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Selected phenomena that affect the structure of the cometary landscape

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Abstract. The paper discusses four processes that may be responsible for shaping the relief of the comet landscape. The considerations take into account the following phenomena: intense sublimation of cometary ice, emission of dust from the surface comet and through jets, migration of dust on the cometary surface, and destruction of fragment the nucleus surface in the context of a change in cometary brightness. These processes appear to be of key importance for the formation of an irregular comet nucleus structure. It should be remembered that the processes discussed in this paper have an impact on the relief of the surface, but on a longer time scale, i.e., more than a few orbital periods.

Keywords. Comets: General—individual – 19P/Borrelly—103P/Hartley—29P/Schwassmann–Wachmann— 67P/Churyumov–Gerasimenko.

1. Introduction

Thanks to space probes, we can really closely examine the surface structure of cometary nuclei. The analysis of the photos taken by the instruments of space probes shows, first of all, the landscape, as well as the local sublimation activity of the comet. Both the structure of the nucleus and its activity are related to the physicochemical processes taking place on the surface and in the subsurface layers of the cometary nucleus. Detailed information on the surface contour of comet 67P/Churyumov–Gerasimenko (hereinafter referred to as 67P) was provided by the Rosetta space probe. The images were taken by Optical, Spectroscopic, and Infrared Remote Imaging System (OSIRIS) onboard the Rosetta spacecraft allowed astronomers to construct a map of the 67P nucleus surface. On its surface, we can distinguish 26 regions, each named after an Egyptian deity.

The conducted research and analyzes show that the 67P nucleus has a conspicuous bilobate shape of the overall dimensions along its main axes: $4.34 \times 2.60 \times 2.12$ km. The two lobes are connected by a short neck and the larger lobe has a size of about $4.1 \times 3.52 \times 1.63$ km, while the smaller lobe has a size of about $2.50 \times 2.14 \times 1.64$ km (Jorda *et al.* 2016). The cometary nucleus rotates with the period $P = 12.4$ h (Preusker *et al.* 2015). The average density of the nucleus $\rho_N = 537.0 \pm 0.7$ kg/m^3 (Preusker *et al.* 2017). The average mean radius is $R_N = 1720$ m, and $g_c = 2.25 \times 10^{-4}$ m/s^2 is the average acceleration due to gravity on the comet surface (Vincent *et al.* 2016a,b). The total surface area S_N of the 67P nucleus based on the SPG SHAP7 model is 51.7 ± 0.1 km^2 (Preusker *et al.* 2017). On the surface of comet 67P, numerous craters, peaks, cracks, and even landslides are visible. In light of what has been said above, we can conclude that the shape of the cometary nucleus is highly irregular (Vincent *et al.* 2016a,b; Pajola *et al.* 2017). In the case of other comets, we can also talk about the complex structures of their nuclei—even taking into account their actual shape and geology. A direct example of this is comets 9P/Tempel and 103P/Hartley (Thomas *et al.* 2007, 2013; Snodgrass *et al.* 2010; A'Hearn *et al.* 2011).

The purpose of this article is to discuss the thermodynamic mechanisms that can significantly contribute to changing the cometary landscape. Of course, it should be clearly emphasized that the entire process of cometary landscape formation does not take place during one orbital period. The

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sequence of these events can span from a few to a few hundred or more orbital periods. This means that the comet is able to modify its structure by itself until it loses water–ice, which acts as a binder of its entire structure. In the context of the sculpture of the comet's landscape, collisions with other small bodies are not without significance. However, in this paper, we focus only on the analysis of thermodynamic processes that may result in the evolution of the relief of the cometary landscape.

2. Intensive sublimation of cometary ice

As the comet approaches the Sun, the individual ices begin to sublimate in its natural order, according to its evaporation temperature. Thermal energy penetrates from the surface layers into the inside nucleus, causing the evaporation of solidified comet gases. More volatile substances, for which the evaporation temperature is relatively low, sublimate from the deeper layers of the cometary nucleus. In the relatively warmest regions of the cometary orbit, sublimation is controlled by the least volatile ices H_2O and H_2O_2. Such a variety of sublimation of individual cometary ices leads to the formation of a porous nucleus structure. It also explains the existence of various gases in the coma as it approaches the Sun. Sublimation of individual ices is related to the temperature on the surface of the nucleus and the conductivity of the cometary matter. This temperature is determined by the energy balance Equation (1).

$$\frac{S_{\odot}}{d^2}(1-A_{\mathrm{N}})\cos\varphi = \epsilon\sigma T_{\mathrm{s}}^4 + h(\psi)K(T)\frac{\Delta T}{\Delta x} + \frac{\dot{Z}L(T)}{N_{\mathrm{A}}}. \tag{1}$$

The left part of this equation describes the input of the solar energy into the comet. Here $S_{\odot}$ means for the solar constant, A_{N} is the albedo of the nucleus, and φ and d denote the zenith angle of the Sun and a heliocentric distance (expressed in au units) of the comet, respectively. In the right part of this equation ϵ, σ, T_{s}, $\dot{Z}$, $L(T)$, and N_{A} denote the infrared emissivity of the comet surface, the Stefan–Boltzmanmn constant, the temperature of the surface of the nucleus, the rate of sublimation, and the latent heat of sublimation for ice H_2O or CO_2, respectively. The Avogadro number and average heat conductivity of cometary material are denoted as N_{A} and $K(T)$, respectively. The heat conductivity $K(T)$ is corrected for the sake of porosity ψ by Hertz factor $h(\psi)$ because of the reduction of the contact surface between cometary particles (Tancredi *et al.* 1994; Davidsson & Skorov 2002). In Equation (1), $\Delta T = T - T_{\mathrm{c}}$, where T_{c} stands for the average temperature in the cavity. In this paper, we assume that $\Delta x = 10$ m, which means that the upper wall of the cavity is placed 10 m below the surface of the cometary nucleus (Gronkowski & Wesołowski 2015b). Solving numerically, Equation (1) should also be taken into account the Clausius–Clapeyron equation, the perfect gas equation, and the rate of sublimation equation. The sublimation rate $\dot{Z}$ of cometary ice is expressed as (Wesołowski 2020b):

$$\dot{Z} = A \cdot \mathrm{e}^{-B/T} \cdot \sqrt{\frac{\pi}{2m_{\mathrm{g}}k_{\mathrm{B}}T}}. \tag{2}$$

In Equation (2), the individual symbols mean: A and B are constants, associated with the sublimation of cometary gas. The values of these parameters are expressed in units of pressure and temperature, respectively. Also, m_{g} is the mass of cometary gas molecules, k_{B} is the Boltzmann constant, and T is the temperature on the surface of the nucleus. Sublimation gas molecules are responsible for the emission of small ice-dust particles into the coma. However, larger fragments remain on the surface of the nucleus. Because the sublimation gas pressure is too small to lift these larger particles. As a result, it creates a cometary mantle, which significantly weakens the rate of sublimation of ice. In general, the analysis of the results for space probes shows that the comet loses about 0.2–0.5% of its mass during one complete cycle. This loss is primarily related to the sublimation of cometary ice. The intense sublimation of cometary ice may be responsible for creating a diverse surface structure of the cometary nucleus. This phenomenon is responsible for the emergence of new and deepening old depressions of different sizes on the surface of the cometary nucleus. This approach was used to study the origin of Hatmehit depression on the surface of the comet of 67P (Kossacki & Czechowski 2018).

3. Dynamics of cometary dust

When considering the dynamics of particles, we need to make some division, if only because of their size. In the simplest approach, we can talk about three types of behavior of particles (Wesołowski *et al.* 2019; Wesołowski 2020a):

- the smallest particles due to the sublimation of given ice are emitted into the coma,
- slightly larger crumbs may migrate across the surface, causing local avalanches,

- the larger particles of the matter remain motionless.

The dimensions of individual particles depend on many factors. The most important of them include the heliocentric distance which translates into the sublimation rate of given comet ice, the density of particles, the shape of the nucleus, and its radius (Gronkowski & Wesołowski 2015b, 2017; Wesołowski 2020a; Wesołowski *et al.* 2019, 2020a). There are several known and widely discussed in the literature mechanisms that are responsible for the emission of particles from the surface of comet nuclei. The most important of them are:

- sublimation of the cometary ice,
- the phenomenon of the cometary jets,
- electrostatic levitation,
- rocketmechanism.

In this paper, we focused on the above first two mentioned mechanisms, because it seems that they have the greatest importance. The first mechanism has been well-known for many decades (Jones 1995; Crifo *et al.* 2005; Molina 2010; Rubin *et al.* 2011; Tenishev *et al.* 2011; Combi *et al.* 2012; Fougere *et al.* 2012, 2014). However, the second mechanism has been confirmed in the current 20 years based on images taken by the spacecraft (Deep Space, Deep Impact, EPOXI, and Rosetta). It should be noted that the rocket force can play an important role only for the particles which sublimate asymmetrically (Kelley *et al.* 2013). Additionally, by definition, the rocket force only works on particles with day–night temperature anisotropies. This effect is caused by the sublimation of surface ice on the day side of ejected particles, which causes them to move in the anti-sunward direction at greater than expected velocities (Reach *et al.* 2009). However, we assume in our analysis that the cometary particles either do not display sublimation activity or sublimate isotropically. In the first case, it means that cometary particles contain only a silicate core (possibly covered by refractories) while in the second case, it means that the particles consist only of ice or they are built of a silicate core, a mantle of organic refractories, and a crust of ice (Greenberg & Hage 1990; Davidsson & Skorov 2002). The occurrence of jets-like phenomena in the form of highly collimated jets of gas and dust has been recently reported for several comets. On September 21, 2001, the spacecraft Deep Space approached the nucleus of Comet 19P/Borrelly at a distance of about 2,170 km. The nucleus of this comet, coma, and dust jets was pictured by an on-board camera. The main jet that dominated in the near-nucleus coma was emitted from a broad central cavity and it had a jets-like form (Yelle *et al.* 2004 and literature therein). On November 4, 2010, the Deep Impact spacecraft in the frame of the EPOXI mission it approached comet 103P/Hartley to a distance of 700 km. On the excellent quality images performed by spacecraft camera, bright jets are visible. Also, long-standing observations of famous Comet 29P/Schwassmann–Wachmann revealed the fact that the activity of this comet is related to the number of jets produced by its nucleus (Ivanova *et al.* 2011 and literature therein). The phenomenon of cometary jets has been confirmed in the case of 67P comet. From the current research, it shows that jets have also contributed to changes in the brightness of the comet 67P (Groussin *et al.* 2015; Keller *et al.* 2015; Lara *et al.* 2015; Lin *et al.* 2015; Vincent *et al.* 2015, 2016a).

3.1 *Gentle sublimation*

In the first step of our considerations, we determine the maximum radius of a cometary particles $a_{\max}$ which are lifted from the surface of a comet as the results of gentle sublimation of cometary volatile species. The dynamics of dust particles laying on the surface of the cometary nucleus are determined by the following forces: gravitation of a comet nucleus, drag force coming from the cometary gases, and the centrifugal force related to the rotation of a comet nucleus. Other forces acting on the particles like solar tidal force (which is the product of the Sun gravitation and inertia force related to the orbital motion of a comet), solar radiation force, and Coriolis forces are negligible for the considered large particles sized in the range of several centimeters. Then the equation of motion for a given particle takes the following form (Gronkowski & Wesołowski 2015b; Wesołowski *et al.* 2020a):

$$m_{\mathrm{gr}} \frac{\mathrm{d}v_{\mathrm{gr}}}{\mathrm{d}t} = \frac{1}{2} C_{\mathrm{D}} \pi a_{\max}^2 (v_{\mathrm{g}} - v_{\mathrm{gr}})^2 \rho_{\mathrm{g}} + m_{\mathrm{gr}} \omega^2 R_{\mathrm{N}} \cos^2 \varphi - g_{\mathrm{c}} m_{\mathrm{gr}}. \quad (3)$$

The first term on the right side of this equation stands for the drag force coming from the comet gases, the second one represents the centrifugal force related to the rotation of a comet nucleus, and the last is the gravitation of the cometary nucleus. Here m_{gr} is the mass of the considered large particles, v_{gr} the its velocity, t the time, C_{D} the modified free-molecular drag coefficient for spherical body (Crifo *et al.* 2005; Skorov *et al.* 2016), $a_{\max}$ is the radius of a large moving particle, v_{g} the gas flow velocity, v_{gr} the velocity of particles, ρ_{g} the density of cometary gas, ω the angular velocity of a cometary nucleus, R_{N} the radius, and g_{c} the gravitational acceleration from the cometary nucleus. When using Equation (3) and condition: $\mathrm{d}v_{gr}/\mathrm{d}t \geq 0$, we can determine the dependence on the maximum radius of the emitted particle into a coma (Wesołowski 2021b):

$$a_{max} = \frac{3C_D v_g^2 \rho_g}{8\rho_{gr}(g_c - (4\pi^2 \cos^2\varphi/P^2) \cdot R_N)}. \tag{4}$$

In Equation (4), the individual symbols have the same meaning as above. Moreover, we will consider two cases: (i) comet nucleus non-rotating ($P \to \infty$) and (ii) comet nucleus rotates with the period ($P = 10\,\mathrm{h}$).

3.2 *Cometary jets-like phenomena*

The approach to the general problem of jet-like phenomena for comets presented in this chapter is based on the assumption that there are many cracks, holes, and cavities inside the comet nucleus (Hughes 1996; Ipatov & A'Hearn 2011; Ipatov 2012; Gronkowski & Wesołowski 2015a; Vincent *et al.* 2015; Wesołowski & Gronkowski 2018a,b). The above assumption seems to be probable for at least two reasons. First, the holes and cavities may be relics from the time of the formation of the Solar System. Second, different kinds of cometary ices have different rates of sublimation. Such a way of cometary material sublimation favors the creation of holes and cavities in a nucleus. So the distribution of holes and cavities in the nucleus structure should reflect the way the comet was formed. In the context of studying the evolution of comet nuclei, the energy balance equation plays a key role. In this place we should bear in the mind two cases: (a) cometary ices sublime from the part of the nucleus surface which is situated over the cavity of jet, and (b) this part of the nucleus does not show any sublimation activity. In case (a), the energy balance equation has the following form (Wesołowski *et al.* 2020a):

$$A_c \frac{S_\odot (1-A)\cos\theta}{d^2} = (A_c - A_{min})\left(\epsilon\sigma T_s^4 + \frac{\dot{Z}L(T)}{N_A} + h(\psi)K(T)\frac{\Delta T}{\Delta x}\right). \tag{5}$$

For case (b), we have the following equation:

$$A_c \frac{S_\odot (1-A)\cos\theta}{d^2} = (A_c - A_{min})\left(\epsilon\sigma T_s^4 + h(\psi)K(T)\frac{\Delta T}{\Delta x}\right). \tag{6}$$

In Equations (5) and (6), the left sides stand for the absorbed by the nucleus solar radiation energy. The right side of Equation (5) is a sum of the re-radiated by nucleus energy, the energy used for the sublimation of cometary ices, and the heat conducted into the interior of the comet nucleus. In Equation (6), the right side is the same as in Equation (5) but the factor related to the sublimation of cometary ices is omitted.

The symbols used in Equations (5) and (6) have the same meaning as for quiet sublimation. In addition, A_c is assumed to be a recess section and A_{min} is a streaming channel section (see Figure 1). Moreover, for the sake of simplicity, we assume that all heat conducted from the surface of the comet nucleus to the cavity is used for the latent heat of sublimation. With this assumption, the following equation is important (Gronkowski & Wesołowski 2015b):

$$L\dot{M} = (A_c - A_{min})h(\psi)K(T)\frac{\Delta T}{\Delta x}, \tag{7}$$

where $\dot{M}$ is the mass flux from the jet (in kg/s units). In the sake of calculation the velocity of gas molecules v_{gey} in the jet at the exit of geyser, we should use the Bernoulli equation (Wesołowski *et al.* 2020a):

$$\frac{\gamma}{\gamma-1}\frac{p_{cav}}{\rho_{cav}} + \frac{v_{cav}^2}{2} = \frac{\gamma}{\gamma-1}\frac{p_{gey}}{\rho_{gey}} + \frac{v_{gey^2}}{2}. \tag{8}$$

Here the parameter γ denotes the ratio of the specific heats of flowing gas. The left side of this equation is dependent on the physical conditions in the cavities and the right side is dependent on the physical condition at the exit of the geyser. In Equation (4), the following variables: v_{cav}, ρ_{cav}, v_{gey}, ρ_{gey} stand for the velocity of gas molecules and its density in the cavity and at the exit of geyser on the surface of cometary nucleus, respectively. Additionally, we should take into account the relation that results from the continuity equation:

$$\dot{M} = A_{min}\rho_g v_{gey}. \tag{9}$$

Using Equations (5)–(9), two systems of equations can be constructed for cases (a) and (b), respectively. To solve these equations, one should additionally take into account: the ideal gas law, the adiabatic law, and the equation of state defined by the Clausius–Clapeyron formula. Moreover, the dynamic relationship for gas molecules escaping from the comet surface into the vacuum must be taken into account. We note that detailed methods for similar calculations are widely described in the literature (Keller 1990; Yelle *et al.* 2004). By proceeding in the same way as in the

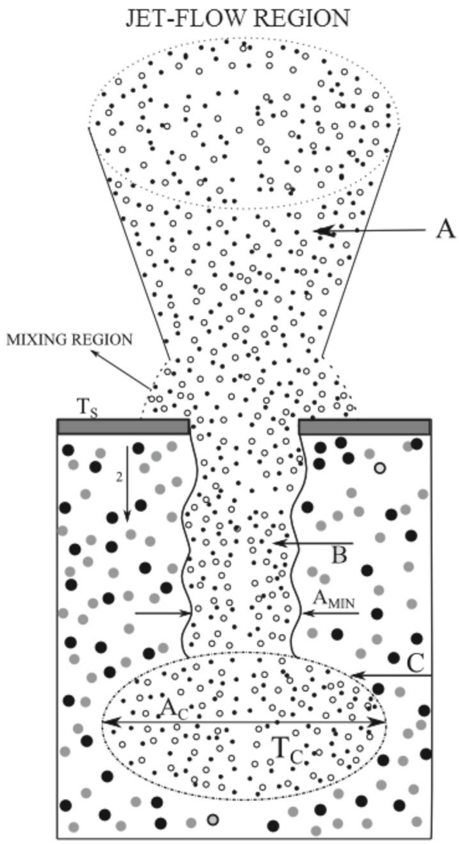

Figure 1. The cross-section through the surface layer of a cometary nucleus in the vicinity of a geyser. The following notations are adopted: A—a jet, B—a channel of geyser, and C—a cavity, T_s is the temperature on the surface of the cometary nucleus. Note that in the geyser model we take into account two areas: gas mixing and jet flow (Belton 2010).

case of quiet sublimation, it can be shown that the maximum size of the particle emitted by the gas stream is given by the relationship:

$$a_{\mathrm{max,jet}} = \frac{3C_{\mathrm{D}}v_{\mathrm{gey}}(1-\alpha)}{8\rho_{\mathrm{gr}}(g_{\mathrm{c}} - (4\pi^2 R_{\mathrm{N}}\cos^2\phi/P^2))\alpha L(T)} \times h(\psi)K(T)\frac{\Delta T}{\Delta x}. \quad (10)$$

In Equation (10), the parameter α stands for the ratio of minimum cross-sectional area in the channel of geyser to the cross-sectional area of the geyser's cavity ($\alpha = A_{\mathrm{min}}/A_{\mathrm{c}} = 0.01$). The other symbols have the same meaning as above.

3.3 *Migration of dust on the surface of the nucleus*

Particle size is a key factor in dust migration on the surface of the comet's nucleus. This problem concerns those particles for which ice sublimation is not sufficient to lift the particle into a coma. On the other hand, this sublimation can initiate the movement of the particle on the comet's surface. In the case of dust migration, we take into account the same forces that were used to determine the dimensions of the particle ejected into the coma. Additionally, we consider two additional forces related to the ground reaction: normal reaction force and frictional force. A detailed description of the model of dust migration along the comet's surface depending on the shape of the nucleus is presented in the study by Wesołowski *et al.* (2019). At this point, we will only present the final form of the equation, based on which we determine particles migration:

$$f(\phi) = \frac{3\pi\cos\varphi\sin\varphi}{G\rho_{\mathrm{N}}P^2(1-(3C_{\mathrm{D}}v_{\mathrm{g}}^2\rho_{\mathrm{g}}/8\rho_{\mathrm{gr}}g_{\mathrm{c}})a_{\mathrm{gr}}) - 3\pi\cos^2\varphi}. \quad (11)$$

In Equation (11), individual symbols mean: G is the gravity constant and ρ_{N} the nucleus density. However, the other symbols have the same meaning as above. Note that in Equation (11) there is a a_{gr} parameter which determines the size of the particle that can migrate across the cometary surface. The movement of particles on the surface of a comet is possible only if the following relation holds: $\mu \le f(\phi)$, where μ means the friction coefficient and $f(\phi)$ is the migration coefficient.

3.4 *Destruction of the comet surface—the cometary outburst*

Another mechanism that can affect a comet's landscape structure is a cometary outburst. This phenomenon consists of a sharp change in the brightness of the comet, most often within 2.5 days (Hughes 1991; Wesołowski 2021a). It is commonly believed that the cause of a cometary outburst is the ejection of a fragment of the outer surface of the nucleus. The deeper regions of the nucleus that contain more volatile comet material are then exposed. The rate of water–ice sublimation increases from the newly exposed subsurface layers. The consequence of this process is the emission of a significant amount of gases and dust into the coma. The sunlight is then scattered efficiently onto the dust particles. The result of this process is a change in the cometary brightness, i.e., its outburst. The direct cause of cometary outbursts is not precisely known, but it is generally accepted that physicochemical processes occurring in the structure of the nucleus are responsible for this phenomenon. In order to explain the phenomena occurring under the surface of the nucleus, several mechanisms were proposed to explain this process. The most frequently considered phenomena include the pressure mechanism (Whitney 1955), the solar wind (Intriligator & Dryer 1991), the idea of the amorphous transformation of water and ice, which tried to explain the mechanism of comet outburst (Prialnik & Bar-Nun 1987, 1992; Enzian *et al.* 1997), the idea of numerous cavities in comets (Ipatov & A'Hearn 2011; Gronkowski & Wesołowski 2015a; Wesołowski & Gronkowski 2018b), melting cometary ice (Miles 2016), the avalanche mechanism and cryovolcanism (Steckloff & Melosh 2016; Wesołowski 2020b; Wesołowski *et al.* 2020c). The exact characteristics of these mechanisms are not the purpose of this article, their analysis can be found in the papers (Hughes 1990; Gronkowski & Wesołowski 2016; Gronkowski *et al.* 2018; Wesołowski & Gronkowski 2018a; Wesołowski 2020b,c,d; Wesołowski *et al.* 2020c). The effect of the above potential mechanisms that occur in the structure of the cometary nucleus is the ejection of a fragment of the cometary nucleus in the form of a cloud of ice–dust particles. This behavior of the comet during the outburst has significance in the context of the evolution of the cometary landscape.

Pogson's law was used to estimate the change in comet brightness in the context of surface destruction. It is worth noting that the paper by Wesołowski *et al.* (2020c) presents three independent approaches for determining the change in comet brightness. In this paper, we use model A, but in a slightly modified form:

$$\Delta m = -2.5 \log \frac{p_{\mathrm{N}}(\theta)C_{\mathrm{N}} + p_{\mathrm{dust}}(\theta)(C_2(t_2) + C_{\mathrm{ej,dust}}) + p_{\mathrm{ice}}(\theta)C_{\mathrm{ej,ice}}}{p_{\mathrm{N}}(\theta)C_{\mathrm{N}} + p_{\mathrm{dust}}(\theta)C_1(t_1)}, \tag{12}$$

where $p_{\mathrm{N}}(\theta)$ is a phase function related to the scattering cross-section from the cometary nucleus C_{N}, $p_{\mathrm{dust}}(\theta)$, and $p_{\mathrm{ice}}(\theta)$ stand for the phase functions of cometary dust particles and cometary ice–dust particles, respectively. Note that the mean value of the phase function for the Jupiter family comets is $p_{\mathrm{N}}(\theta) = 0.053 \pm 0.016$ mag deg^{-1} (Snodgrass *et al.* 2011; Muinonen *et al.* 2019). Moreover, it was assumed that C_2 and C_1 are the total scattering cross-sections of cometary particles that were raised by sublimation and remain in the coma of the normal non-active phase (t_1) and the active outburst phase (t_2), the $C_{\mathrm{ej,dust}}$ and $C_{\mathrm{ej,ice}}$ are the total cross-sections of scattering resulting from the ejection part of the surface of the nucleus for dust and ice particles, respectively. The individual scattering sections that appear in Equation (12) can be defined by the following equations (Wesołowski & Gronkowski 2018a; Wesołowski 2020b, 2021a):

$$C_{\mathrm{N}} = A_{\mathrm{N}} \cdot S_{\mathrm{N}}, \tag{13}$$

$$C_1(t_1) = \frac{3\pi\eta(t_2)\kappa R_N^2 \dot{Z} R_{\mathrm{c}}(t_1) m_{\mathrm{g}} \int_{\mathrm{r_{min}}}^{\mathrm{r_{max}}} Q_{\mathrm{si}} r^2 f(r)\mathrm{d}r}{v_{\mathrm{g}}\rho_{\mathrm{N}} \int_{\mathrm{r_{min}}}^{\mathrm{r_{max}}} r^3 f(r)\mathrm{d}r}, \tag{14}$$

$$C_2(t_2) = \frac{3\pi\eta(t_1)\kappa R_{\mathrm{N}}^2 \dot{Z} R_{\mathrm{c}}(t_2) m_{\mathrm{g}} \int_{\mathrm{r_{min}}}^{\mathrm{r_{max}}} Q_{\mathrm{si}} r^2 f(r)\mathrm{d}r}{v_{\mathrm{g}}\rho_{\mathrm{N}} \int_{\mathrm{r_{min}}}^{\mathrm{r_{max}}} r^3 f(r)\mathrm{d}r}, \tag{15}$$

$$C_{\mathrm{ej,dust}} = \frac{3c_{\mathrm{dust}} M_{\mathrm{ej}} \int_{\mathrm{r_{min}}}^{\mathrm{r_{max}}} Q_{\mathrm{dust}} r^2 h(r)\mathrm{d}r}{4\rho_{\mathrm{dust}} \int_{\mathrm{r_{min}}}^{\mathrm{r_{max}}} r^3 h(r)\mathrm{d}r}, \tag{16}$$

and

$$C_{\mathrm{ej,ice}} = \frac{3b_{\mathrm{ice}} M_{\mathrm{ej}} \int_{\mathrm{a_{min}}}^{\mathrm{a_{max}}} Q_{\mathrm{ice}} a^2 f(a)\mathrm{d}a}{4\rho_{\mathrm{ice}} \int_{\mathrm{a_{min}}}^{\mathrm{a_{max}}} a^3 f(a)\mathrm{d}a}. \tag{17}$$

The individual symbols that have been used in Equations (13)–(17) mean: S_{N} is the total area of the cometary nucleus, κ is the dust–gas mass ratio, $R_{\mathrm{c}}(t_1)$ and $R_{\mathrm{c}}(t_2)$ are the radius of the coma in the quiet sublimation phase and during the outburst, respectively. The M_{ej} is the mass ejected during the outburst, m_{g} the mass of the cometary gas, Q_{ice} and Q_{dust} stand for the scattering efficiencies of water–ice particles a and dust particles r, respectively. Moreover, it was assumed that b_{ice} is the fractional content (percentage) of ice particles in the total amount of particles contained in the coma, c_{dust} stands for the percentage of dust particles in the total amount of particles in the coma (of course, $b_{\mathrm{ice}} + c_{\mathrm{dust}} = 1$). Also, we assume that $\eta(t_1)$ is a fraction of the surface of the nucleus, which is active of the gentle sublimation. The equivalent of the parameter $\eta(t_1)$ during the outburst is $\eta(t_2)$. The other symbols have the same meaning as before. A detailed analysis of individual scattering sections are presented in the papers (Gronkowski & Wesołowski 2012, 2015a; Wesołowski & Gronkowski 2018a; Wesołowski 2020b, 2021a; Wesołowski *et al.* 2020b).

Note that in Equations (14)–(17), we used two distribution functions for water ice and dust particles, respectively. These functions can be expressed using the following Equations (18) and (19):

- for ice particles:

$$f(a) = k\left(1 - \frac{a_0}{a}\right)^M \left(\frac{a_0}{a}\right)^N, \tag{18}$$

where k is the normalization constant and $a_0 = 1 \times 10^{-6}$ m. The exponent M depends on the heliocentric distance of a comet. The exponent N defines the slope of the size distribution function, for the large a it is ≈ 4 (Newburn & Spinrad 1985).

- for dust particles:

$$h(r) = C \cdot r^{-3.7}, \tag{19}$$

where r and C are the radius of the effective cross-section of fluffy aggregate and the normalizing constant, respectively (Lin *et al.* 2017).

4. Results

TTable 1 represents a list of the most important constants that were used in numerical simulations. In the first case, we assume that the cometary activity is controlled by the sublimation of water–ice (Figures 2–8). However, in the second case, it was taken into account that this activity is controlled by carbon dioxide sublimation (Figures 9–15). The calculations assume that the comet is at a heliocentric distance equal to $d = 2$ au. Based on these assumptions, Figures 2 and 9 show the sublimation rate distribution as a function of the cometocentric latitude which refer to water–ice and carbon dioxide, respectively. This parameter plays a key role in relation to the considered mechanisms. The article presents selected thermodynamic mechanisms that may affect the relief of the comet landscape. It should be emphasized once again that these mechanisms may affect the appearance of the cometary nucleus but on a longer time scale, i.e., more than a few orbital periods. The result of this mechanism is the emission of comet particles on the cometary surface. We considered two cases here: a non-rotating model and a rotating of the cometary nucleus. The developed numerical model takes into account the mathematical formulas presented in Sections 2 and 3.1. The simulation results are presented in Figures 3 and 10 which refer to water ice and carbon dioxide, respectively. The second mechanism is also associated with the emission of dust into the coma, but this time the phenomenon of comet jets was used. In the case of jets, two energy balance equations were taken into account: (a) the surface above the pit sublimates and (b) the surface above the pit does not sublimate. As in the first case, two models of non-rotating and spinning comet nuclei were considered. The developed numerical model takes into account the mathematical formulas presented in Sections 2 and 3.2. The simulation results are presented in Figures 4 and 11 which refer to case (b). On the other hand, the calculations for case (a) are almost the same as for the quiet sublimation mechanism. The third mechanism discussed concerns those particles that are too large to be thrown into a coma by quiet sublimation or jet-like phenomena. For these particles, the possible migration across the comet nucleus must be considered. The developed numerical model takes into account the mathematical formulas that are presented in Sections 2 and 3.3. The key role in this mechanism is played by the particle size and the value of the friction coefficient between the particle and the surface of the nucleus. The results of these simulations are presented in Figures 5 and 12 which refer to water ice and carbon dioxide, respectively. The last mechanism discussed in this article concerns the destruction of a part of the cometary nucleus when it outbursts. In this case, we will focus on calculating the scattering of incident sunlight on ice and dust particles and their combinations with each other. The key parameter that determines the change in a cometary brightness is the ejected mass. This mass is directly related to the rejected surface. The developed numerical model took into account the mathematical formulas presented in Sections 2 and 3.4. The results of the numerical calculations are presented in Figures 6–8 and 13–15 which refer to water ice and carbon dioxide, respectively.

5. Discussion and conclusions

The considerations presented in this paper are related to the modeling of the cometary landscape structure. The considered mechanisms may be responsible for the evolution of the comet nucleus shape. In these considerations, the key parameter is the rate of sublimation of matter, which has a significant impact on the discussed thermodynamic processes.

In phenomena related to the emission of cometary particles, the maximum temperature and sublimation rate were taken into account in the calculations. It was dictated by the fact that the maximum dimensions of ice–dust particles that were emitted from the surface of the nucleus were analyzed. For this purpose, two mechanisms were used: quiet sublimation and the phenomenon of comet jets. In both of these cases, a wide range of densities of individual cometary particles was considered. The

Table 1. Values of the physical cometary parameters used in the numerical calculations and simulations.

Parameter	Value(s)	References
Radius of the comet nucleus (m)	$R_N = 2000$	Adopted value
Heliocentric distance (au)	$d = 2.00$	Adopted value
Mean depth of depression (m)	$h = 10$	Adopted value
Albedo of cometary nucleus (–)	$A_N = 0.04$	Richardson *et al.* (2007)
Emissivity (–)	$\epsilon = 0.9$	Wesołowski *et al.* (2019)
Density of cometary nucleus (kg/m^3)	$\rho_N = 500$	Richardson *et al.* (2007)
Density of dust particles (kg/m^3)	$\rho_{dust} = 2400$	Adopted value
Density of ice particles (kg/m^3)	$\rho_{ice} = 917$	Adopted value
Radius of coma during quiet sublimation (m)	$R_c(t_1) = 1 \times 10^8$	Wesołowski & Gronkowski (2018b)
Radius of coma during the outburst (m)	$R_c(t_2) = 3 \times 10^8$	Wesołowski & Gronkowski (2018b)
The solar constant (for $d = 1$ au) (W/m^2)	$S_{D\odot} = 1360.8 \pm 0.5$	Kopp & Lean (2011)
Constant A_{H_2O} for water ice (Pa)	$A_{H_2O} = 3.56 \times 10^{12}$	Fanale & Salvail (1984)
Constant B_{H_2O} for water ice (K)	$B_{H_2O} = 6141.667$	Fanale & Salvail (1984)
Latent heat of H_2O (J/kg)	$L(T)_{H_2O} = 2.83 \times 10^6$	Prialnik (2006)
Constant A_{CO_2} for carbon dioxide (Pa)	$A_{CO_2} = 107.9 \times 10^{10}$	Prialnik (2006)
Constant B_{CO_2} for carbon dioxide (K)	$B_{CO_2} = 3148.0$	Prialnik (2006)
Latent heat of carbon dioxide sublimation (J/kg)	$L(T)_{CO_2} = 0.594 \times 10^6$	Prialnik (2006)
The refractive index for ice (–)	$n_{ice} = 1.31 + 0.02i$	Adopted value
The refractive index for dust (–)	$n_{si} = 1.60 + 0.02i$	Adopted value
The average radius of the cometary ice particles (m)	$r_{ice} = 1.59 \times 10^{-6}$	Wesołowski *et al.* (2020b)
The average radius of the cometary dust particles (m)	$r_{dust} = 14.2 \times 10^{-6}$	Wesołowski *et al.* (2020b)
The scattering factor for cometary ice particles (–)	$Q_{ice} = 1.44$	Wesołowski *et al.* (2020b)
The scattering factor for cometary dust particles (–)	$Q_{dust} \approx 1.00$	Wesołowski *et al.* (2020b)
The value of the phase function for dust particles (–)	$p_{dust}(\Theta) = 0.080$	Calculate value
The value of the phase function for ice particles (–)	$p_{ice}(\Theta) = 0.177$	Calculate value

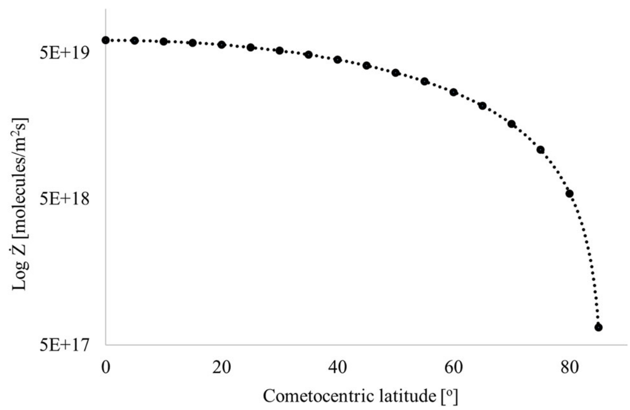

Figure 2. Logarithmic distribution of sublimation rate as a function of cometocentric latitude. The calculations assume that comet activity is controlled by the sublimation of water–ice.

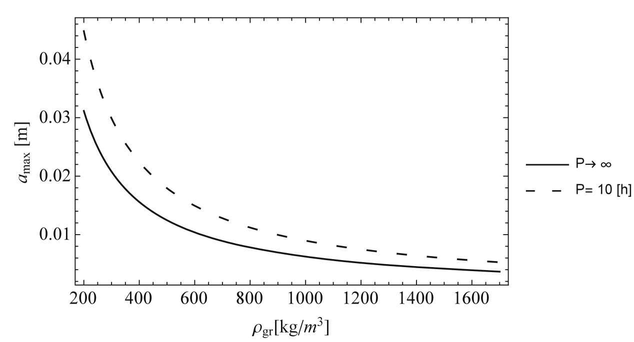

Figure 3. The maximum radius of cometary particles a_{max} (in meters), lifted up from a comet surface as a function of its particle density ρ_{gr}. It is assumed that the average radius of the nucleus is equal to $R_N = 2$ km, the heliocentric distance of the comet is equal to $d = 2$ au, and the cometary sublimation is controlled by water–ice.

analysis shows that the rate of sublimation, as well as the density of the comet material, has a significant impact on the size of the emitted comet particles. Moreover, the rotation of the comet nucleus increases the particle size by an average of 20%. In the case of cometary jets, the particles of matter that are ejected from the interior of the comet via streams of cometary gases are much larger than in the case of quiet sublimation (on average even seven times larger). Also, the ejection of gas and dust through the channel and the sublimation that occurs directly from the walls may contribute to the weakening of the geyser wall structure. As a consequence, there may be local depression

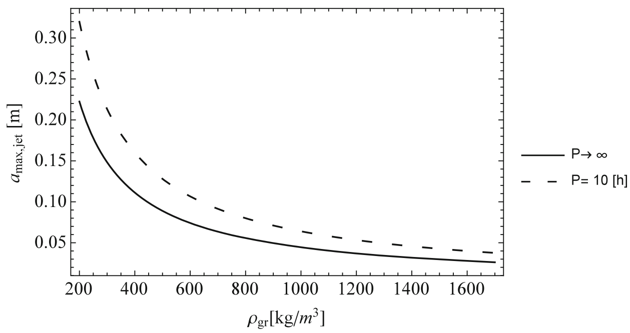

Figure 4. The maximum radius of cometary particles $a_{max,jet}$ (in meters), that are ejected from the inside of the nucleus via the jet as a function of its particle density ρ_{gr}. The remaining variables are the same as in the description of Figure 3.

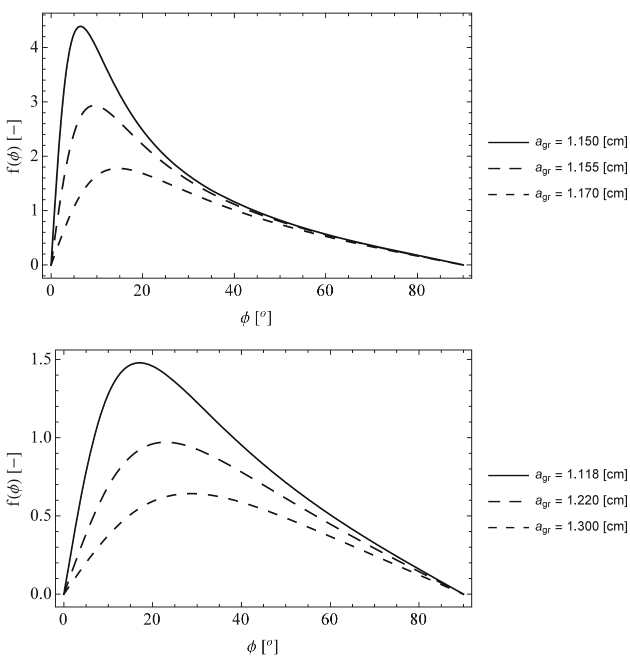

Figure 5. Coefficient $f(\phi)$ as the function of the comet-centric latitude ϕ. The calculations show the migration of dust towards the cometary equator—i.e., the angular width for the migrating particle, depending on its size and the value of the friction coefficient.

(Leliwa-Kopystyński 2018), which directly affects the surface appearance of the cometary nucleus.

The phenomenon of dust migration on the surface of comets also contributes to the change in the appearance of the nucleus. The key parameter, in this case, is the size of the particle that moves under given conditions. Dust migration is an important factor when it comes to causing local avalanches (Steckloff & Melosh 2016; Pajola *et al.* 2017; Wesołowski *et al.* 2020c). The phenomenon of dust migration may contribute to the emission of cometary matter from the

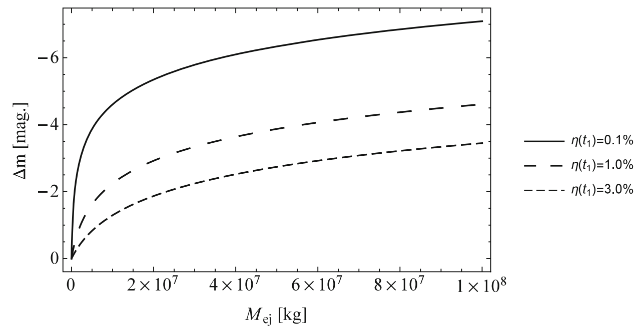

Figure 6. The brightness jump of the comets during its outbursts as the function of mass ejected M_{ej}. In the calculations, we assume that the parameter $\eta(t_1)$ is equal to 0.1% and 3.0%. Note that this parameter represents the ratio of the active sublimation area of the nucleus to its total surface during the inactive phase. The calculations assume that the cometary sublimation activity is controlled by water ice and the scattering of incident sunlight occurs on the ice particles. The calculations were performed using Equations (1), (2) and (12)–(17).

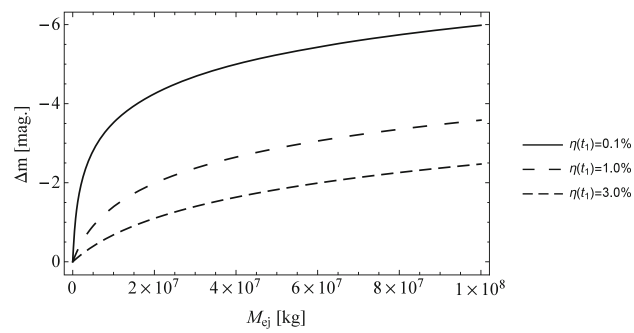

Figure 7. Similar to that in Figure 6, but the scattering of incident sunlight occurs on the dust particles.

nucleus into space. The smallest particles escape from the nucleus, but the larger ones can fall back on the comet in other places that differ from that they were emitted. This "rain" of falling back cometary matter can form smooth plains that can be up to several meters thick. This was confirmed by the observations made by the Rosetta mission. According to Tenishev *et al.* (2011), the main reason for the migration of cometary particles is the intensive sublimation of water ice. This phenomenon is crucial in the context of dust lifting and descending in a new location, the main cause of which, apart from sublimation, is the rotation of the cometary nucleus. Also, the ice particles that have been moved to another location on the surface of a comet can contribute to the sublimation of water ice. The total effect of these particles on the gas production rate was studied by Rubin *et al.* (2014). As already mentioned, dust migration can lead to an increase in the amount of dust particles in the coma on

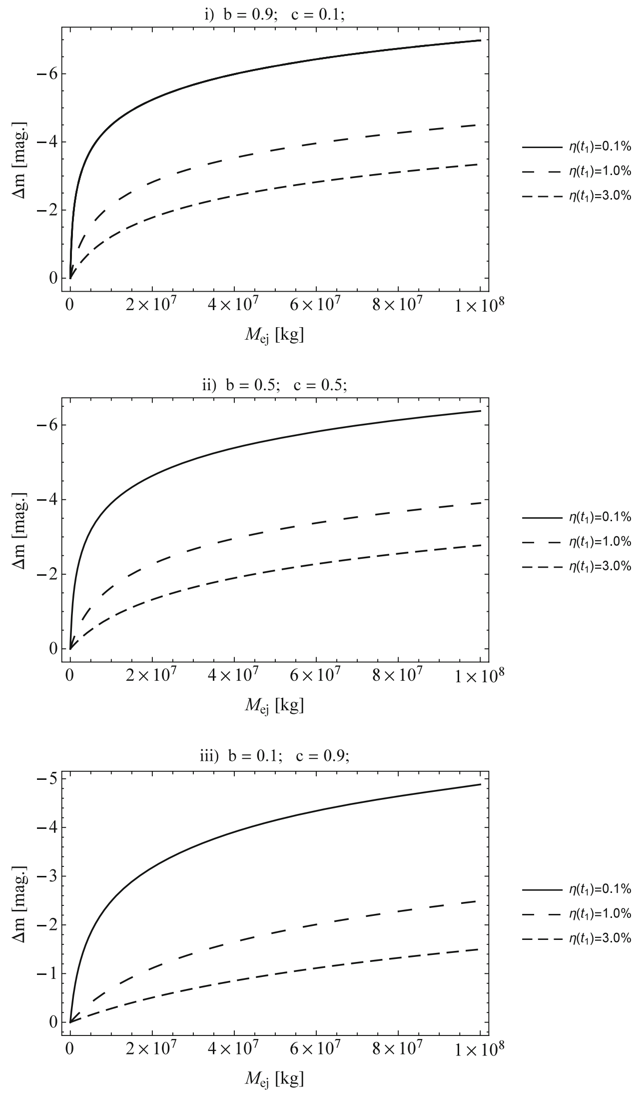

Figure 8. The brightness jump of comets during their outbursts as a function of the mass ejected M_{ej}. In these calculations, we assume the same values of the $\eta(t_1)$ parameter as shown in Figures 6 and 7. It is also assumed that the respective percentage of dust and ice particles in a coma from which the incident sunlight is scattering is (i) $b = 0.9$; $c = 0.1$; (ii) $b = 0.5$; $c = 0.5$; (iii) $b = 0.1$; $c = 0.9$.

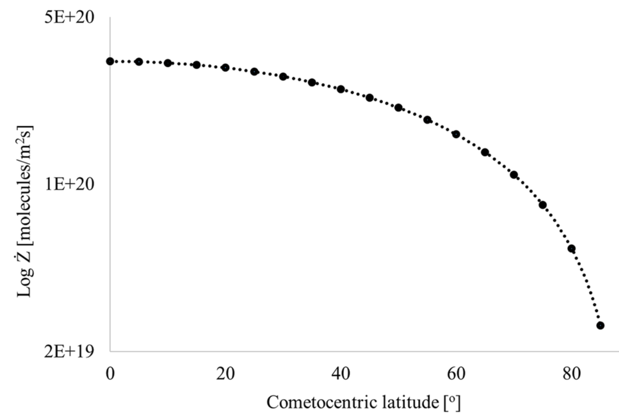

Figure 9. Similar to Figure 2, but calculations assume that cometary activity is controlled by carbon dioxide sublimation.

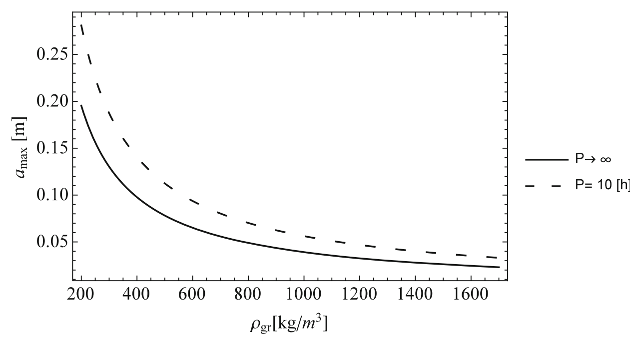

Figure 10. The calculations show a situation similar to that shown in Figure 3. The only difference is that the cometary activity is controlled by carbon dioxide sublimation.

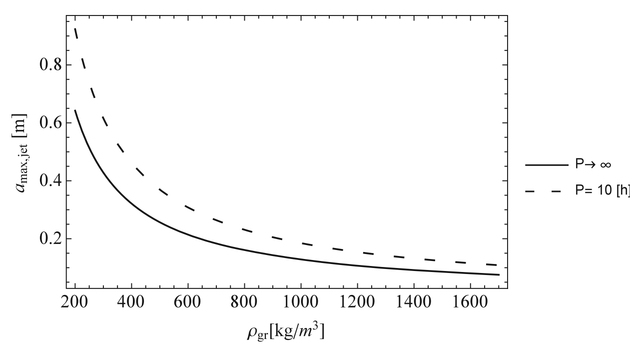

Figure 11. The calculations show a situation similar to that shown in Figure 4. The only difference is that the cometary activity is controlled by carbon dioxide sublimation.

which the incident sunlight is scattered. As a consequence, this leads to an increase in the brightness of the comet and even to its outburst. The consequence of the outburst is to throw away a fragment of the surface of the cometary nucleus. As a result, significant amounts of gases and dust are emitted into a coma (Gronkowski & Wesołowski 2015a; Wesołowski 2020b, 2021a). The sudden increase in the brightness of a comet is related to the fraction of the nucleus area that is active during quiet sublimation as well as during an outburst. These two phases are represented by the following two parameters: $\eta(t_1)$ and $\eta(t_2)$. Thus, the measure of the amount of cometary material in the coma is the rejected mass, which depends on the amplitude of the change in the brightness. The analysis shows that both the surface

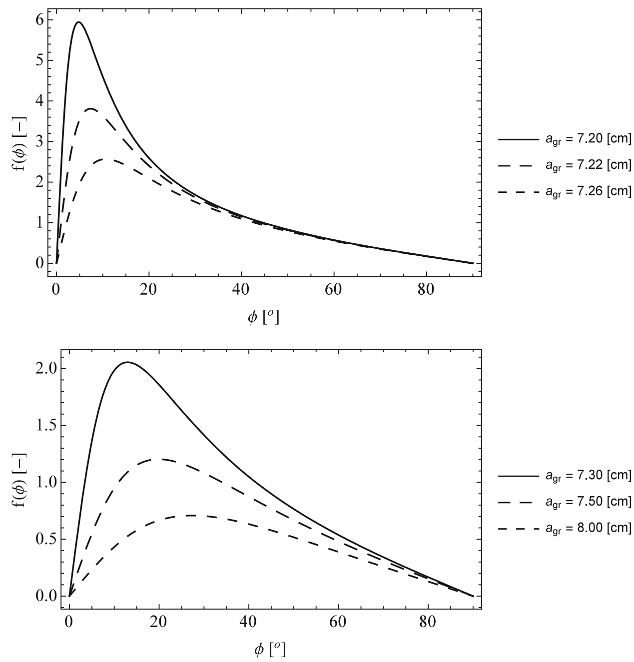

Figure 12. The calculations show a situation similar to that shown in Figure 5. The only difference is that the cometary activity is controlled by carbon dioxide sublimation.

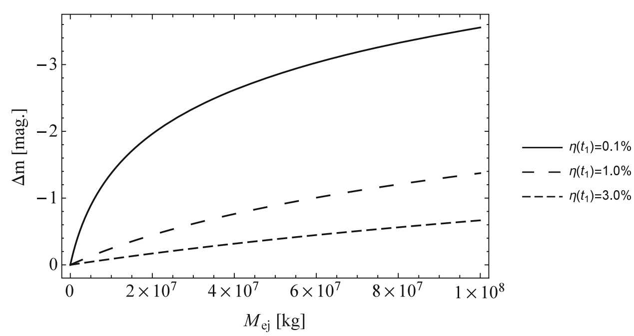

Figure 13. The calculations show a situation similar to that shown in Figure 6. The only difference is that the cometary activity is controlled by carbon dioxide sublimation.

active in the quiet sublimation phase and the rejected mass seem to be of significant importance in the case of comet outbursts. Additionally, the phenomenon of a cometary outburst by destroying a fragment of the surface is part of the processes related to the evolution of the cometary landscape.

The article discusses four mechanisms that may be important in the modeling of the comet nucleus structure. Additionally, they are related to the assumed heliocentric distance of the comet equal to $d = 2$ au. Of course, a comet that moves in the solar system may be active in different places in its orbit. Therefore, the

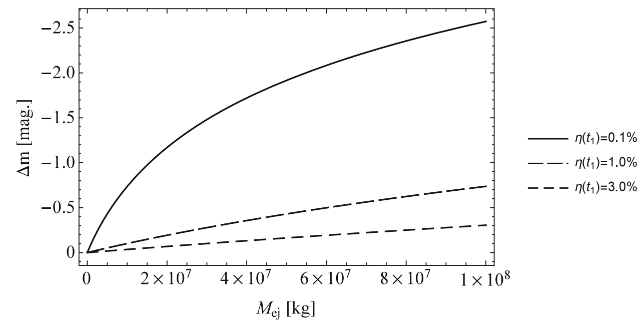

Figure 14. The calculations show a situation similar to that shown in Figure 7. The only difference is that the cometary activity is controlled by carbon dioxide sublimation.

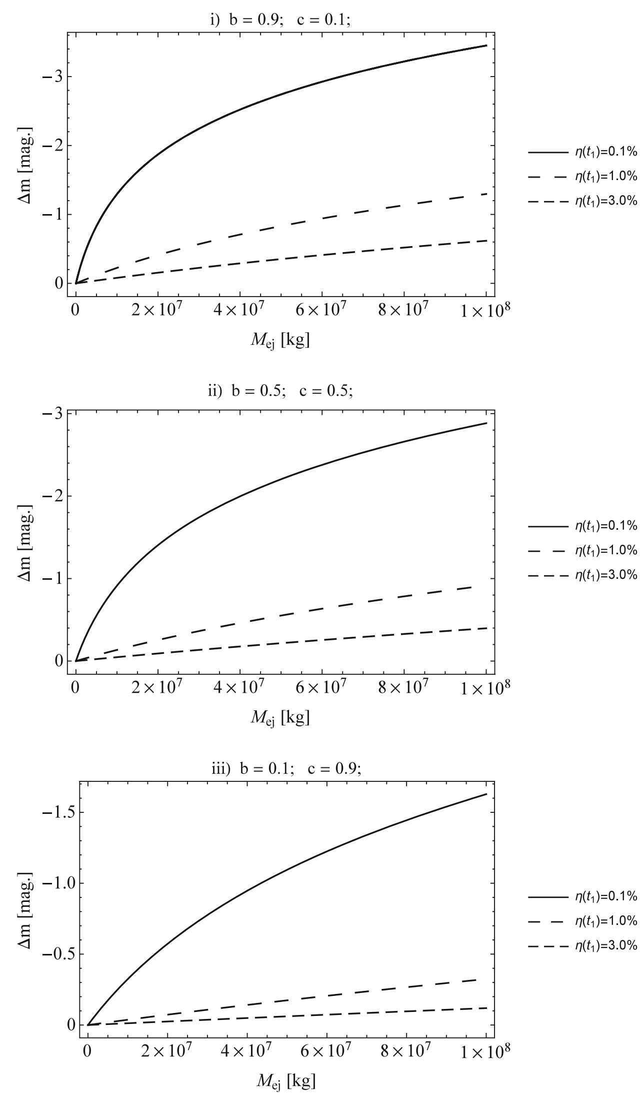

Figure 15. The calculations show a situation similar to that shown in Figure 8. The only difference is that the cometary activity is controlled by carbon dioxide sublimation.

presented results should be treated as examples of the results of the problem discussed. It is worth adding that in all the discussed mechanisms the key role is played by the so-called “active particles.” Their measure is the amount of matter that has been released into the coma. Taking into account the entire orbit of comets, as well as the number of individual orbital periods, the discussed process of the evolution of the comet landscape relief is naturally increased.

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References

A’Hearn M. F., Belton M. J. S., Delamere W. A. *et al.* 2011, Science, 332, 1396
Belton M. J. S. 2010, Icarus, 210, 881
Combi M. R., Tenishev V. M., Rubin M. *et al.* 2012, Astrophys. J., 749, 29
Crifo J. F., Loukianov G. A., Rodionov A. V. *et al.* 2005, Icarus, 176, 192
Davidsson B. J. R., Skorov Y. V. 2002, Icarus, 156, 223
Enzian A., Cabot H., Klinger J. 1997, Astron. Astrophys., 319, 995
Fanale F. P., Salvail J. R. 1984, Icarus, 60, 476
Fougere N., Combi M. R., Tenishev V. *et al.* 2012, Icarus, 221, 174
Fougere N., Tenishev V., Bieler A. M. *et al.* 2014, A 3D Description of the Coma of Comet 67P/Churyumov-Gerasimenko Constrained by Rosetta Observations. American Geophysical Union, Fall Meeting 2014, P41C-3930
Greenberg J. M., Hage J. I. 1990, Astrophys. J., 61, 260
Gronkowski P., Wesołowski M. 2012, Astron. Nachr., 333, 721
Gronkowski P., Wesołowski M. 2015a, Mon. Not. Roy. Astron. Soc., 451, 3068
Gronkowski P., Wesołowski M. 2015b, Astron. Nachr., 336, 362
Gronkowski P., Wesołowski M. 2016, Earth, Moon, Planets, 119, 23
Gronkowski P., Wesołowski M. 2017, Astron. Nachr. 338, 385
Gronkowski P., Tralle I., Wesołowski M. 2018, Astron. Nachr., 339, 37
Groussin O., Jorda L., Auger A.-T. *et al.* 2015, Astron. Astrophys., 583, A32
Hughes D. W. 1990, Royal Astron. Soc., Q. J., 31, 69
Hughes D. W. 1991, Possible Mechanisms for Cometary Outbursts, Comets in the post-Halley era. Vols. 1 & 2. Proceedings of IAU Colloq. 116. Ed. Newburn R. L., Jr., Neugebauer M., Rahe J., Kluwer Academic Publishers (Astrophysics and Space Science Library, vol. 167), p 825
Hughes D. W. 1996, Planetary Space Sci., 44, 705
Intriligator D. S., Dryer M. 1991, Nature, 353, 407
Ipatov S. I., A’Hearn M. F. 2011, Mon. Not. Roy. Astron. Soc., 414, 76
Ipatov S. I. 2012, Mon. Not. Roy. Astron. Soc., 423, 3474
Ivanova O. V., Skorov Y. V., Korsun P. P. *et al.* 2011, Icarus, 211, 559
Jones J. 1995, Mon. Not. Roy. Astron. Soc., 275, 773
Jorda L., Gaskell R., Capanna C. *et al.* 2016, Icarus, 277, 257
Keller H. U. 1990, In Huebner W. F., ed., Physics and Chemistry of Comets. Springer-Verlag, Berlin, p. 21
Kelley M. S., Lindler D. J., Bodewits D. *et al.* 2013, Icarus, 222, 634
Keller H. U., Mottola S., Davidsson B. *et al.* 2015, Astron. Astrophys., 583, A34
Kopp G., Lean J. L. 2011, Geophys. Res. Lett., 38, L01706
Kossacki K. J., Czechowski L. 2018, Icarus, 305, 1
Lara L. M., Lowry S., Vincent J.-B. *et al.* 2015, Astron. Astrophys., 583, A9
Leliwa-Kopystyński J. 2018, Icarus, 302, 266
Lin Z.-Y., Ip W.-H., Lai I.-L. *et al.* 2015, Astron. Astrophys., 583, Article ID A11
Lin Z.-Y., Knollenberg J., Vincent J.-B. *et al.* 2017, Mon. Not. Roy. Astron. Soc., 469, 731
Miles R. 2016, Icarus, 272, 387
Molina A. 2010, Revista Mexicana de Astron. Astrofisica, 46, 323
Muinonen K., Väisänen T., Martikainen J. *et al*. 2019, J. Visual. Exp. 149, e59607.
Newburn R. L., Spinrad H. 1985, Astron. J. 90, 2591
Pajola M., Höfner S., Vincent J.-B. *et al.* 2017, Nature Astron., 1, 92
Preusker F., Scholten F., Matz K.-D. *et al.* 2015, Astron. Astrophys., 583, Article ID A33
Preusker F., Matz K.-D., Roatsch T. *et al.* 2017, Astron. Astrophys., 607, 1
Prialnik D., Bar-Nun A. 1987, Astrophys. J., 313, 893
Prialnik D., Bar-Nun A. 1992, Astron. Astrophys., 258, L9
Prialnik D. 2006, What makes comets active? Asteroids, comets, meteors. In: Lazzaro D., Ferraz-Mello S., Fernández J. A. (eds.), Proceedings of the 229th Symposium of the International Astronomical Union. Rio de Janeiro, Brasil, Cambridge University Press, Cambridge, p 153
Reach W. T., Vaubaillon J., Kelley M. S. *et al.* 2009, Icarus, 203, 571
Richardson J. E., Melosh H. J., Lisse C. M. *et al.* 2007, Icarus, 190, 357

Rubin M., Tenishev V. M., Combi M. R. *et al.* 2011, Icarus, 213, 655
Rubin M., Fougere N., Altwegg K. *et al.* 2014, Astrophys. J., 788, 168
Skorov Y., Reshetnyk V., Lacerda P. *et al.* 2016, Mon. Not. Roy. Astron. Soc., 461, 3410
Snodgrass C., Meech K., Hainaut O. 2010, Astron. Astrophys., 516, L9
Snodgrass C., Tubiana C., Fitzsimmons A. *et al.* 2011, Solar phase functions of cometary nuclei. EPSC-DPS Joint Meeting 2011, held 2–7 October 2011 in Nantes, France, 1524
Steckloff J. K., Melosh H. J. 2016, Are Comet Outbursts the Result of Avalanches? In: DPS Meeting, Vol. 48. American Astronomical Society, 206.06
Tancredi G., Rickman H., Greenberg J. M. 1994, Astron. Astrophys., 286, 659
Tenishev V., Combi M. R., Rubin M. 2011, Astrophys. J., 732, 104
Thomas P. C., Veverka J., Belton M. J. S. *et al.* 2007, Icarus, 187, 4
Thomas P. C, A'Hearn M. F., Veverka J. *et al.* 2013, Icarus, 222, 550
Vincent J. B., Bodewits D., Besse S. *et al.* 2015, Nature, 523, 63
Vincent J. B., Oklay N., Pajola M. *et al.* 2016a, Astron. Astrophys., 587, A14
Vincent J. B., A'Hearn M. F., Lin Z.-Y. *et al.* 2016b, Mon. Not. Roy. Astron. Soc., 462, 184
Wesołowski M., Gronkowski P. 2018a, New Astron., 62, 55
Wesołowski M., Gronkowski P. 2018b, Earth, Moon, Planets, 121, 105
Wesołowski M., Gronkowski P., Tralle I. 2019, Mon. Not. Roy. Astron. Soc., 484, 2309
Wesołowski M. 2020a, J. Astrophys. Astron., 40, 1
Wesołowski M. 2020b, Icarus, 351, 113950
Wesołowski M. 2020c, Planetary Space Sci., 194, 105117
Wesołowski M. 2020d, Res. Astron. Astrophys., 20, 132
Wesołowski M., Gronkowski P., Tralle I. 2020a, Icarus, 338, 113546
Wesołowski M., Gronkowski P., Tralle I. 2020b, Planetary Space Sci., 184, 104867
Wesołowski M., Gronkowski P., Tralle I. 2020c, Icarus, 352, 114005
Wesołowski M. 2021a, Icarus, 357, 114116
Wesołowski M. 2021b, Res. Astron. Astrophys., 21, 69
Whitney C. 1955, Astrophys. J., 122, 190
Yelle R. V., Soderblom L. A., Jokipii J. R. 2004, Icarus, 167, 30