Research Article

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Thermal evolution of the nucleus of the comet 67P for 120 years: numerical simulations

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Abstract: The purpose of this paper is to estimate to what temperatures and to what depth the outer layers of the cometary nuclei are heated for several dozen revolutions around the Sun, and what changes in the composition of the volatiles occur in this case. This is important because it is not clear how much the experimentally obtained results on the composition of cometary comes depend on how long the comet is in the current orbit.

Our approach to this problem is based on using 3D model of the geometry and dynamics of a cometary nucleus that takes into account the diurnal rotation and orientation of the rotation axis relative to the Sun to simulate the irradiance to take value of temperature the surface of the nucleus and 1D thermal model of the porous ice-rock body. The results of the numerical simulation of heat propagation in the subsurface layers of some points the MA'AT region of the 67P core, obtained for the 20 orbital cycles (close to 130 years), are presented in this paper.

Keywords: comets; models of thermal evolution; depth of heat propagation

1 Introduction

Results of studying the composition of comets give every reason to believe that these cosmic objects were formed at the very beginning of the evolution of the solar system. Their accumulation occurred in the far cold regions of the solar protoplanetary gas-dust disk, therefore most components of the nebula substance, including the most volatile ones, were included in the composition of the comet substance. Most of their life that is, 4.5 billion years, the comets were on the periphery of the solar system, where only the outermost layers of their nuclei underwent a change because of the action of cosmic rays, and therefore they basically retained their primordial substance, including the volatiles. Comets can serve as an important source of information in the study of various problems of cosmochemistry and planetary cosmogony. However, when the nuclei of comets fall into the inner region of the solar system, the change in insolation during the motion in the circumsolar orbit, they experience a lot of processes, such as degassing of volatiles, destruction of outer layers, phase transformations that can significantly change

the initial composition of cometary substances. But it is at this time that comets are studied by ground-based observations and during space flights. Thus, in order to correctly use the experimental information, it is necessary to understand how deep changes in the matter of cometary nuclei can occur over a sufficiently long time of the existence of comets in orbits close to the Sun. It was possible to study these processes by creating numerical models when more reliable ideas about the structure and composition of cometary nuclei were obtained with the help of spacecraft approaching them at relatively close distances. These were the space missions Vega 1, Vega 2, Sakigake, Suisei and Giotto to the comet 1P / Halley (1984-1986), Deep Space 1 to comet 19P / Borrelly (2001), Deep Impact to comet 9P / Tempel (2005), and then to 103P / Hartley (2010) as EPOXI mission, Stardust to comet Wild 2 (2004-2006). But the greatest amount of information was obtained as a result of the Rosetta mission, which for two years studied the short-period Jupiter family comet: the 67P / Churyumova-Gerasimenko (further 67P/C-G) (2014-2016). The spacecraft was approaching the comet nucleus for a distance of up to 100 km, and when its activity was low, the distance was reduced to 10 km and even less; in November 2014 for the first time in the history the Philae landing module was lowered onto the nucleus. An analysis of the entire volume of data indicates that the comet nuclei are small (from a few tenths to several tens of kilometers in diameter) of an irregular body shape having low gravity, which are not

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fragments of larger bodies. They consist of a mixture of rock dust (30-50 mass %), refractory organic compounds - CHON (20-30 mass %), and a mixture of ice (30 mass %), the main component of which is ice H_2O ; they also contain ice of CO_2 , CO , CH_4 , CH_3OH , etc. (Mumma and Charnley, 2011; Bockelée-Morvan, 2011). The density of cometary nuclei is $0.5g/cm^3$ (Lamy et al., 2015), which corresponds to a porosity of 70% for this composition (Pätzold et al., 2016), and causes their high thermal inertia. A characteristic feature of cometary nuclei is their low optical albedo - of the order of several %; is due to the fact that their surface is covered with a thin layer of silicate dust and a refractory organic substance of black color. The surface of cometary nuclei has a complex structure with a large (up to several hundred meters) height difference. Some nuclei have a bimodal structure, so in the region of the "neck" the difference in altitude is even more significant. To date, a significant number of models have been developed that describe the heat distribution that comets obtain due to insolation in their nuclei. In these models, the effect of the core composition, the mass dust to gas ratio, the composition and thickness of the outer degassed layer, as well as dynamic characteristics is investigated. Some models take into account not only heat transfer, but also mass transfer within cometary nuclei. Their detailed review can be found for instance in (Hu et al., 2017). However, in all these models, the distribution of thermal profiles in the nucleus of a comet is considered during one of its passage near the Sun only. At the same time, the processes occurring in the inner layers of cometary nuclei can be divided into two types: fast-flowing - associated with the sublimation of ice and dissipation of gases and slow-flowing - that associate with the propagation of thermal energy deep into the cometary nuclei.

The purpose of this paper is to estimate to what depth and to what temperatures the outer layers of the cometary nuclei are heated for several dozen revolutions around the Sun, and what changes in the composition of the volatiles occur in this case. In this formulation the problem is solved for the first time. Moreover, the calculation was carried out for a real comet (67P/C-G), for specific points on its surface, characterized by different illumination and, as a consequence, different current activity.

2 Model of the irradiance of the nucleus of the comet 67P/Churyumov-Gerasimenko

For a numerical description of the insolation of the surface of the nucleus of comet 67P, we used a 3D model of its surface, which we developed. The model makes it possible to investigate the inhomogeneity of its heating. This is very important, because in zones with a maximum surface temperature chemical and physical transformations of material are possible in subsurface layers, for example, the transition of water ice from an amorphous form to a crystalline one, the formation of crystalline hydrates and clathrate hydrates of the gases that constitute the cometary nuclei, and their sublimation. We propose the 3D model of the geometry and dynamics of a cometary nucleus to simulate the irradiance of both the nucleus as a whole and its individual regions with reference to the nucleus of the comet 67P, since the nature of its surface has been most thoroughly studied. The results of the ROSETTA mission provide sufficient factual material for constructing the triangulations of the surface of the comet 67P/C-G with an accuracy that satisfies the tasks posed. Our model takes into account the diurnal rotation of the nucleus and the orientation of its rotation axis relative to the Sun during the orbital motion of the comet. This allows the surface irradiance of cometary nuclei to be simulated for various parameters of their orbits, inclinations, and spin characteristics. Based on the irradiance data obtained, we calculate the surface temperature distributions that serve as boundary conditions for the models of the thermal evolution of subsurface regions of the comet 67P nucleus during its diurnal and orbital motion.

Figure 1. The 3D model of the 67P comet nucleus: the polygonal partition, the surface relief, and the cloud of normals to the partition elements

The polygonal 3D model is constructed as a system of contiguous plane polygons, in our case, triangles, whose vertices are a cloud of points lying on the surface being modeled. Thus, there exists some geometrical limit upon

reaching which a further increase of the number of points in the 3D model does not add any geometrical details of the surface being modeled. Given the resolution of the available images for the comet 67P surface, it turned out that a 3D model consisting of 5689 vertices and 11420 triangular elements (Figure 1) could be adopted for its satisfactory description. The model of a cometary nucleus allows the orientation of normals to elements to be calculated for any orbital position of the nucleus and any moment of its diurnal rotation around the spin axis. Knowing the orientation of the normal for a specific triangular element makes it possible to calculate the position angle of the Sun relative to this element and to determine the amount of absorbed energy and temperature of this element from the position angle and distance to the Sun with allowance made for the albedo. Repeating this procedure for all elements gives the temperature distribution over the surface of the cometary nucleus at a given instant of time. For more detailed description of 3D model of shape, irradiance and surface temperature of the comet 67P see (Marov et al., 2017).

3 Model of temperature propagation in comet nucleus subsurface layers

As we noted earlier, the goal of this research is long-term thermal energy propagation deep in subsurface layers of cometary nuclei. Previous studies (Rusol and Dorofeeva, 2015; Rusol, A.V., A.; Hu et al., 2017) showed the presence of regions with the most intense thermal processes in the subsurface layers of cometary nuclei. This region does not extend to large distances from the surface. This fact allows us to limit the depth considered in numerical simulation, without losing the generality of the problem under consideration. The investigation of physical and chemical processes occurring in subsurface regions of cometary nuclei and surrounding gas-dust structures includes mathematical modeling of their thermal evolution. A necessary stage of this is to construct a model of the temperature distribution over the surface of the cometary nucleus considering its complex topological shape which leads to a significantly non-uniform irradiance of the nuclear surface.

Mathematical formulation and boundary conditions describing the heat energy balance on the surface of the nucleus were proposed in the work (Marov et al., 1987)

$$c(T)\rho \frac{\partial T}{\partial t} = \nabla(\kappa(T)\nabla T), \quad t \geq 0, \quad r_0 \leq r \leq R_N \quad (1)$$

$$S_{\odot}(1 - A_v)R_H^{-2}e^{-\tau}\xi = (1 - A_{IR})\sigma_B T^4$$

$$+ \Sigma(nv)_{\alpha} \Delta h_{\alpha}(T) - \kappa(T)\nabla T \Big|_{r=R_N}$$

where $S_{\odot}$ is the solar constant; σ_B is the Stefan–Boltzmann constant; $\Delta h_{\alpha}(T)$ is the sublimation heat of particles of type α at a temperature T ; A_v and A_{IR} are respectively the Bond albedo and the infrared albedo of the nuclear surface; τ is the effective optical depth of the coma; R_H is the heliocentric distance; ξ is the coefficient depending on the local zenith angle; $(nv)_{\alpha}$ is the rate of the sublimation of particles of type α ; $c(T)$ heat capacity; ρ density; $\kappa(T)$ thermal conductivity.

The correspondence between the temperature of the nuclear parts and the solar radiation flux arriving at the surface, taking into account the orbital position, the orientation of the rotation axis and the time of day on the nucleus, we investigated in works (Rusol and Dorofeeva, 2015; Rusol et al., 2016). As the reliable data necessary to consider all operating factors are not available we adopted in this paper a simplified formulation of the problem of heat distribution in the subsurface layers of the cometary nucleus; however, it doesn't break the generality and entirety of the results obtained.

Firstly, since the nucleus of 67P/C-G comet has no spherical symmetry, a one-dimensional formulation of the equation in Cartesian coordinates was accepted

$$c\rho \frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial x^2}, \quad t \geq 0, \quad 0 \leq x \leq L \quad (2)$$

Secondly, a simpler statement of the boundary conditions was adopted

$$T \Big|_{x=0} = T_{surf} \quad \text{and} \quad \frac{\partial T}{\partial x} \Big|_{x=L} = 0 \quad (3)$$

where c heat capacity; ρ density; κ thermal conductivity; L maximum depth considered in the model; T_{surf} is the surface temperature determined in the work (Marov et al., 2017) from the simplified state of the energy balance on the surface

$$\sigma_B T_{surf}^4 S_{el} - \sum L_i^{sub} Q_i = (1 - A) S_{el} W_R \cos \beta \quad (4)$$

where W_R is the energy of solar radiation per unit area at the heliocentric distance R ; A is the optical albedo of the nucleus; S_{el} is the area of the surface element and β is the angle between the outward normal to the surface element and the direction toward the Sun. The second term on the left-hand side in (4) describes the cooling effect caused by summary sublimation of various ices. The sublimation term is the sum of the product of the latent heat of sublimation L_i^{sub} and the mass-loss term Q_i caused by sublimation of the ice kind i . This paper is devoted to the study of the long evolution of the inner layers of the substance

of cometary nuclei, therefore, fast processes related to the sublimation of ice are excluded from consideration, and only the first term remains in the left-hand side of expression (4). This does not violate the generality of the examination, since, firstly, the fast flowing processes occur in a relatively narrow near-surface region, and secondly, on the surface of the comet's core there is a layer of silicate dust remaining after the previous passage of perihelion.

Thermophysical characteristics of the cometary nucleus parameters of (2) heat capacity c , density ρ and thermal conductivity κ , are defined as the properties of the mix of water ice c_{ice} , ρ_{ice} , κ_{ice} and silicate dust c_{dust} , ρ_{dust} , κ_{dust} , taking into account their mass fractions Δ_{dust}

$$\rho = \left(\frac{\Delta_{dust}}{\rho_{dust}} - \frac{1 - \Delta_{dust}}{\rho_{ice}} \right)^{-1} \quad (5)$$

$$\kappa = (\Delta_{dust}\kappa_{dust} + (1 - \Delta_{dust})\kappa_{ice}) \quad (6)$$

$$c = (\Delta_{dust}c_{dust} + (1 - \Delta_{dust})c_{ice}) \quad (7)$$

The effect of porosity on the thermophysical properties of the porous rock-ice composition was carried out by analogy with the approaches used in the theory of structural materials (Karpinos and Klimenko, 1978; Cheremskoy et al., 1990). Due to the lack of initial data, at this stage of the research processes associated with phase transitions are not considered, and therefore the characteristics of the porous rock-ice composition are assumed to be temperature independent.

For the numerical solution of (2) with boundary conditions (3), an implicit finite-difference scheme was realized. We chose several points in different parts of the MA'AT region of the comet 67P nucleus (Figure 2a) for numerical simulation of heat propagation within nucleus matter. The choice of points is dictated by the need to investigate the thermal evolution of the substance of the cometary nucleus under different light conditions. Selected points are characterized by a change of "day" and "night" during the orbital movement, with differing durations and peak daytime temperatures (Figure 3). As a range of account time, a time period corresponding to 20 revolutions around the Sun of the cometary nucleus was adopted. As can be seen from Figure 2a, at the "hot" segment of the orbit, between points 12 and 15, the largest surface heating has occurs.

4 Results of numerical simulation

In that paper, a numerical simulation of the thermal evolution of the substance of the nucleus of comet 67P / C-G

Figure 2. Basic parameters of numerical simulation: a) points in different parts of the MA'AT region and b) orbital points for numerical simulations

Figure 3. Dependence of surface temperature of selected points: a) for one orbital revolution and b) for 20 orbital revolutions

over 20 revolutions around the Sun was carried out, which is about 130 years. From the analysis of Figures 4, 5 and 6 it is clear that the temperature distribution curves tend to

some general limiting distribution. Thus, the temperature distribution obtained for 20 revolutions can, without loss of generality, be recognized as corresponding to the modern temperature distribution in the nucleus of comet 67P.

For all the investigated points of simulation an initial temperature distribution was taken as a uniform temperature level of 10 K. The thermophysical properties of the substance for all points are assumed to be temperature independent and calculated as properties of the porous ice-rock body. Let us consider in more detail the results of a numerical simulation of the thermal evolution of matter in cometary nuclei.

Point 27

At the point 27 comet "day" during one orbital revolve have a maximum temperature close to 180 K (as shown in Figure 3a). Numerical simulation demonstrates that because of the features of the thermophysical properties of the porous ice-rock body at the first stage (first orbital revolution) of simulation a zone of accumulating of thermal energy at a depth of 1.25 m is formatting in the subsurface layer of the comet 67P nucleus with a maximum temperature close to 45 K. Further simulation showed that over 20 comet orbital revolution, the heating front propagated deeper into the subsurface layers (Figure 4a). From the results of the modeling it can be seen that within 20 orbital revolution of comet 67P the nucleus being at orbital movement, the heating region of subsurface layers in the point 27 of MA'AT region spread to values of 7.0 m, and the maximum of internal temperatures 105 K was at the level of 0.45–0.55 m. At the "hot" segment of the orbit maximum temperature achieved at the surface (Figure 4b).

Point 364

At the point 364 comet "day" during one orbital revolve have a maximum temperature close to 167 K (as shown in Figure 3a). Numerical simulation demonstrates that because of the features of the thermophysical properties of the porous ice-rock body at the first stage (first orbital revolution) of simulation a zone of accumulating of thermal energy at a depth of 1.25 m is formatting in the subsurface layer of the comet 67P nucleus with a maximum temperature close to 55 K. Further simulation showed that over 20 comet orbital revolution, the heating front propagated deeper into the subsurface layers (Figure 5a). From the results of the modeling it can be seen that within 20 orbital revolution of comet 67P the nucleus being at orbital move-

The heat distribution in sub-surface layers in point 27 of MA'AT region

(a)

The heat distribution in sub-surface layers in point 27 of MA'AT region

(b)

Figure 4. The depth temperature distribution in the point 27 of MA'AT region for the 20 comet orbital revolution

ment, the heating region of subsurface layers in the point 364 of MA'AT region spread to values of 7.0 m, and the maximum of internal temperatures 107 K was at the level of 0.35–0.45 m. At the "hot" segment of the orbit maximum temperature achieved at the surface (Figure 5b).

Point 453

As shown in Figure 3a, at point 453 of the MA'AT region, "night" lasts 2.67 times longer than at point 27 and 4 times longer than at point 364. At the point 453 comet "day" during one orbital revolve have a maximum temperature close to 275–280 K (as shown in Figure 3a). Numerical simulation demonstrates that because of the features of the thermophysical properties of the porous ice-rock body at the first stage (first orbital revolution) of simulation a zone of accumulating of thermal energy at a depth of 1.25 m is formatting in the subsurface layer of the comet 67P nucleus with a maximum temperature close to 15 K. Further simulation showed that over 20 comet orbital revolution, the heating front propagated deeper into the subsurface layers (Figure 6a). From the results of the modeling it can be seen that within 20 orbital revolution of comet 67P the nucleus

The heat distribution in sub-surface layers in point 364 of MA'AT region

(a)

The heat distribution in sub-surface layers in point 364 of MA'AT region

(b)

Figure 5. The depth temperature distribution in the point 364 of MA'AT region for the 20 comet orbital revolution

The heat distribution in sub-surface layers in point 453 of MA'AT region

(a)

The heat distribution in sub-surface layers in point 453 of MA'AT region

(b)

Figure 6. The depth temperature distribution in the point 453 of MA'AT region for the 20 comet orbital revolution

being at orbital movement, the heating region of subsurface layers in the point 453 of MA'AT region spread to values of 7.0 m, and the maximum of internal temperatures 75 K was at the level of 0.65–0.75 m. At the "hot" segment of the orbit maximum temperature achieved at the surface (Figure 6b).

5 Conclusions

Numerical simulations showed that even with a prolonged stay of a comet in the current orbit, the heat is accumulated only in the thin outer (subsurface) layer of the core. If we assume that the conditional critical temperatures are 25°K (T of sublimation of one of the ice fraction's main components – CO ice), 90°K (sublimation of CO₂ ice), and 140°K (sublimation of H₂O ice), then, according to the calculations, layers with significantly different temperature conditions can be distinguished in the subsurface regions (Table 1).

Assuming that the current temperature distribution in the subsurface areas of the nucleus of comet 67P is close to the distribution that was obtained during the time of 20 revolutions around the Sun, we can compare our re-

Table 1. Critical temperatures distribution

Point	Temperature, °K	Depth, m
27	25	3.75
	90	1.0
	140	$\sim 7 \times 10^{-2}$
364	25	3.75
	90	1.0
	140	$\sim 4 \times 10^{-2}$
453	25	3.35
	90	15×10^{-2}
	140	$\sim 9 \times 10^{-2}$

sults with the results of modeling performed by other authors. From the results of our study, it is clear that, despite intensive changes in surface temperature during the illuminated and shaded periods of time, thermal energy is accumulated in the inner regions of the substance of the comet's nucleus. The accumulating energy in some cases is sufficient for the initialization of phase transitions in the substance of the cometary nucleus, which can serve as an explanation for the observed activity of the nucleus of the comet 67P/C-G at the postperigee period of the orbit.

The conclusions obtained regarding the depth of propagation of heat are in good agreement with the results

of previous models, for example, with (Guilbert-Lepoutre and Jewitt, 2011). In this paper, numerical simulation was used to study the influence of the surface albedo on the velocity and depth of propagation of thermal waves in a spherical body 2 km in diameter, based on thermophysical properties similar to cometary substances. The calculation was carried out for one turnover of 18.5 years. The authors have obtained that even if the albedo of the surface is 0.6 the depth of heat propagation in the body of the comet does not exceed 10 m during the whole period of the comet's circulation.

The results obtained in this paper do not contradict also the results of calculation of thermal models conducted for various regions of comet 67P during one revolution around the Sun. In particular, in (Hu et al., 2017) for points having a maximum surface temperature of 170-180 K, it was obtained that the temperature of the inner regions is 140 K is reached at a depth of 4-5 cm, analogous values were calculated by us and are shown in Figure 5b and Table 1. This, from our point of view, indicates an acceptable choice of the initial description of the thermophysical properties of the porous rock-ice composition, which was adopted in our model.

Another conclusion that follows from our results is that as solar radiation absorbs during many revolutions around the Sun, thermal energy accumulates in the inner regions of the cometary nucleus with a gradual advance of the temperature maximum deep into the interior. However, as can be seen from Figure 4-6, the position of the temperature maximum gradually stabilizes, approaching a certain constant value of depth, depending on the change in the nature of the illumination of the surface of the section under consideration and the thermophysical properties. This type of accumulation of thermal energy provides the possibility of intensive production of the gas component of the coma in the part of the orbit after the passage of perihelion. This conclusion obtained by us qualitatively coincides with the results of modeling the heat propagation in a comet-like body simulating the interstellar asteroid 1I/2017 U1 'Oumuamua (Fitzsimmons, A. et al.). The authors showed that even at a surface temperature of the body of about 600°K, the temperature of sublimation of ice $CO_2 \approx 90^\circ K$ is reached only two months after approaching the minimum distance of the object with the Sun.

We can also estimate the depth of possible sublimation of various ices in regions where the outer layer will have significant defects (faults, cracks): to a depth of 0.1 to 0.65 m the layer will be almost completely degassed, to a depth of 0.13 to 0.85 m it will be substantially depleted of CO_2 . The distribution of the most volatile macro component of the cometary nucleus, CO , should change to the

greatest degree. CO could be completely degassed from the layer to a depth of 0.9-1.5 m, but if the outer layer does not have the defects mentioned above, CO , subliming in relatively deep layers, can be redeposited in the outer layers as crystalline hydrate $CO \cdot 5.75H_2O$; its sublimation temperature is approximately 20°K higher than that of CO ice.

It is important to note that the phenomenon of gas activity of the nucleus of the comet 67P is significantly affected not so much by the maximum values of surface temperatures as by the ratio of the duration of the "day" and "night". For example, in the active points of the MAAT region 27 and 364, the ratio of the duration of "day" and "night" is 17/3 and 18/2, respectively, and for the inactive point 453 the ratio of the duration of "day" and "night" is 12/8.

Future works: Further development of the model can go in several directions.

Firstly, the including of the thermophysical properties of a porous rock-ice composition that depend on the temperature of the substance of the comet's nucleus will make it possible to pass from the problem of heat conductivity to the study of the Stefan problem. The study of thermal processes, taking into account phase and structural transitions in the substance of the cometary nucleus, will allow us to make more correct conclusions about variations of the chemical composition of the comet coma and the nucleus itself, in the course of prolonged thermal evolution. Secondly, if the observational data is sufficient to construct a detailed triangulation of the surface of the comet nucleus, as such as for comet 67P, it is advisable to proceed to different-scale grids to construct the surface profile. This will allow for more detailed modeling of the variation in illumination of the regions under consideration, with relatively "rough" detailing of the rest of the comet core surface.

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