_g) is calculated from a simple Knudsen law, where the gas pressure is computed from the Clausius Clapeyron equation with two experimental parameters (a and b). It is proportional to the ratio r_d/D, where D is the thickness of the dust mantle. Thus the factor r_d/D determines largely the permeability of the mantle for a gas flowing through. For that part of the system which consists of porous ice, a somewhat different heat conduction equation has to be utilized. It is given by

$$(1-\psi_i)\varrho_i c_i \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left[\lambda_{\rm eff}(T)\frac{\partial T}{\partial x}\right] - \phi_g c_g \frac{\partial T}{\partial x} \tag{3}$$

where ϕ_g is the gas flux into the interior, and $\lambda_{\rm eff}$ is the sum of the ice matrix conductivity and the conductivity caused by sublimation-condensation processes inside the pores:

$$\lambda_{\rm eff}(T) = h\frac{567}{T} + \frac{8}{3}\psi_i\left(\frac{m}{2\pi kT}\right)^{1/2}\frac{b}{T^2}ae^{-b/T}Hr_i \tag{4}$$

where h is the so-called Hertz factor describing the reduction of the solid state conductivity of compact ice caused by the grainy structure, r_i is the average radius of the pores in the ice, and H is the latent heat of sublimation. The remaining symbols in equations (1)–(4) are the porosity ψ, the density ρ, and the heat capacity c. The indices i, d, and g stand for ice , dust mantle, and gas, respectively. For all other symbols standard notation is used. Both estimates and detailed calculations (Steiner et al., 1991) have shown that the convective term in equations (1) and (3) has only a very minor influence on the result and can be neglected. For completeness, it was included in the following calculations. In the volume element containing the sublimation front (dust-ice interface) the difference of in- and outgoing heat fluxes is set equal to the energy flux carried by the gas escaping through the mantle. At the dust surface the absorbed energy is partially re-radiated as thermal radiation and partially conducted downward through the mantle.

RESULTS

Inspection of equations (1)–(4) reveals that the thermal evolution of a dust-ice system depends on a number of parameters. Among the most sensitive ones (because they may vary over a wide range in cometary ices and are largely unknown) are the solid state conductivity of the ice matrix (determined by the Hertz factor h), the solid state conductivity of the dust mantle (λ_d') and the average pore sizes in the ice and dust material (r_i, r_d). In the following we show some representative examples illustrating the dependence of the dust mantle surface temperature T_d and the dust-ice interface temperature on the pore sizes and on the thickness of the non-volatile mantle. Hereby the solid state conductivity of the mantle is taken as $\lambda_d' = 0.12\,\mathrm{WK^{-1}m^{-1}}$, which corresponds to the conductivity of coal dust (Grigull and Sandner, 1986). The Hertz factor for the ice is taken as 5×10^{-3}, a value found to be representative for porous water ice used in recent laboratory experiments (Kömle et al., 1991). In all cases the calculations of the thermal evolution of the

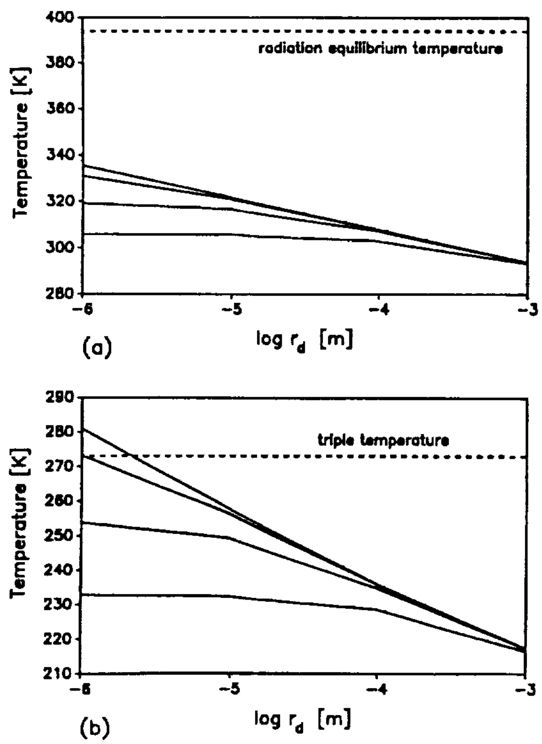

Figure 1 *(a) Dust surface temperature and (b) dust-ice interface temperature for a coal dust layer of 1 cm thickness overlying porous ice. The temperatures are plotted as a function of dust mantle pore radius r_d. The different curves correspond to ice pore radii of (top to bottom) 1 μm, 10 μm, 100 μm, and 1 mm.*

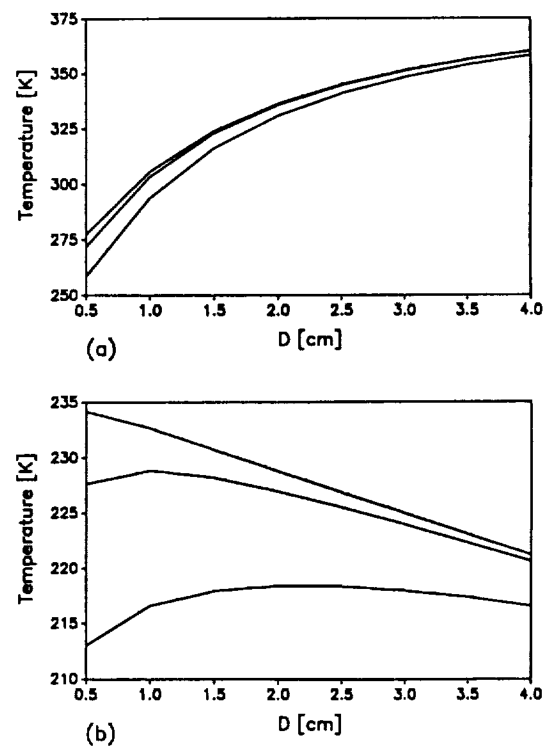

Figure 2 *(a) Dust surface temperature and (b) dust-ice interface temperature as a function of dust mantle thickness. It is assumed that the ice is coarse grained (r_i = 1 mm). The different curves correspond to dust mantle pore radii of (top to bottom) 10 μm, 100 μm, and 1 mm.*

system have been pursued to the point, where a quasi-stationary value was reached for T_i and T_d. This was the case after 4 hours of irradiation with 1 solar constant, assuming an albedo of zero and an infrared emissivity of one.

Figures 1a and 1b show the dependence of T_d and T_i on the pore radii r_d and r_i for a 1 cm thick coal dust mantle irradiated with 1 solar constant. Note that for ice containing only very fine capillaries which is covered by a similarly unpermeable dust mantle the ice temperature may increase up to the triple point of water ice (273 K). For coarse-grained mantle material with pore sizes in the millimeter range typical ice temperatures lie around 215 K. This is still higher than the corresponding free sublimation temperature of 205 K, which a black water ice in absence of a dust mantle would reach. Looking at Figure 1a one sees that the dust surface temperature also is quite sensitive to the pore sizes and varies between 295 K and 335 K in our example. It always remains clearly below the radiation equilibrium temperature of 394 K, which indicates the importance of inward directed heat flow in the case of such a moderately insulating mantle. Finally, Figures 2a and 2b illustrate the variation of T_d and T_i as a function of dust mantle thickness, for an ice of high permeability (r_i = 1 mm) and different values of r_d. Note that in the case of a dust mantle with low permeability the ice temperature decreases with increasing mantle thickness, while for a mantle with high permeability a temperature maximum at a certain mantle thickness is seen.

Dust surface temperatures also vary significantly with the mantle thickness.

DISCUSSION AND CONCLUSIONS

What is the reason for the behavior of the ice surface temperature as a function of mantle thickness, displayed in Figure 2 ? There are two counteracting physical processes that determine the value of T_i. On the one hand the dust mantle acts as a thermal insulator for the underlying ice. A significant part of the incoming energy is re-radiated already from the surface and cannot reach the ice any more. This tends to reduce T_i. On the other hand, the gas flow resistance of the dust mantle and the underlying ice quenches the gas flux in both directions, and leads to a pressure build-up below the surface. This effect tends to increase the ice temperature. Thus, the existence of a temperature maximum at a certain mantle thickness, as clearly seen in the middle curve ($r_d = 100\mu$m) in Figure 2b, appears physically plausible. Of course the position of the maximum depends not only on the pore radii, but also on the thermal conductivity of the dust mantle. However, this dependence has not yet been explored in detail. Nevertheless, the present study shows that the existence of an ice temperature maximum at a certain mantle thickness is possible.

Summarizing the results, we have found that the pore sizes of the material have a vast effect on the thermal evolution of a porous dust-ice system. Ice temperatures up to the triple point of water ice are possible for systems with low gas permeability. However, we believe that the cases with large effective pore sizes are more probable to be realistic for cometary surface layers, because very fine-grained dust particles tend to be blown away by sublimating gases, and those not blown away are likely to form aggregates with larger pore sizes. Only if a reasonable amount of organic (tar-like) material is present, which might 'seal' the pores and give the mantle a certain amount of coherence, higher ice temperatures may—at least temporarily—occur below cometary dust mantles.

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