Heating and destruction of the porous surface layer of a cometary nucleus

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A thermal model of a cometary surface layer with closed pores is considered. Closed cavities (pores) could have formed as a result of accretion of the cometary nucleus from icy and refractory particles and its further evolution. With a heating of the surface layer, the gaseous products of sublimation escape into outer space through open pores. The amount of ice decreases and gas from previously closed pores creates high pressure in the surface layer sufficient for its destruction and formation of dusty-gas flow.

Keywords: comets, porous near-surface layer of a cometary nucleus, thermal conductivity, gas diffusion, numerical simulation.

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Comets are unique objects of the Solar System, which were formed at the initial stage of its evolution [1]. Investigations of the comets are important for developing of the Solar System formation model [1–3], assessments of collision probability with the Earth, and verification of existing hypotheses of the origin of life on our planet.

The comets are inactive over the major part of their trajectory. With approaching to the Sun, due to solar radiation volatiles sublimate from a surface layer of the nucleus and leave the nucleus entraining the dust particles.

Thermal models of cometary nucleus are developing for quite a while [4–9]. All these models are based on the solution of a classical thermal conductivity equation with taking into account specific features of a surface layer structure, which determines boundary conditions on the nucleus surface and values of thermophysical parameters,. These models differ in a layer structure detail level, including presence/absence of a „dry“ mantle, surface/volume sublimation, taking into account diffusion of volatile species, etc.

Some models are able to predict integral gas production of the nucleus in agreement with experimental data. However, there are unresolved issues related to mechanism of dust removal from the surface and correct prediction of integral dust fluxes. Dust shall be understood as large (fraction of a micron and greater) particles that can generally contain both inclusions of minerals (silicates, carbides, sulfides) as well as ice of a various nature (H_2O, CO_2, CO). It is assumed that the dust particles are bonded with each other by Van der Waals forces. For example, pressure of about 1 Pa is required for detachment of a millimeter size dust aggregate [10]. For the majority of comets, the prevailing volatile species is water ice. The surface temperature of a pure water ice nucleus at heliocentric distance $S = 1$ AU is about 207 K, that corresponds to the saturation pressure of 0.46 Pa. In the major part of the path ($S > 1$ au), the saturated-vapor pressure turns out to be significantly (by orders of magnitude) lower. Presence of the mantle (for which emissivity factor is close to unity and there is no heat removal caused by an ice sublimation process) increases the temperature of the „dry“ layer, but does not result in a significant increase of pressure of sublimated molecules in a depth beyond its limits. Carbon dioxide and carbon monoxide in the solid phase have high saturation pressures for a pre-defined temperature as compared to water ice. But their volumetric fraction is usually much lower.

The aim of the present study is to formulate a thermal model of a porous surface layer of the comet nucleus under effect of solar radiation with taking into account volume sublimation of the volatile species and their diffusion and to investigate distribution of pressure of the gas phase inside the layer and its destruction. The proposed model is based on applying the conservation laws in the form of partial differential equations. Its specific features include consideration of microcavities (pores) inside the surface layer, which are initially isolated and further open during evolution of the surface layers due to ice sublimation. Thus, the model describes both a subsurface layer with open pores and sublimating ices as well as internal space of the comet nucleus with closed pores as well as an area of a transition between them. A structure of the porous medium is generally described by means of volume fractions of the species. The proposed model of heating and destruction of the surface layer predicts sufficient pressures for destruction of the surface layer of the nucleus.

Refractory grains are covered with a layer of volatile component's ices. During formation and evolution of the comet space distribution of ices changes as a result of coalescence. Surface tensioning and a dependence of equilibrium pressure on curvature result in formation of the closed cavities — pores. During sublimation, the ice layer is thinned and the pores open. Vapor contained therein increases pressure in the „dry" increasing probability of breakaway of dust.

The considered option of the model takes into account only ice H_2O, but the model can be easily generalized to any number of the volatile species. In order to describe a multi-component porous medium, we introduce a volume fraction of refractory dust ψ_d and ice ψ_i. Then the volume fraction of the pores is $\psi_p = \psi_o + \psi_c = 1 - \psi_i - \psi_d$, where ψ_o and ψ_c is the volume fraction of the open and closed pores, respectively. A concentration of molecules of the gas phase is calculated per the full volume of a comet substance: $n_i = dN_i/dV$, where dN_i is a number of molecules of the gas phase (in our case — water vapor) within the volume $dV = dx \cdot dy \cdot dz$.

In the closed pores (parameters with an index c) the gas pressure is an equilibrium one (the surface curvature is not taken into account). Since the pressures are not high, a density of the gases is by at least three orders less than that of their solid phase and, consequently, a change of its volume during sublimation can be neglected. Then the following equation of state is fulfilled for them: $p_i = n_{i,c}kT/\psi_c$, $n_{i,c} = p_{i,s}(T)\psi_c/kT$, where $p_{i,s}(T)$ is an equilibrium vapor pressure at the temperature T, k is the Boltzmann constant.

Equations of heat- and mass-transfer are written in a one-dimensional approximation. Since the thickness of the heated layer (tens of centimeters) is much less than the sizes of the comet, the surface curvature can be neglected and a Cartesian coordinate x can be used. The origin of the coordinates is on the comet surface.

For the open pores (the parameters with the index o), we write a diffusion equation with source terms on the right-hand side, which take into account diffusion, evaporation/condensation and pore opening

$$\frac{\partial n_{i,o}}{\partial t} = -\frac{\partial}{\partial x} g_i + q_i - n_{i,c}\frac{\partial \psi_c}{\partial t}. \qquad (1)$$

Since the concentration of the gas phase is small, the molecules much more frequently collide with pore wall than with each other. Therefore, a diffusion flow is determined by Knudsen diffusion [8]:

$$g_i = -D_i^{ch}\frac{\partial(n_{i,o}\sqrt{T})}{\partial x}, \quad D_i^{ch} = \frac{1}{3}d_p\left(\frac{8k}{\pi m_i}\right)^{1/2}, \qquad (2)$$

where d_p is a typical pore diameter. Sublimation/condensation occurs in a free-molecular mode, therefore, the sublimation rate q_i is

$$q_i = \frac{4\psi_o}{d_p}\frac{\psi_i}{\psi_i + \psi_d}\sqrt{\frac{1}{2\pi m_i kT}}\Delta P_i,$$

$$\Delta P_i = p_{i,s}(T) - p_{i,o}, \qquad \psi_i > 0. \qquad (3)$$

If the solid phase is absent ($\psi_i = 0$), then only condensation is possible.

The volume portion of ice decreases as a result of its sublimation

$$\frac{\partial \psi_i}{\partial t} = -q_i\frac{m_i}{\rho_i}, \qquad (4)$$

where m_i, ρ_i is a weight of a water molecule and a density of solid ice, respectively. As the thickness of the ice layer decreases, there is an increase of the fraction of the open pores and a decrease of that of the closed ones $\psi_c = \psi_p\chi(\psi_i)$, $\chi(\psi_i|_{t=0}) \approx 1$, $\chi(0) \approx 0$. Here, $\psi(\psi_i)$ is a smooth step-like function (a sigmoid), whose parameters are chosen based on the following assumptions: in the initial position most of the pores are closed and after complete exhaustion of ice they are open.

Variation of the temperature is described by the equation [5]:

$$(\rho_d\psi_d c_d + \rho_i\psi_i c_i + n_o C + n_c C)\frac{\partial T}{\partial t}$$

$$= \frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right) - Cg_i\frac{\partial T}{\partial x} - q_i H. \qquad (5)$$

A coefficient of the time derivative of the temperature on the left-hand side takes into account heat capacities of all the species of the comet substance — dust $\rho_d\psi_d c_d$, ice $\rho_i\psi_i c_i$ (ρ, c are the density and specific heat capacity of the solid substance) and vapors in the closed and open pores $n_o C + n_c C$ (C is heat capacity per one molecule). The terms on the right-hand side take into account thermal conductivity and evaporation/condensation (H is enthalpy of the phase transition per one molecule). The thermal conductivity coefficient is summed up by thermal conductivity of gas, the dust and ice porous medium as well as by radiation heat exchange.

Thermal conductivity is mainly contributed by the porous medium, whose thermal conductivity significantly depends on its structure. The literature deals with various models that provide values of thermal conductivity, which are close to the experimental data, with respectively selecting the parameters. In the present study, we limit ourselves with pre-setting values of λ that is $0.002\,\mathrm{W\cdot m^{-1}K^{-1}}$ [8].

Boundary conditions are pre-defined on the comet surface for the concentration of the gaseous component (the index s corresponds to values of the concentration and the temperature on the surface, i.e. when $x = 0$)

$$D_i^{ch}\frac{\partial(n_o\sqrt{T})}{\partial x} = \frac{1}{4}n_{o,s}\left(\frac{8kT_S}{\pi m_i}\right)^{1/2}, \qquad (6)$$

and the temperature

$$I_0 \left(\frac{r_\mathrm{H}}{1\,\mathrm{au}}\right)^{-2} (1-A)\cos\upsilon = \varepsilon\sigma T_S^4 - \lambda(T)\frac{\partial T}{\partial x}\bigg|_{x=0}. \quad (7)$$

Here, $I_0 = 1360\,\mathrm{W/m^2}$ is intensity of sunlight at the distance of 1 au, r_H is a distance to the Sun, A is an comet albedo, υ is an angle between a local normal to the surface and a direction to the Sun, ε is an emissivity factor (in the far-IR range), σ is the Stefan–Boltzmann constant.

The calculations by the proposed model were performed using a designed program code [11]. The equations of diffusion (1) and thermal conductivity (5) were discretized in the finite difference method. We have used an implicit scheme with difference operators that have the first order in terms of time accuracy and the second order in terms of space accuracy. In each time step, the processes of heating and diffusion are considered sequentially [8,12]. First, the thermal conductivity equation is solved. A specific feature of this part of a calculation algorithm is that it is necessary to determine the temperature at a boundary of the calculation area using the non-linear equation (7). Then, the diffusion equation is solved using temperature distribution data. A regular calculation grid has a step of $4\cdot10^{-5}$ m, a layer depth of 0.2 m, a time step of 0.01 s and a considered time interval of 10 revolutions of the comet nucleus is 124 h.

The main series of calculations is performed for a distance of the comet to the Sun, which is 2.5 au. We consider a porous layer that consists of dust (the initial fraction $\psi_d = 0.2$), ice (the initial portion $\psi_i = 0.1$) and water vapors that fill in the pores (the initial portion $\psi_0 = 0.013$). The density of dust is $2000\,\mathrm{kg/m^3}$ and that of ice is $920\,\mathrm{kg/m^3}$ [8]. Heat capacity of ice and dust was assumed to be $1000\,\mathrm{J/(kg\cdot K)}$. The calculations are given for a surface element of the spherical nucleus at the equator. An axis of nucleus rotation is perpendicular to a plane of the comet orbit. The rotation period is $T = 12.4$ h.

Fig. 1 shows variation of the temperature of the nucleus surface element during its rotation around its own axis.

The flux of solar radiation at the considered distance to the Sun is $217\,\mathrm{W/m^2}$. Since the comet nucleus rotates, the surface element transits from a day (illuminated) side to a night side, and vice versa. The temperature changes periodically. Because of radiation to space and heat removal by thermal conductivity the surface cools down and the minimum temperature is about 110 K. A quasi-periodic mode is set upon completion of 3–5 revolutions and then graphs of time variation of the temperature are repeated at each revolution with good accuracy.

For 10 revolutions, a heat wave goes inside the comet nucleus for about 15 cm. Fig. 2 shows temperature distribution along the nucleus depth in various times: 0 and $T/8$ — the day side (0 and 1.55 h, respectively), $T/4$ — the boundary of the day and night side (3.1 h) and $T/2$ — the night side (6.2 h). The changes of the temperature affect only a subsurface layer, while at a sufficient distance to the surface the temperature distribution does not depend on time. The temperature along the depth of the subsurface layer changes significantly non-linearly.

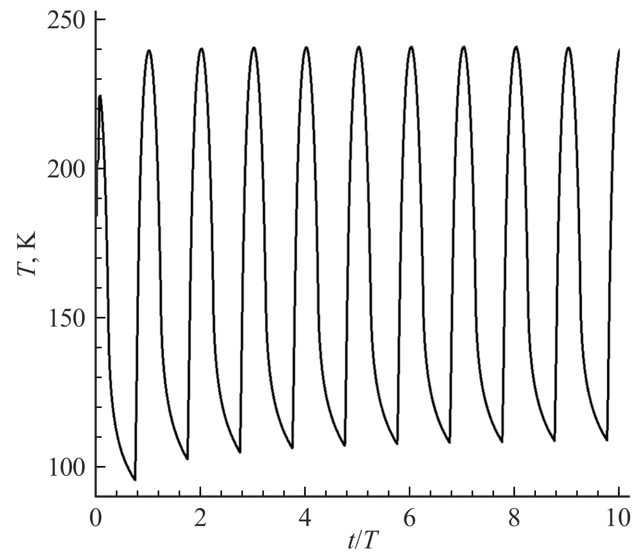

Figure 1. Dependence of the surface element temperature on the equator on time.

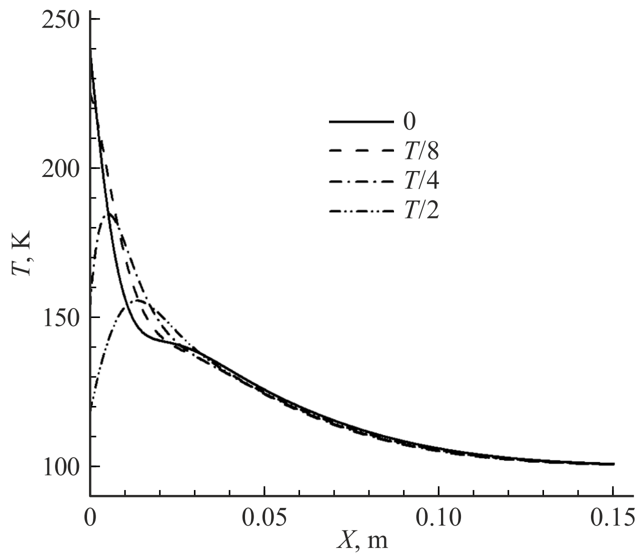

Figure 2. Temperature distribution along the layer depth in various times.

The pressure in the subsurface layer is determined by an integral contribution by the open and closed pores. The pressure distribution along the layer depth is shown in Fig. 3 for various times.

For the considered distance of the nucleus to the Sun (2.5 au), the maximum pressure on the day sided part significantly exceeds the value of 1 Pa. Thus, according to [10], layer destruction and ejection of the dust aggregates are possible even for conditions of low values of the sun radiation energy flux. With approaching to the Sun, the observed effect is expected to be enhanced. At the night

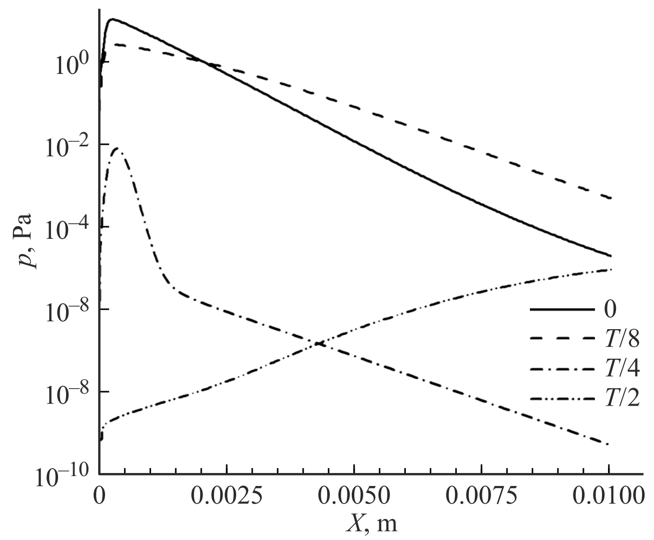

Figure 3. Pressure distribution along the layer depth for various times.

side, the pressure in the layer drops due to the decrease of the temperature (Fig. 2) and the molecules are condensed on the walls of the open/closed pores.

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Conflict of interest

The authors declare that they have no conflict of interest.

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