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The influence of the cometary particles dynamics on the activity of comets

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Abstract. The paper deals with the dynamics of particles which are on the surface of the cometary nucleus. The key point is to research the behavior of the particles as a result of local sublimation. Generally, we can describe three mechanisms related to the particles behavior. Relatively small particles (of the order of micrometers) are ejected into the atmosphere of the comet due to sublimation. Slightly larger particles (of the order of centimeters) can migrate across the comet's surface towards the equator, while much larger rubbles of cometary matter remain at rest. The angular width of the particles is the main factor influencing the migration time towards the equator of the comet. The measure of angular width and particles' migration time is its size and coefficient of friction. The numerical calculations presented in the paper refer to a hypothetical comet X/P and the comet 67P/Churyumov–Gerasimenko.

Keywords. Comets—cometary particles—migration of particles—time scale.

1. Introduction

The basic mechanism responsible for the activity of comets is the sublimation of cometary ice. As a result of this process, the comet significantly increases its size. Sublimation of gas molecules is also responsible for the transport of particles to the atmosphere of the comet, and this affects the movement of particles on the surface of the nucleus as well. Let us explain that comet particles are agglomerates which contain much smaller grains as building blocks (Skorov *et al.* 2016; Wesołowski *et al.* 2020). Of course, this is not the only known mechanism responsible for the activity of comets. It is worth noting that other mechanisms, such as cometary geysers, electrostatic levitation and material recoil mechanism (rocket mechanism), etc. also affect comet activity. However, it would not be an overstatement to say that the sublimation of cometary ice is a key mechanism responsible for it. This fact has been confirmed by extensive observational material.

When the comet approaches the Sun, its nucleus begins to sublimate gradually under the influence of electromagnetic solar radiation. That particular cometary ice begins to sublimate in a well-defined order consistent with their evaporation temperatures. At further distance from the Sun, as the first sublimates, the most volatile substances, such as N, CO and CH_4 also sublimate. In relatively warmer regions, sublimation activity is dominated by CO_2 or NH_3. At the closest distance to the Sun, i.e., in the warmest regions, sublimation of ice H_2O or H_2O_2 begins. It should be noted that sublimation can occur from the surface as well as from subsurface layers. The presented sublimation mechanism is responsible for the formation of the porous structure of the comet nucleus. In addition, it explains the existence of various gases in the cometary head.

In turn, sublimation of cometary gas contributes to the ejection of particles from the nucleus surface. This phenomenon is well known and widely discussed in scientific literature (see Jones 1995; Crifo *et al.* 2005; Molina & Moreno 2011; Rubin *et al.* 2011; Tenishev *et al.* 2011; Combi *et al.* 2012; Fougere *et al.* 2012, 2013; Lin *et al.* 2016; Wesołowski *et al.* 2019, 2020). At first, the calculations were done for hypothetical comet X/P with spherical nucleus. The use of the spherical comet nucleus in calculations should be considered as the first approximation. However, such regular structures are not observed because the sublimation of cometary ice significantly hinders this. Comet

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moving in an orbit loses on an average about 0.5% of its total mass, which translates into a change in its dimensions. This means that after several passes through perihelion, the shape of the comet nucleus may differ from the original one. In order to thoroughly study the dynamics of processes related to the activity of a given comet, in the first step we must accurately determine its gravitational acceleration which is a consequence of the assumed shape of the nucleus. In this case, it was assumed that the comet is at the heliocentric distance equal to $d = 1$ au and its activity is controlled by water ice sublimation. Then, we considered the dust migration on the surface of the actual comet 67P/Churyumov–Gerasimenko (hereafter referred to as 67P/Ch-G). For this comet, it was assumed that its activity is controlled by the sublimation of water ice and carbon dioxide (Fougere *et al.* 2015). As per our calculations it was assumed that the comet is at the heliocentric distance equal to $d = 3.463$ au. The obtained results allow to calculate the angular width for a given particle and to determine how the sublimation of a given ice affects the particles' migration time.

2. Model and basic assumptions

2.1 *Nucleus of spherical shape*

In order to describe the dynamics of cometary particles which are on the surface of the rotating comet nucleus, one should make some preliminary assumptions. For simplicity, we assume that the comet's nucleus has a spherical shape, it rotates around one of its diameters and the rotation axis is perpendicular to the plane of the orbit having a form of an ellipse (Gronkowski & Wesołowski 2015b, 2017; Wesołowski *et al.* 2019). We assume that the following forces act upon the cometary particles:

- gravitation of the comet nucleus,
- drag force resulting from the sublimation of the nucleus matter,
- centrifugal force coming from the comet rotation,
- the force related to the electromagnetic solar radiation,
- solar tidal force which is related to the orbital motion of the comet,
- Coriolis force which is a consequence of the comet rotation and the particles movement,
- rocket force.

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 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 grains contain only a silicate core (possibly covered by refractories) while in the second case, it means that the grains consist only of ice or they are built of a silicate core, a mantle of organic refractories, and a crust of ice (for more details, see Greenberg & Hage 1990; Davidsson & Skorov 2002). Namely, we adapt this model for further consideration.

Gronkowski and Wesołowski (2015b) demonstrated that due to great number of numerical tests, only the first three forces have dominant effect on the size of the emitted cometary particles.

For the particles to be emitted from the surface of the nucleus, the following relationship must be met:

$$F_{\mathrm{gr}} \leq F_{\mathrm{dr}} + F_{\mathrm{c}} \cdot \cos\varphi. \quad (1)$$

Using Equation (1) and the definitions of particular forces acting on the particles, one can write the following equation:

$$m_{\mathrm{gr}} \frac{\mathrm{d}^2 R}{\mathrm{d}t^2} = \frac{1}{2} C_{\mathrm{D}} \pi a_{\mathrm{gr}}^2 (v_{\mathrm{g}} - v_{\mathrm{p}})^2 \rho_{\mathrm{g}} + m_{\mathrm{gr}} \left(\frac{2\pi}{P}\right)^2 R_{\mathrm{N}} \cos^2\varphi - \frac{G M_{\mathrm{N}} m_{\mathrm{gr}}}{R_{\mathrm{N}}^2}. \quad (2)$$

In Equation (2), m_{gr} is the mass of the cometary particles, C_{D} is the modified free-molecular drag coefficient for spherical cometary particles of the radius a_{gr}, v_{g} and v_{p} denote the velocity of the cometary gas molecules and the velocity of particles, respectively, and ρ_{g} is the cometary gas density. For the particles which are at rest on the comet nucleus surface we take $v_{\mathrm{p}} = 0$. The angular rotation speed of the nucleus is denoted by ω, the rotational period by P, R_{N} is the nucleus radius, φ is the cometocentric latitude, G is the gravitational constant and M_{N} is the total mass of the rotating cometary nucleus.

If we assume $\frac{\mathrm{d}^2 R}{\mathrm{d}t^2} = 0$, then after simple transformations one can get the following formula for the maximum radius of cometary particles that can be raised from the surface of the nucleus:

$$a_{\max} = \frac{9 C_{\mathrm{D}} M v_{\mathrm{g}} \dot{Z}}{32\pi G \rho_{\mathrm{gr}} \rho_{\mathrm{N}} R_{\mathrm{N}} \left(1 - \frac{3\pi \cos^2\varphi}{G \rho_{\mathrm{N}} P^2}\right)}. \quad (3)$$

In this equation, the parameter M is the mass of molecules of the sublimated cometary ice and φ is the comet-centric latitude. The maximum sizes of the emitted cometary particles depend mainly on the rate of sublimation $\dot{Z}$, which is a function of temperature on the surface of cometary nucleus. Generally, the temperature of the comet surface can be determined by taking into account the balance between solar energy input, the energy re-emitted in infrared frequency domain and that transferred into the interior and absorbed there to sublimate cometary ice which are on the nucleus surface. This balance is described by the following:

$$\frac{S_{\odot}(1-A_{\rm N})\cos\theta}{d^2} = \epsilon\,\sigma\,T^4 + f\,\frac{\dot{Z}\,L(T)}{N_{\rm A}} + h(\psi)\,K(T)\,\nabla T. \quad (4)$$

Here $S_{\odot}$ is the solar constant at heliocentric distance $d = 1$ au, $A_{\rm N}$ is the albedo of the cometary nucleus, θ is the angle between the normal to the surface of the nucleus and the direction to the Sun, d is the heliocentric distance of the comet, ϵ is the infrared emissivity of the nucleus, σ is the Stefan Boltzmann constant, f is the percentage of the active sublimation surface of the comet nucleus, $L(T)$ is the latent heat of cometary ice sublimation, $N_{\rm A}$ is the Avogadro number and $K(T)$ is the average heat conductivity of a cometary nucleus. Note that in Equation (4), the heat conductivity $K(T)$ is multiplied by the Hertz factor $h(\psi)$ which depends on the porosity ψ. This is because porosity leads to the reduction of the contact surface between cometary particles (Tancredi *et al.* 1994; Davidsson & Skorov 2002) and hence, it should be taken into account.

In the next step, one should take into account the migration of particles towards the equator of the comet. The model of the particles' migration with its exact description has been discussed by Wesołowski *et al.* (2019). Here we present only the final form of the equation, by means of which we determine the particles' migration:

$$f(\phi) = \frac{3\pi\cos\varphi\sin\varphi}{G\rho_{\rm N}P^2\left(1-\frac{9C_{\rm D}v_{\rm g}\dot{Z}M}{32\pi G R_{\rm N}\rho_{\rm N}\rho_{\rm gr}a}\right) - 3\pi\cos^2\varphi}. \quad (5)$$

The movement of particles on the surface of a comet is possible, only if the following relation holds: $\mu \leq f(\phi)$, where μ is the friction coefficient and $f(\phi)$ is the migration coefficient.

The next step includes determining of angular width for each particle along with their migration time, by means of the following equation:

$$-\frac{{\rm d}^2 s}{{\rm d}t^2} = -\frac{4\pi^2}{P^2}\cdot\cos(\varphi)\cdot\sin(\varphi) + \frac{4}{3}\mu\pi G\rho_{\rm N} - \frac{4\pi^2}{P^2}\mu\cos^2(\varphi) - \frac{C_{\rm D}\mu\pi a_{\rm gr}^2 v_{\rm g}^2\rho_{\rm g}}{2m_{\rm gr}R_{\rm N}}. \quad (6)$$

This equation allows to estimate the time of particles' migration on the surface of the spherical comet nucleus X/P.

2.2 *The actual model of the cometary nucleus—the case 67P/Ch-G*

The comet 67P/Ch-G was examined in detail in the years 2014–2015 in the frame of Rosetta mission launched by ESA. The images taken by OSIRIS (Optical, Spectroscopic and Infrared Remote Imaging System) on-board the Rosetta spacecraft allowed astronomers to construct a map of the 67P/Ch-G nucleus surface. It is noteworthy that in recent years many valuable and advanced papers have been published which are devoted to the study of comet 67P67P/Ch-G gravitational field (Groussin *et al.* 2015; Preusker *et al.* 2015; Sierks *et al.* 2015; Jorda *et al.* 2016; Lhotka *et al.* 2016; Pätzold *et al.* 2016; Reimond & Baur 2016; Tubiana 2015; Vincent *et al.* 2016b). Summarizing the results of these works it can be stated that the 67P/Ch-G 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 $P = 12.4$ hr (Preusker *et al.* 2015). This leads to the average density of the nucleus $\rho_{\rm N} = 537.0 \pm 0.7$ kg/m^3 (Preusker *et al.* 2017). The average mean radius is $R_{\rm N} = 1720$ m, and $g_{\rm c} = 2.25 \times 10^{-4}$ ms^{-2} is the average acceleration due to gravity on the comet surface (Vincent *et al.* 2016a, b). The total surface area $S_{\rm N}$ of the 67P/Ch-G nucleus based on the SPG SHAP7 model is 51.7 ± 0.1 km^2 (Preusker *et al.* 2017).

Since the shape of the comet 67P/Ch-G nucleus is complicated, in order to carry out calculations we have to use some approximations, namely, we approximated the irregular shape of the nucleus by the prolate ellipsoid with an axial ratio of $a/b > 1.7$, where a and b are the axes of the ellipsoid. A similar approach was used for the study of this comet by Lowry *et al.* (2012). Prolate ellipsoid model allows to calculate the values of angles, appearing in Equations (7)–(10). Other values

Table 1. The values of particular parameters used in numerical simulations for comet X/P. They are the same as the works of González *et al.* (2014), Gronkowski and Wesołowski (2015a, b, 2017), Kossacki and Szutowicz (2013) Kopp and Lean (2011), Reach *et al.* (2010), Richardson *et al.* (2007), Wesołowski and Gronkowski (2018), Wesołowski (2019) and literature therein.

Parameter	Value(s)
Average radius of the comet nucleus (m)	$R_N = 1000$
Density of the comet nucleus (kg m^{-3})	$\rho_N = 400$
Density of the cometary dust (kg m^{-3})	$\rho_{dust} = 200...1600$
Crystalline ice thermal conductivity (W m^{-1} K^{-1})	$K(T) = 567/T$
Rotation period of comet nucleus (h)	$P = 10$
Hertz factor (–)	$h = 0.001, \ldots, 0.1$
Porosity (–)	$\psi = 0.75$
Albedo (–)	$A_N = 0.04$
Emissivity (–)	$\epsilon = 0.9$
The heliocentric distance (au)	$d = 1$
Latent heat of H_2O sublimation (J kg^{-1})	$L_{H_2O} = 33.480 \cdot 10^3 - 12.924 \cdot T_{H_2O}$
Temperature of H_2O ice (K)	$T_{H_2O} = 168.659$
The velocity of the gas molecules to H_2O ice (m s^{-1})	$v_{H_2O} = 349.795$
The rate of sublimation of H_2O ice (molecules/m^2 s)	$\dot{Z}_{H_2O} = 2.609 \cdot 10^{19}$
Latent heat of CO_2 sublimation (J kg^{-1})	$L_{CO_2} = 30.915 \cdot 10^3 - 30.308 \cdot T_{CO_2}$
Temperature of CO_2 ice (K)	$T_{CO_2} = 90.304$
The velocity of the gas molecules of CO_2 ice (m s^{-1})	$v_{CO_2} = 163.709$
The rate of CO_2 ice sublimation (molecules/m^2 s)	$\dot{Z}_{CO_2} = 3.272 \cdot 10^{19}$
Solar constant (for $d = 1$ au) (W m^{-2})	$S_\odot = 1360.8 \pm 0.5$

of individual parameters are related directly to comet 67P/Ch-G.

In our analysis, we assume that on the surface of comet 67P/Ch-G the particles are subjected to the same forces as in the case of the first model considered in section (2.1), with one exception related to the force of gravity. The difference results from the shape of the comet 67P/Ch-Gt nucleus, which is adopted by us here.

Taking all these into account, one can formulate the equation which governs the particles' motion over the nucleus surface:

$$m_{gr}\frac{d^2R}{dt^2} = \frac{1}{2}C_D\pi a_{gr}^2 v_g^2 \dot{Z}M + m_{gr}\left(\frac{2\pi}{P}\right)^2 a\cos(t)\sin(\beta) - m_{gr}\cdot g_c. \quad (7)$$

Proceeding in the same way as was done previously, it can be shown that the radius of the particles emitted from the surface of comet 67P/Ch-G is given by

$$a_{gr} = \frac{3C_D v_g \dot{Z}M}{8\rho_{gr}\left(g_c - \frac{4\pi^2 a\cos(t)\sin(\beta)}{P^2}\right)}. \quad (8)$$

For comet 67P/Ch-G, the condition of particles' migration is determined by the following expression:

$$f'(\phi) = \frac{-\frac{4\pi^2}{P^2}a\cos(t)\cos(\beta) + g_c\cos(\beta-\gamma)}{\left(g_c\sin(\beta-\gamma) - \frac{4\pi^2}{P^2}a\cos(t)\sin(\beta) - \frac{3C_D v_g\dot{Z}M}{8\rho_{gr}a_{gr}}\right)}. \quad (9)$$

The particles migrate across the comet 67P/Ch-G surface, if the following condition is fulfilled: $\mu \le f'(\phi)$.

Proceeding in the same way as in the case of the first model, one can estimate the angular width and particles' migration time on the surface of comet 67P/Ch-G by means of the following equation:

$$-\frac{d^2s}{dt^2} = \frac{4\pi^2}{P^2}a\cos(t)\cos(\beta) - g_c\cos(\beta-\gamma) + \mu_s g_c\sin(\beta-\gamma) + \frac{4\pi^2}{P^2}\mu_s a\cos(t)\sin(\beta) + \frac{3\mu_s C_D v_g\dot{Z}M}{8\rho_{gr}a_{gr}}. \quad (10)$$

3. Results of numerical calculations

The numerical values of physical parameters which were used in the calculations are presented in Table 1. At first, we focus on determining the angular width for

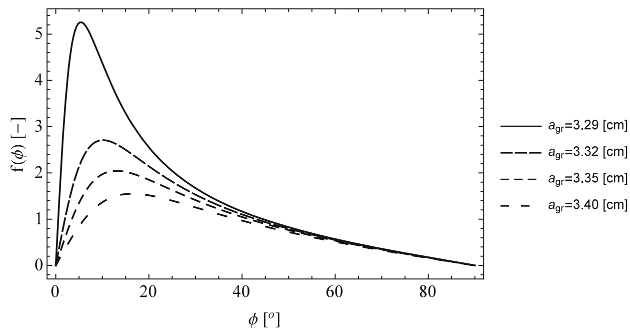

Figure 1. Coefficient $f(\varphi)$ as a function of the comet-centric latitude φ. In the calculations it was assumed that the particles' density is equal to $\rho_{gr} = 200\,\mathrm{kg\,m^{-3}}$. In this case, the maximum size of particles that can be ejected from the surface of the nucleus as a result of sublimation is equal to $a_{max} = 3.28$ cm. Calculations were carried out in accordance with Equation (5). The maximum radius of particles that can migrate over the nucleus surface is $a_{mig} = 4.24$ cm.

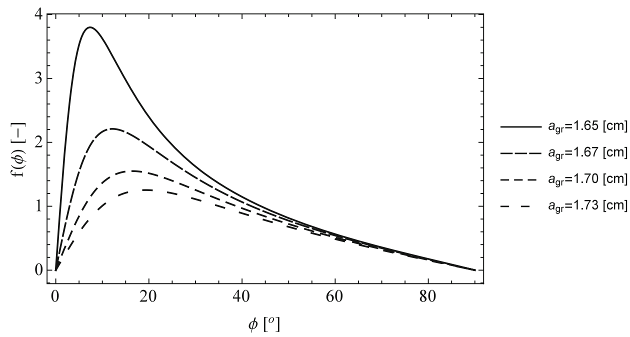

Figure 2. Similar to that of Figure 1, but the calculations were done on the assumption that the particles' density is equal $\rho_{gr} = 400\,\mathrm{kg\,m^{-3}}$, and the maximum radius of the ejected particles is $a_{max} = 1.64$ cm. The maximum radius of particles that can migrate is $a_{mig} = 2.12$ cm.

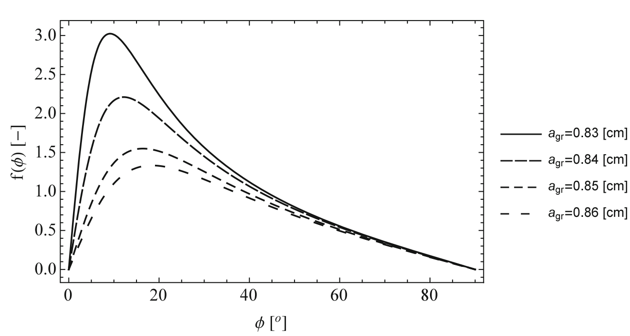

Figure 3. Similar to that of Figure 1, but the calculations were done on the assumption that the particles' density is equal $\rho_{gr} = 800\,\mathrm{kg\,m^{-3}}$, and the maximum radius of the ejected particles is $a_{max} = 0.82$ cm. The maximum radius of particles that can migrate is $a_{mig} = 1.05$ cm.

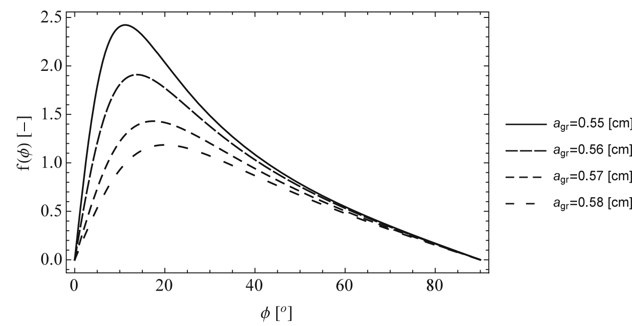

Figure 4. Similar to that of Figure 1, but the calculations were done on the assumption that the particles' density is equal to $\rho_{gr} = 1200\,\mathrm{kg\,m^{-3}}$, and the maximum radius of the ejected particles is $a_{max} = 0.54$ cm. The maximum radius of particles that can migrate is $a_{mig} = 0.71$ cm.

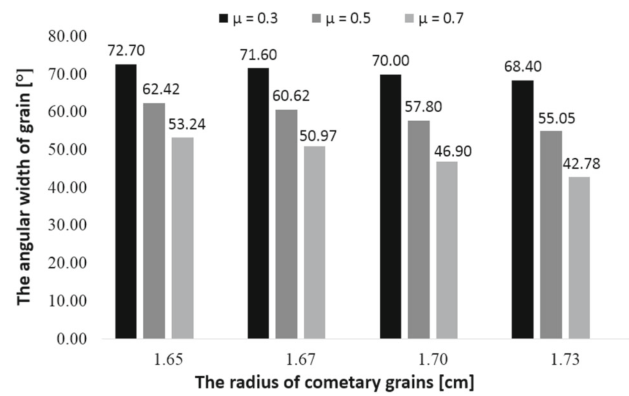

Figure 5. The average distribution of angular width for exemplary comet particles depending on the friction coefficient μ. During calculations, it was assumed that the activity of comet is controlled by the sublimation of water ice. This bar-graph corresponds to Figure 2.

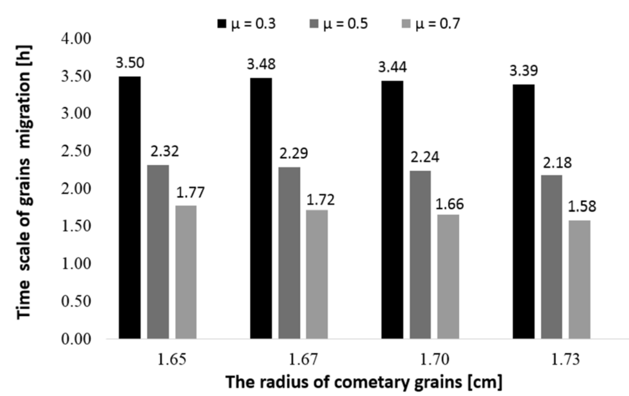

Figure 6. Time scale of particles' migration on the surface of the comet depending on the friction coefficient μ. During calculations, it was assumed that the activity of the comet is controlled by the sublimation of water ice. The calculations were carried out using the results presented in Figures 2 and 5.

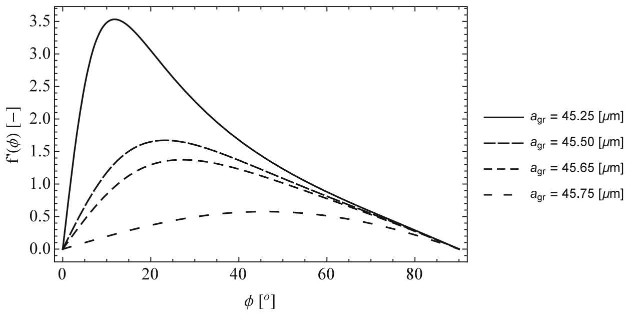

Figure 7. Similar to that of Figure 1, but the calculations were done for the comet 67P/Ch-G. During calculations, it was assumed that the particles' density is equal to $\rho_{\rm gr} = 500\,{\rm kg\,m^{-3}}$. The maximum particles' size that can be ejected from the surface of the nucleus as a result of sublimation is equal to $a_{\rm gr} = 39.80\,\mu$m. Calculations were carried out in accordance with Equation (9). The maximum radius of particles that can be migrated is $a_{\rm mig} = 48\,\mu$m.

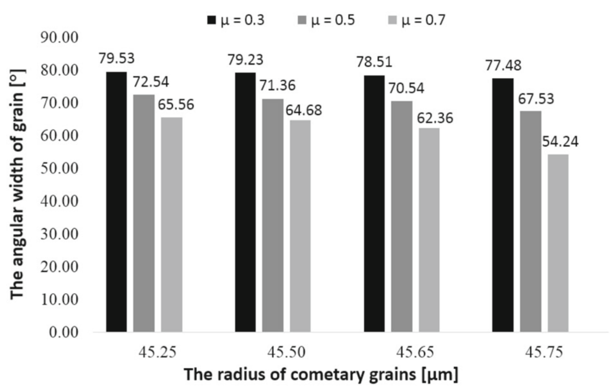

Figure 8. Distribution of angular width for particles' migration on the surface of the comet 67P/Ch-G depending on the friction coefficient μ. During calculations, it was assumed that the comet activity is controlled by sublimation of water ice. The calculations correspond to Figure 7.

individual particles. The results which are shown in Figures 1, 2, 3, and 4 refer to the comet X/P. For each of these cases the maximum dimensions of the particles ejected off the surface of the nucleus as a result of intense sublimation were determined. The maximum sizes of particles that could migrate freely across the nucleus surface was also estimated. For calculations, the coefficient of friction between the particles and the surface of the comet was assumed to be $\mu = 0.5$. In the next step, the angular width for the particles and the time of their migration on the surface of the nucleus, depending on the friction coefficient μ, were determined. These results are shown in Figures 5 and 6.

In the second case, the discussion focuses on the model of real 67P/Ch-G comet nucleus. For this comet,

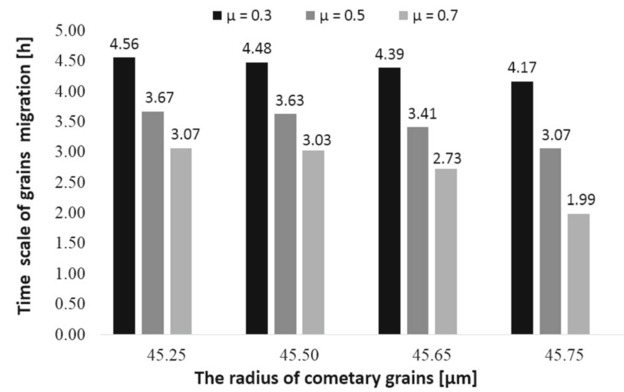

Figure 9. Time scale of particles' migration on the surface of the comet 67P/Ch-G depending on the coefficient of friction μ. During calculations, it was assumed that the activity of the comet is controlled by the sublimation of water ice and the results presented in Figures 7–8 are used.

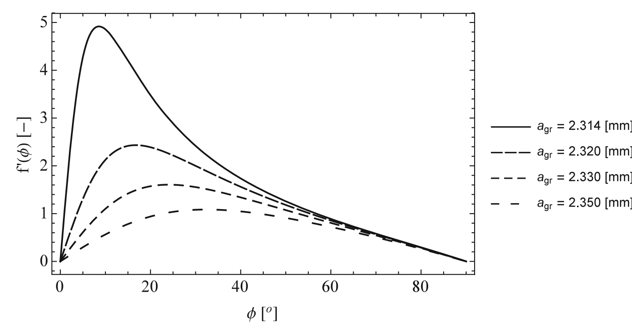

Figure 10. Similar to that of Figure 7, but the comet activity is assumed to be controlled by carbon dioxide sublimation. In this case, the maximum size of particles that can be ejected from the surface of the nucleus as a result of sublimation is equal to $a_{\rm gr} = 2.04$ mm. The maximum radius of particles that can migrate on the surface is $a_{\rm mig} = 2.46$ mm.

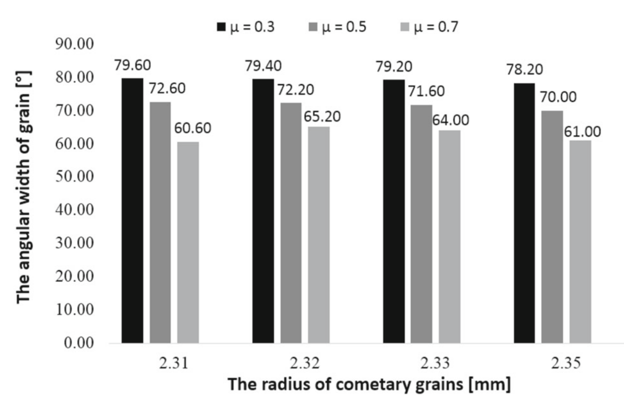

Figure 11. Similar to that of Figure 8, but the comet activity is assumed to be controlled by carbon dioxide sublimation. These calculations correspond to Figure 10.

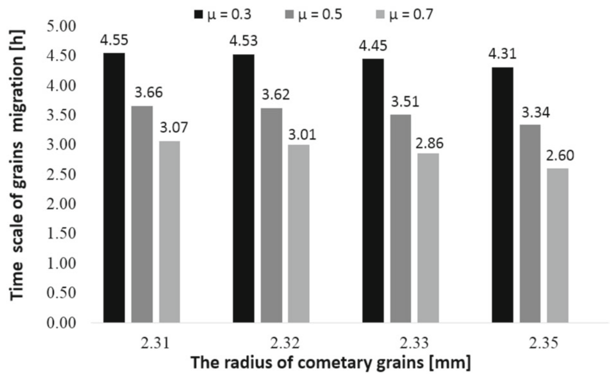

Figure 12. Similar to that of Figure 9, but the comet activity is assumed to be controlled by carbon dioxide sublimation. During calculations, the results presented in Figures 10–11 are used.

having knowledge of its actual parameters, we determined maximum dimensions of particles that were ejected from the comet surface, the angular width and time of particles' migration. The maximum sizes of particles that can migrate over the surface of comet 67P/Ch-G were estimated as well. In addition, two situations were considered, namely, when comet activity is controlled by sublimation of water ice or by sublimation of carbon dioxide. The results of these calculations are shown in Figures 7, 8, 9, 10, 11 and 12.

4. Remarks and conclusions

The ejection of cometary matter, as well as the migration of cometary particles is one of the most interesting aspect of comet activity. The dynamics of particles considered in the work allows to determine the maximum size of the particles that are emitted from the surface of the comet's nucleus. When talking about the ejection or migration of particles, it should be noted that their main cause is the sublimation of cometary ice (Tenishev *et al.* 2011). This is important in the context of changing the location of particles on the comet surface, as well as in the rising and falling of particles (Thomas *et al.* 2015a, b). Particles that appear in a new location can make an important contribution to increase the rate of sublimation. Such total contribution was estimated by Rubin *et al.* (2014). Migrating a variety of particles can cause uprising cliffs, sharp edges of hills and even avalanches on the surface of a comet – as it was confirmed by Rosetta's mission (Pajola *et al.* 2015, 2017).

From the results presented in the paper it follows that particular angular widths of particles do not differ essentially from each other. It is clear that such situation takes place only if the friction coefficient is the same. It is worth mentioning that from one side, the difference in these two types of sublimation do not affect considerably the angular width and time migration of particles. However, from the other side, the sublimation of a given cometary ice considerably influences the size of particles ejected from comet nucleus, as well as those that can migrate over the comet surface.

When analyzing the obtained calculation results, one should, in particular, pay attention to the dimensions of individual particles for which we consider migration on the surface of the cometary nucleus. Their dimensions play a key role when it comes to the value of the coefficient $f(\phi)$ and $f'(\phi)$. As a consequence, it affects the angular width and particles' migration time depending upon the adopted friction coefficient.

Finally, it is also worth emphasizing that the results of our numerical simulations make contribution to the analysis of causes evoking avalanches and cometary depressions. The importance of such analysis is related to the fact that avalanches can be responsible for the initiation of cometary outbursts.

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References

Combi M. R. *et al.* 2012, Astrophys. J., 749, 29
Crifo J. F. *et al.* 2005, Icarus, 176, 192
Davidsson B. J. R., Skorov Y. V. 2002, Icarus, 156, 223
Fougere N. *et al.* 2012, Icarus, 221, 174
Fougere N. *et al.* 2013, Icarus, 225, 688
Fougere N. *et al.* 2015, A&A, 588, A134
González M., Gutiérrez P. J., Lara L. M. 2014, A&A, 563, 98
Greenberg J. M., Hage J. I. 1990, Astrophys. J., 361, 260
Groussin O., Jorda L., Auger A. T. *et al.* 2015, A&A, 583, 32
Gronkowski P., Wesołowski M. 2015a, MNRAS, 451, 3068
Gronkowski P., Wesołowski M. 2015b, Astron. Nachr., 336, 362
Gronkowski P., Wesołowski M. 2017, Astron. Nachr., 338, 385
Jones J. 1995, MNRAS, 275, 773

Jorda L., Gaskell R., Capanna C. *et al.* 2016, Icarus, 277, 257
Kelley M. S. *et al.* 2013, Icarus, 222, 634
Kopp G., Lean J. L. 2011, Geophys. Res. Lett., 38, 1706
Kossacki K. J., Szutowicz S. 2013, Icarus, 225, 111
Lhotka C., Reimond S., Souchay J. *et al.* 2016, MNRAS, 455, 3588
Lin Z.-Y. *et al.* 2016, A&A, 588, 3
Lowry S., Duddy S. R., Rozitis B. *et al.* 2012, A&A, 548, A12
Molina A., Moreno F. 2011, Astron. J., 141, 148
Pätzold M., Andert T., Hahn M. *et al.* 2016, Nature, 530, 63
Pajola M. *et al.* 2015, A&A, 583, A37
Pajola M. *et al.* 2017, Nature Astron., 1, 92
Preusker F., Scholten F., Matz K.-D. *et al.* 2015, A&A, 583, A33
Preusker F., Scholten F., Matz K.-D. *et al.* 2017, A&A, 607, 1
Reach W. T. *et al.* 2009, Icarus, 203, 571
Reach W. T. *et al.* 2010, Icarus, 208, 276
Richardson J. E. *et al.* 2007, Icarus, 190, 357
Rubin M. *et al.* 2011, Icarus, 213, 655 (2011)
Rubin M. *et al.* 2014, Astrophys. J., 788, 168
Skorov Y., Reshetnyk V., Lacerda P., Hartogh P., Blum J. 2016, MNRAS, 461, 3410
Sierks H., Barbieri C., Lamy P. L. *et al.* 2015, Science, 347, a1044
Tancredi G., Rickman H., Greenberg J. M. 1994, A&A, 268, 659
Tenishev V., Combi M. R., Rubin M. 2011, Astrophys. J., 732, 104
Thomas N. *et al.* 2015a, Science, 347, a0440
Thomas N. *et al.* 2015b, A&A, 583, A17
Vincent J.-B., A'Hearn M. F., Lin Z.-Y. *et al.* 2016a, MNRAS, 462, 184
Vincent J.-B., Oklay N., Pajola M. *et al.* 2016b, A&A, 587, A14
Wesołowski M., Gronkowski P. 2018, Earth, Moon and Planets, 121, 105
Wesołowski M., Gronkowski P., Tralle I. 2019, MNRAS, 484, 2309
Wesołowski M. 2019, J. Astrophys. Astron. 40, 20
Wesołowski M., Gronkowski P., Tralle I. 2020, Icarus, 338, article number: 113546