Earth, Moon, and Planets (2018) 121:105–125
https://doi.org/10.1007/s11038-018-9517-1

A New Simple Model of Comets-Like Activity of Centaurs

M. Wesołowski[1] · P. Gronkowski[1]

Received: 14 December 2017 / Accepted: 20 July 2018 / Published online: 26 July 2018

Abstract
Outbursts and variations of brightness are well known manifestations of the physical activity of the comets. Most cometary outbursts are recorded not very far from the Sun, where sublimation of water ice plays a major role in the activity of this celestial bodies. However, comets sometimes show physical activity far from the Sun, where the rate of water ice sublimation is small. Also a special kind of small bodies, i.e. centaurs sometimes show strong physical activity far from the Sun. The paper is based on the idea that the nuclei of centaurs may contain numerous cavities that are filled with gas under pressure and debris of cometary material. Numerical simulations were carried out for realistically assumed values of a wide range of physical parameters of centaurs. The obtained results are consistent with the observations of the physical activity of these celestial bodies.

Keywords Comets: general–comets: individual: the centaur 95P/Chiron · The comet 29P/Schwassmann–Wachmann

1 Introduction

The physical activity of comets is often manifested by outbursts and variations in the brightness of these celestial bodies. The essence of the comet's brightness outburst is the sudden increase of its luminosity by more than -1^{m} (average by -2^{m} to -5^{m}) from a few hours to several days. Usually *in non-outbursting phase* comet's head looks like a diffuse cloud which sometimes has a small central condensation. Suddenly the comet's head expands and becomes much larger than before the outburst. The phenomenon can last from a few to dozens of days. Finally a comet returns to its previous state. According to Hughes (1990, 1991) no changes in its orbit as the result of outburst are observed. It should be emphasized that the comet's brightness outburst can not be equated with a physical explosion, for example, a bomb detonation. It is above all a rapid brightening of an object. Unlike the cometary outbursts, their brightness variations show a brightness

✉ M. Wesołowski
marwes@ur.edu.pl

P. Gronkowski
gronk@ur.edu.pl

[1] Faculty of Mathematics and Natural Sciences, University of Rzeszów, Pigonia 1 Street, 35-310 Rzeszów, Poland

jump less than -1^m and have the time of duration in the range of few hours not several days. It seems probable that these two phenomena have the same sources. However, the important difference lies in intensity and duration time of these two phenomena. The most famous representative of comets that shows the outburst activity is the comet 29P/Schwassmann–Wachmann (hereafter 29P/SW). This object was discovered in November 1927, by two Germans astronomers Arnold Schwassmann and Arno Wachmann, most likely during one of its frequent outbursts. The comet 29P/SW moves with the period $P \approx 16$ years along the quasi-circular orbit which is placed near the ecliptic plane between orbits of Jupiter and Saturn. The semimajor axis of the orbit is equal to $a \approx 6$ AU and its eccentricity is equal to $e \approx 0.044$. Despite the relatively large distance from the Sun, at which sublimation of water ice is negligible, this object shows unexpected outburst activity, many times a year. It should be emphasized that the phenomenon of outbursts is often observed for both periodic and parabolic comets. However, most comets are outburst active at heliocentric distances $d < 5$ AU, i.e. where sublimation of water ice is possible. Therefore, the 29P/SW is, in terms of its outburst activity, an exception. There are several other cases of cometary outbursts at large distances from the Sun. Here, under the concept of a large distance from the Sun, we will understand a distance, where water ice sublimation no longer occurs. At this point it is worth recalling that in 1964 the comet Humason C/1961 R1 showed the large outburst of about -6^{m} at the heliocentric distance equal to 6 AU (Wyckoff 1982). Also, the famous comet 1P/Halley underwent the strong outbursts of about -6^{m} on February 12, 1991 at the heliocentric distance of 14.3 AU (Hainaut et al. 1991; West 1991). However, the most enigmatic physical activity of cosmic bodies similar to the activity of comets is represented by a group of objects called centaurs. We note that centaurs are the transition bodies between the Kuiper Belt frigid objects and the objects belonging to Jupiter Family comets which include quickly sublimating, disintegrating comets which are placed in the relatively hotter inner regions of the solar system.

It is worth recalling that due to the parameters of its orbit, the 29P/SW is also counted among centaurs.

According to Jewitt (2009) we define centaurs as follows:

1. Two basic parameters of the centaur orbit, i.e. the perihelion distance q and the semimajor axis a meet the following conditions: $a_J < q < a_N$ and $a_J < a < a_N$, where $a_J = 5.2$ AU and $a_N = 30$ AU are the semimajor axis of Jupiter orbit and the semimajor axis of Neptune orbit, respectively.
2. The mean motion of the centaurs is not in the resonance of 1:1 with the mean motion of any planet.

Two of the most famous objects belonging to centaurs, which show cometary physical activity, is already mentioned the comet 29P/SW and Chiron. Since its discovery in 1977 (Kowal and Gehrels 1977) Chiron has become an object of interest to many astronomers. Long-term observations (Luu 1993; Campins et al. 1994; Bus et al. 2001; Ruprecht et al. 2015) of this centaur lead to the following conclusions related to the trends in changes of its luminosity:

1. Long-term brightening by $\approx -1^{\mathrm{m}}$ on time scale of ~ 1 year.
2. Short-term brightening which last on order of $\sim$ days with rates as high 15 millimag/h.
3. The largest recorded night-to-night variations in Chiron brightness were in the range of $\pm 0.3^{\mathrm{m}}$.

Due to the large distance of Chiron from the Sun the most common cometary volatiles like H_2O and CO_2 can not be responsible for its activity. Therefore, it is often suggested that CO as a very volatile substance is the source of observed Chiron behavior (Meech and Belton 1990; Stern et al. 1994). However, the transformation of amorphous ice into crystalline form, and the release of trapped CO from a porous matrix of amorphous and crystalline water ice as a cause of Chiron activity was also suggested (Prialnik and Podolak 1995; Capria et al. 2000). In addition to Chiron, other centaurs have been observed that exhibit cometary-like activity, for example 174P/Echeclus and 10199 Chariklo (Rousselot 2008; Jewitt 2009; Fornasier et al. 2014). In conclusion, the centaurs, in addition to long-term changes in brightness associated with changes in their distance from the Sun and short-term variations of the luminosity which are associated with the rotation of the nucleus, also show random changes of brightness changes that are similar to the cometary outbursts. The centaur's physical activity, as well as the outburst activity of comets, still remain an intriguing phenomenon in the evolution of these celestial bodies. The purpose of the current paper is to draw attention to the possibility of explaining the activity of centaurs by analysis of the destructive process that may take place in the subsurface layers of their nuclei. The destruction of subsurfaces caves in nuclei of centaurs will be considered.

2 The Centaurs Activity: Probable Mechanism

In order to describe the course of phenomenon under consideration we have to make certain assumptions. Generally, we assume that physical structure of centaurs is similar to the structure of comets. Therefore, for the sake of simplicity, we assume that centaur's nucleus is spherical in shape and its main component is water ice mixed with the cometary dust and some amount of carbon monoxide. Generally, water ice could be present under both amorphous and crystalline forms. We will consider the activity of centaurs in the range of heliocentric distance ~ 5–20 AU. We remind that generally CO is, after H_2O, the second chemical compound in comets as far as the chemical percentage is concerned. CO is still active in the throughout assumed range of heliocentric distance. Therefore, it seems unlikely that carbon monoxide could survive on the surface of the centaur's nucleus exposed to the solar radiation. This chemical compound can exist only inside the centaur's nucleus or possibly in the surface nucleus layers in the form of inclusions frozen in larger fragments of cometary debris or trapped in a water ice matrix. We also assume that a nucleus of a centaur, just like cometary nuclei, contains a number of large cavities located in a subsurface layers of the nucleus. This assumption is a consequence of the idea that cometary nuclei contains many cavities located a few meters below the surface of the nuclei which contain dust and gas under pressure (Ipatov and A'Hearn 2011; Ipatov 2012). This idea follows from the analysis of dynamics of particles ejected from the Comet 9P/Tempel after collision with the Deep Impact impactor (Ipatov 2012). It is worth stressing that this idea is consistent with the conclusions of the space mission to the comet 67P/Churyumov–Gerasimenko (Agarwal et al. 2017). The authors of this work suggest that the comet nucleus may contain under surface caves and cavities that act as pressurized gas reservoirs. This assumption can explain the activity of the comet 67P/Churyumov–Gerasimenko. In the interior of the comet the CO could sublimate into cavities. If the pressure of CO in the cave is large enough, then we can expect that the nucleus layer placed over cavity is going to break. This event would occur if the destructive forces exceeded the binding forces acting on it. The destructive forces are the result of gas pressure and nucleus rotation. The binding forces come from a gravity of the comet and tensile strength σ_t of nucleus material. In other words the pressure of CO should overcome the sum of the effective weight of the layer placed over the cavity (per unit area) and the tensile strength of the nucleus (for more details see: Gronkowski 2014; Gronkowski and Wesołowski 2015). Therefore we have:

$$p_{\geq} \Delta x \rho_N R_N \left(\frac{4}{3} \pi G \rho_N - \omega_N^2 \cos^2 \phi \right) + \sigma_t. \tag{1}$$

Here p, Δx, ρ_N, R_N, G, ω_N, ϕ and σ_t stand for the CO pressure in the cavity, thickness of the layer placed over the cavity, the density of nucleus, radius of the centaur's nucleus, the gravitational constant, the angular spin velocity of the nucleus, 'centaurocentric latitude' and the tensile strength of cometary material, respectively. Practically for the case of centaur's nuclei the dominant term for the right side of Eq. (1) is the tensile strength of nuclei material. We assume that the tensile strength of centaur's nucleus is in the range of the tensile strength of cometary nucleus. We must bear in mind that the lower limit for this cometary parameter is 10 kPa for outer part of the comet/centaur nuclei on the decametres scale (Reach et al. 2010). In our calculations we will take into consideration two objects as representatives for centaurs which show cometary-like activity at large heliocentric distances. They are: (1) centaur like-comet 95P/Chiron and (2) hypothetical object like-centaur (hereafter XP/C) which has orbit with perihelion distance $q = 10$ AU, aphelion distance $Q = 20$ AU and the inclination of the orbit plane $i = 0°$. The values of the physical cometary parameters which were used in the numerical calculations and simulations are presented in Table 1. The temperature inside the centaur's nucleus is determined by two factors. The first is the energy balance equation for the surface of the nucleus. The second is the temperature of the center of the nucleus depending on the location in the the solar system in which the object was formed and no radiogenic heating is considered. The energy balance equation for the surface of the centaur's nucleus can be expressed as follows:

$$\frac{S_{\odot}}{d^2}(1 - A_N)\cos\theta = \epsilon\sigma T(0)^4 + h(\psi)K(T)\frac{\Delta T}{\Delta x} + f_{CO}\frac{\dot{Z}_{CO}L_{CO}(T(0))}{N_0}. \tag{2}$$

In this equation the left part stands for the input of the solar energy into the object. We adopt the following notation: $S_{\odot} = 1360\,\mathrm{W/m^2}$—the solar constant for 1 AU, A_N—the albedo of the centaur's nucleus (we assume that $A_N = 0.11$ Groussin et al. 2004), θ—the zenith angle of the Sun, d—the heliocentric distance (expressed in AU units) of the centaur. The right side of the equation represents the energy consumed by the nucleus for irradiation, heat conduction to its interior, and sublimation. Here the following notation is used: ε—infrared emissivity of the comet surface, σ—the Stefan–Boltzmanmn constant, $T(0)$—the temperature of the surface of the nucleus, f_{CO}—the surface fraction covered by CO ice, $\dot{Z}_{CO}$—the rate of CO sublimation, $L_{CO}(T)$ the latent heat of sublimation CO ice, N_0—the Avogadro number, $K(T)$—average heat conductivity of centaur's material. This Eq. (2) is solved together with the equation of state called the equation of Clausius–Clapeyron, the ideal gas equation and the dynamic relationship of gas escaping from the surface of the nucleus into vacuum (see e.g. Keller 1990). The dependence of the surface temperature $T(0)$ of the 95P/Chiron nucleus on its heliocentric distance calculated based on the Eq. (2) is illustrated in Fig. 1. As was mentioned above, we assume that the centaur's nucleus is spherical in shape, and revolves around the Sun along the elliptical orbit and simultaneously spinning around an axis, which is its diameter. As consequence of orbital and spin motion there are two heat waves that penetrate the interior of centaur's nucleus with an

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

Parameters for the comet 95P/Chiron	Value (s)
Parameters for the comet 95P/Chiron	
The radius of the comet's nucleus (km)	$R_N = 107.80–135.69$
The albedo (–)	$A_N = 0.057–0.160$
The semimajor axis of the cometary orbit (AU)	$a = 13.648$
The eccentricity of the cometary orbit (–)	$e = 0.3823$
The orbital inclination of the cometary orbit	$i = 6.9497°$
The orbital period (years) of the comet	$P_o = 50.42$
The spin rotation period of the comet nucleus (h)	$P_s = 5.918$
The radius of the cometary coma (km)	$R_{coma} = 50000$
Parameters for the comet's XP/C	
The radius of the comet's nucleus (km)	$R_N = 50$
The albedo (–)	$A_N = 0.06$
The semimajor axis of the cometary orbit (AU)	$a = 15.00$
The eccentricity of the cometary orbit (–)	$e = 0.333(3)$
The orbital inclination of the cometary orbit	$i = 0°$
The orbital period (years) of the comet	$P_o = 58.01$
The spin rotation period of the comet nucleus (h)	$P_s = 10$
The radius of the cometary coma (km)	$R_{coma} = 30000$
Thermodynamic parameters common to both cases	
The CO ice conductivity ($Wm^{-1} K^{-1}$)	$K_{CO} = 10^{-4}$
The dust conductivity ($Wm^{-1} K^{-1}$)	$K_d = 2$
The heat capacity of CO ice ($J\ kg^{-1} K^{-1}$)	$C_{CO} = 2010$
The heat capacity of dust ($J\ kg^{-1} K^{-1}$)	$C_d = 1300$
The hertz factor (–)	$h = 0.01, ..., 0.1$
Parameters for the comet 29P/SW	
The radius of the comet's nucleus (km)	$R_N = 27$
The albedo (–)	$A_N = 0.04$
The semimajor axis of the cometary orbit (AU)	$a = 5.986 \approx 6.00$
The eccentricity of the cometary orbit (–)	$e = 0.0441$
The orbital inclination of the cometary orbit	$i = 9.3903°$
The orbital period (years) of the comet	$P_o = 14.65$
The sublimation rate of cometary ice ($\frac{molecules}{m^2\ s}$)	$\dot{Z} = 2.7025 \times 10^{18}$

They are the same as in the papers of Brown and Luu (1998), Groussin et al. (2004), Fornasier et al. 2013, Gronkowski and Wesołowski 2015 and literature therein

orbital period P_o and a spin period P_s, respectively. The depth of penetration of these two waves is described by the thermal skin depth S which can be expressed as follows:

$$S = \sqrt{(KP)/(\pi \rho_N C)}. \tag{3}$$

In Eq. (3) we adopt the following notation: K—thermal conductivity, P—the period of the motion ($P = P_o$ for orbital motion and $P = P_s$ for spin motion, respectively), the density

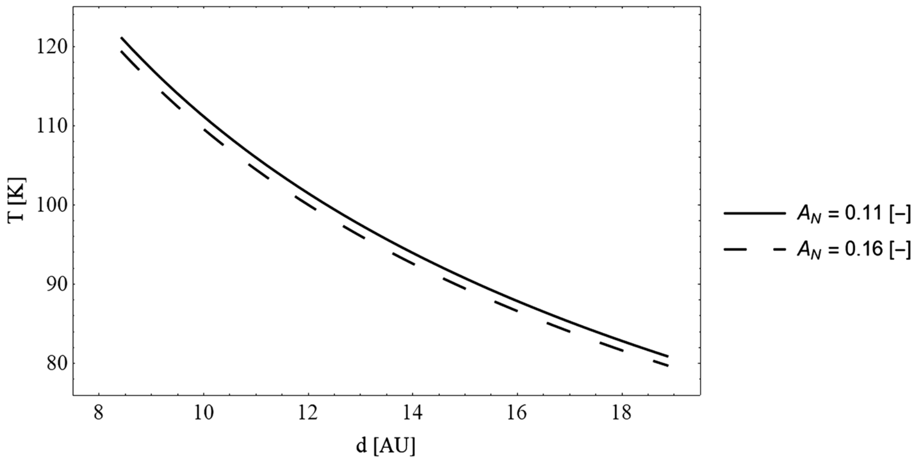


Fig. 1 The temperature of the nucleus surface of centaur 95P/Chiron as the function of its heliocentric distance. Two probable values of its nucleus albedo $A_N = 0.11$ and $A_N = 0.16$ are assumed

and the average specific heat, ρ_N—the density of the nucleus, C—its average specific heat. In this place we have to explain three things.

First, the precise definition of the thermal skin depth. Thermal skin depth is a depth at which the amplitude of the thermal wave is attenuated by a factor e ≈ 2.71 (e denotes the Euler's number).

Second, the thermal effects which are the results of heats wave are confined to a subsurface layer several times S in thickness.

Third, the orbital skin depth is much larger than the spin skin depth because $P_o >> P_s$. Consequently, we will take into account only orbital skin S_o depth.

The thermal skin depth S depends on the average thermal conductivity K which depends on the porosity ψ of a nucleus material, and the mass percentage of solid components of the comet nucleus. The thermal conductivity is also corrected by a Hertz factor $h(\psi)$ because of the reduction of the contact surface between grains which are the main component of the nucleus (Tancredi et al. 1994; Davidsson and Skorov 2002). Therefore the thermal conductivity is expressed as follows:

$$K = (1-\psi)^{\frac{2}{3}} h(p_{H_2O}K_{H_2O} + p_{CO}K_{CO} + p_d K_d). \tag{4}$$

Here K_{H_2O}, K_{CO}, K_d denote the conductivity of ices of water, carbon monoxide and dust, respectively. In this equation p_{H_2O}, p_{CO}, p_d denote the percentage of water ice mass, carbon monoxide mass and dust mass, respectively. Analogically we assume that the average specific heat of centaur nucleus is given *by the following formula*:

$$C = p_{H_2O}C_{H_2O} + p_{CO}C_d + p_i C_i; \tag{5}$$

In this formula C_{H_2O}, C_{CO}, C_d denote the heat capacity of water ice, carbon monoxide ice and dust, respectively. Using Eqs. (3), (4) and (5), we can calculate the probable values of the thermal skin depths related to the orbital motion S_o of 95P/Chiron. Now we can approximate the temperature inside the centaur's nucleus in the following way (see: Kührt 1984; Jewitt 1990; Gronkowski and Wesołowski 2015):

$$T(x) = T_{\mathrm{int}} + T_0 \exp\left(-\frac{x}{S_{\mathrm{o}}}\right) \tag{6}$$

Here x stands for the depth below the surface of the nucleus, $T(x)$ denotes the temperature at the deep x, T_{int} is the temperature of the deep interior (for $x \gg S_{\mathrm{o}}$), and $T_0 = T(0) - T_{int}$ is equal to the excess of the temperature at the surface of the nucleus which is the result of the heating by the solar radiation. Figure 2 shows the temperature profiles of centaur 95P/Chiron. It is worth noting that these profiles are generally consistent with the results of papers by Tambovtseva and Shestakova 1999 which are based on the solutions of heat diffusion equation for spherical cometary nucleus. Having temperature profiles we can also obtain pressure distribution for CO in the subsurface cavities of the Chiron nucleus (Fig. 3). Taking into consideration Fig. 2 it is easy to conclude that the condition [Eq. (1)] is being fulfilled in the whole range of considered heliocentric distances. Therefore, the surface layers of Chiron nucleus can be subject to destruction, indeed. In this way, the interior of cavities which can be rich in volatile ices (CO) can be exposed to the solar radiation. The *temperature* of sublimation from a centaur can increase considerably. As a consequence, a phenomenon similar to the outburst of comet's brightness can be observed. We note that the similar calculations for a comet XP/C [object (2)] lead to the conclusion that it can also undergo outbursts along its whole orbit.

3 The Calculations of the Characteristics of Cometary Outbursts

3.1 The Amplitude in the Jump of Cometary Brightness

The amplitude in the jump of the centaur brightness Δm is a key characteristics of the considered phenomenon. As it was mentioned in the previous chapter the jump in the brightness of a comet should be produced by ejection of some layers of its nucleus into space and due to sublimation of exposed subsurface layers of a nucleus. We assume that the outbursts of centaurs brightness has the same cause. The calculations are based on the Pogson law and were carried out in the similar way to the following papers: Gronkowski 2007, 2009, 2014. The main numerical problems related to the estimation of jump Δm in these works and references therein are described in more detail. Therefore, in this paper only the fundamental formulae are briefly presented. We obtain the luminosity jump of a centaur from the following formula:

$$\Delta m \approx 2.5 \log \frac{C_{\mathrm{sca}}(n) + C_{\mathrm{sca}}(t_2) + C_{\mathrm{sca}}(M_{\mathrm{ej}})}{C_{\mathrm{sca}}(n) + C_{\mathrm{sca}}(t_1)}. \tag{7}$$

Here $C_{\mathrm{sca}}(n)$ stands for the scattering cross-section of a bare nucleus of a comet (we remind that $C_{\mathrm{sca}}(n) = A_{\mathrm{N}} \pi R_{\mathrm{N}}^2$, where A_{N} is its albedo), $C_{\mathrm{sca}}(t_1)$ and $C_{\mathrm{sca}}(t_2)$ stand for the total scattering cross-section of the cometary water-ice dust particles that were raised by sublimation and remain in the atmosphere of a comet at the time of normal inactive t_1 and active—outburst phase t_2, respectively. The parameter $C_{\mathrm{sca}}(M_{\mathrm{ej}})$ stands for the total scattering cross-section of the cloud of the debris which was created after the destruction of some nucleus layers placed over cavities and ejected into space. Here one thing must be explained. We assume that particles coming from the destruction of *the surface layer of* centaur's nuclei are similar to the cometary dust-ice grains which are spherical in shape. Such an approach is the approximation of the real shape of cometary grains. This method is widely used by

Fig. 2 The temperature inside the 95P/Chiron nucleus as the function of deep x for its three assumed heliocentric distances: **a** the perihelion q, **b** the average distance d_{av} and **c** the aphelion Q. There are assumed three values of initial deep interior temperature T_{int}

many authors (Hage and Greenberg 1990; Davidsson and Skorov 2002; Gunnarsson 2003). The scattering cross-sections which occur in Eq. (7) can be obtained from the following formula:

$$C_{\mathrm{sca}}(t_i) = \pi N_{\mathrm{gr}}(t_{\mathrm{i}}) \int_{a_{\min}}^{a_{\max}} Q(\lambda, a, m^*) a^2 f(a) \mathrm{d}a, \tag{8}$$

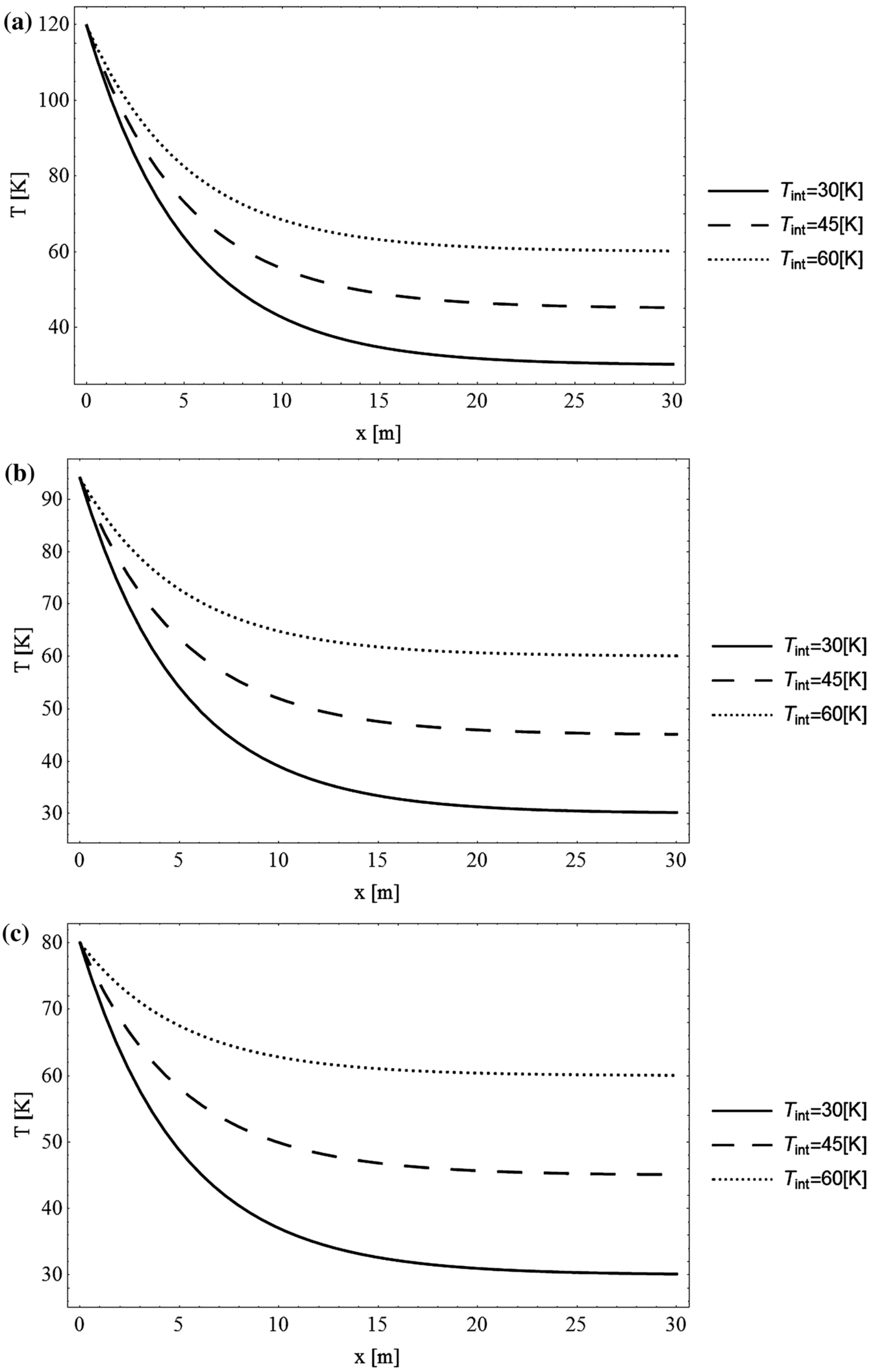
Here $N_{\mathrm{gr}}(t_1)$ and $N_{\mathrm{gr}}(t_2)$ stand for the total number of particles which remain in the head of the centaur as a result of sublimation in the normal-quiet phase and outbursts phase, respectively. The efficiency parameter $Q(\lambda, a, m^*) = Q_{\mathrm{SCAT}}$ is the scattering efficiency of cometary particles and $f(a)$ denotes their size distributions function. In this equation index i is equal to 1 or 2. Other designations are as follows: a, λ, m^* stand for the radius of centaur's grain, the wavelength of electromagnetic solar radiation and the complex effective index of grain material, respectively. We note that scattering efficiency Q_{SCAT} may be calculated on the basis of Mie's theory (Bohren and Huffman 1983). In numerical calculations it is assumed that the size distribution function $f(a)$ for grains is the same which was given by Newburn and Spinrad (1985) for cometary particles. In the calculation we must also take into account that the number $N_{\mathrm{gr}}(t_i)$ fulfils the conditions:

$$\frac{4}{3} \pi N_{\mathrm{gr}}(t_{\mathrm{i}}) \rho_{\mathrm{gr}} \int_{a_{\min}}^{a_{\max}} a^3 f(a) \mathrm{d}a = M_{\mathrm{inc}}(t_{\mathrm{i}}), \tag{9}$$

In this relation parameter $M_{\mathrm{inc}}(t_{\mathrm{i}})$ denotes the mass of grains included in the coma as the results of the normal sublimation of the 95P/Chiron ice ($i = 1$) and during its outburst ($i = 2$), respectively. These masses can be expressed as (Gronkowski 2009):

$$M_{\mathrm{inc}}(t_{\mathrm{i}}) = 4\pi R_{\mathrm{n}}^2 \eta(t_{\mathrm{i}}) \chi \left(J_{\mathrm{CO,v}}(t_{\mathrm{i}}) \frac{R_{\mathrm{coma}}}{v_{\mathrm{CO,v}}} \right). \tag{10}$$

Here the following notation is used: $\eta(t_{\mathrm{i}})$ denotes the ratio of the active sublimation area of the nucleus to its total surface in inactive ($i = 1$) and active phase ($i = 2$), respectively, $J_{\mathrm{CO,v}}(t_{\mathrm{i}})$ stands for a flux of CO vapour in these phases (expressed in $\mathrm{kg}/(\mathrm{m}^2\ \mathrm{s})$ units), χ is the dust-gas mass ratio, R_{coma} stands for the radius of the centaur's coma, and $v_{\mathrm{CO,v}}$ denotes the mean radial velocity of CO vapour molecules. As it was mentioned above we assume the structure of grains derived from the destruction of the centaur's nucleus layer is similar to the structure of the cometary grains. Therefore, we will take into consideration three models of grains. The first one (a) assumes that grains are spherical in shape, and they include pure water ice. The second one (b) takes into consideration the grains which are spherical in shape and they consist of two layers: the silicate core which is surrounded by organic shell. The most complicated is the third model of grains (c). According to following papers: Hage and Greenberg (1990), Davidsson and Skorov (2002) and Gunnarsson (2003) we assume that the grains have complex heterogeneous structure. Therefore we accept that the considered particles are spherical in shape and they consist of three layers. The core which is the deepest inner layer, is built from a silicate. The core is surrounded by organic components and is covered by water-ice crystalline mantle. For the sake of calculation of the refractive index m_{eff} for these particles we use the Maxwell-Garnett effective


(a)
T [K]
x [m]
T_{int}=30[K]
T_{int}=45[K]
T_{int}=60[K]
(b)
T [K]
x [m]
T_{int}=30[K]
T_{int}=45[K]
T_{int}=60[K]
(c)
T [K]
x [m]
T_{int}=30[K]
T_{int}=45[K]
T_{int}=60[K]

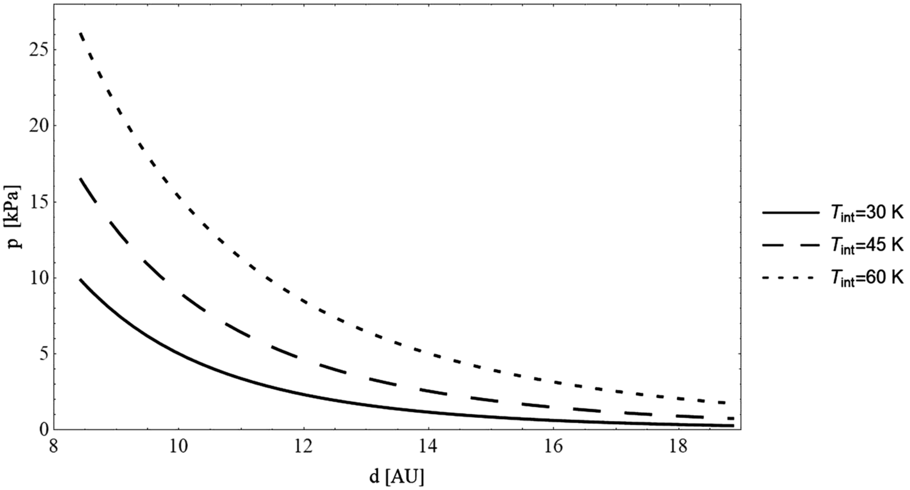


Fig. 3 The pressure p inside the 95P/Chiron's cave on the depth $x = 2.25$ m as the function of its heliocentric distance and parameter $f_{CO} = 0.05$. There are assumed three values of initial deep interior temperature T_{int}

medium theory (for more details see, e.g., Davidsson and Skorov 2002). Therefore we have:

$$m_{eff} = m_s \sqrt{1 + 3q^3 \frac{\frac{m_c^2 - m_s^2}{m_c^2 + 2m_s^2}}{1 - q^3 \frac{m_c^2 - m_s^2}{m_c^2 + 2m_s^2}}}, \tag{11}$$

where q denotes the ratio between the core radius and the shell radius, m_c and m_s are refractive indices of core and shell, respectively. For the model (b) grain structure we use Eq. (11) to obtain the refractive index of the silicate core and organic shell. It must be emphasized that for the model of grains (c) Eq. (11) should be used twice. First, to obtain the effective refractive index of the silicate core and organic shell, and second, to obtain the effective refractive index for water ice mantle added to that. The detailed methods of refractive index calculation for the cometary material and numerical values of appropriate optical characteristics are very-well known (see for example: Mukai 1986; Li and Greenberg 1997; Davidsson and Skorov 2002; Gunnarsson 2003 and references therein). The ratio q occuring in Eq. (11) is a function of the geometrical structure of particles. The following relations are valid (Davidsson and Skorov 2002):

$$a_{org} = a_{sil} \left(\frac{M_{org}}{M_{sil}} \frac{\rho_{sil}}{\rho_{org}} + 1 \right)^{1/3}, \tag{12}$$

$$a_{ice} = a_{sil} \left(\frac{M_{ice}}{M_{sil}} \frac{\rho_{sil}}{\rho_{ice}} + \left(\frac{a_{org}}{a_{sil}} \right)^3 \right)^{1/3}. \tag{13}$$

The following notation was used: a_{org}, a_{sil}, a_{ice} stand for the radii of organic shell, silicate core and the ice shell, respectively. The organics-to-silicates mass ratio is $M_{\mathrm{org}}/M_{\mathrm{sil}} = 0.95$ and the ice-to silicates mass ratio is $M_{\mathrm{ice}}/M_{\mathrm{sil}} = 3.05$ (Hage and Greenberg 1990). We accept the following values of densities for cometary material: for silicates $\rho_{\mathrm{sil}} = 2950$, for organics refractories $\rho_{\mathrm{or}} = 1600$ and for water ice $\rho_{\mathrm{ice}} = 933$ in SI units (Davidsson and Skorov 2002). The results of the scattering efficiency calculations for spherical in shape water ice grains and for three wavelengths of the solar light are shown in Fig. 4. We clearly see that the differences between obtained three graphs for λ_{violet}, λ_{yellow} and λ_{red} are relatively small. Therefore, the calculations of the scattering efficiency were carried out for the average length of a solar radiation wave $\lambda = 0.5015\,\mu\mathrm{m}$, which results according to the applied Wien law from solar radiation. Figure 5 shows the scattering efficiency for three types of considered grains (a), (b), (c) calculated for average length of the solar radiation

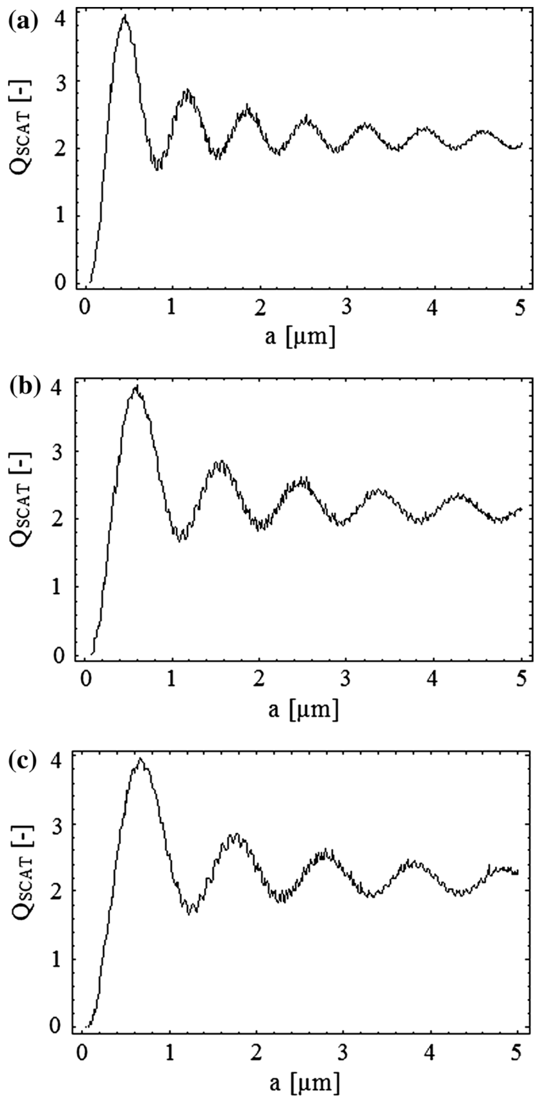


Fig. 4 The scattering efficiencies for spherical in shape grains containing a pure water ice with a refractive index $n = 1.31 + 1 \times 10^{-8}i$ as the function of their radius for three assumed wave lengths of solar light **a** $\lambda = 0.420\,\mu\mathrm{m}$ (violet), **b** $\lambda = 0.560\,\mu\mathrm{m}$ (yellow) and **c** $\lambda = 0.632\,\mu\mathrm{m}$ (red)

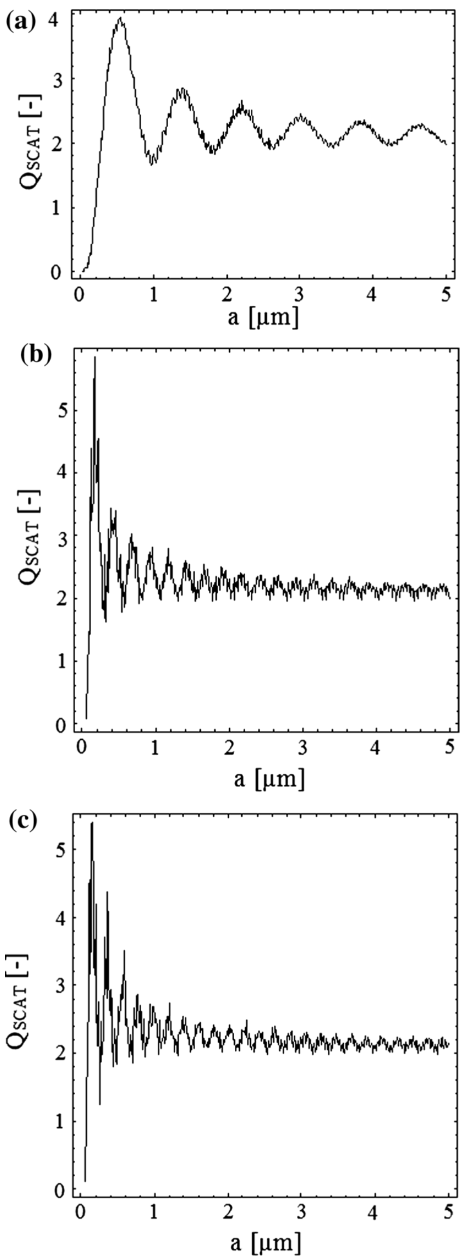


Fig. 5 The scattering efficiencies for three types of grains **a**, **b**, **c**, respectively. It is assumed according to the Wien law that the average length of a solar radiation wave is $\lambda = 0.5015\ \mu m$

wave. Now it is easy to note that the graphs differ between each other. Finally, a jump in the brightness of 95P/Chiron during its outbursts is calculated. The Fig. 6 shows the brightness jump Δm for 95P/Chiron outburst for three heliocentric distances: perihelion, average and aphelion of this object. The results of analogous calculations for the XP/C are presented in Fig. 7. The analysis of Figs. 6 and 7 leads to the conclusion that the amplitude of the jump Δm is an increasing function of distance d from the Sun. This relationship is simple to explain.

The sublimation activity of the centaur is the decreasing function of the parameter d. Therefore any amount of the cometary material ejected during the outburst into the coma is, in comparison with the amount of matter placed over there due to sublimation before the outburst, proportional bigger for larger heliocentric distance. *At the current paper* we show the results of calculations only for model (c) because the results for the model (a) and (b) do not differ significantly. Taking the following papers: Luu 1993; Duffard et al. 2002; Jewitt 2009 and Lin et al. 2014 into consideration we conclude that the obtained results are in good agreement with observations of real outbursts of centaurs at large heliocentric distances. Bear in mind that this method of *calculating the amplitude in the jump* of brightness may be applied to the centaurs which have halos dominated by water ice-dust grains. Meaning that this method can be used for objects which produce the dominant part of their radiance from the reflection of the solar light.

3.2 The Expansion Velocity of Halo

The dynamics of water-ice particles (grains) moving in the atmosphere of a comet (centaur) at large heliocentric distances is determined by the following forces: (a) gravitation of a comet/centaur nucleus, (b) drag force which is caused by the fact that the molecules of sublimating CO ice strikes into other particles, (c) radiation pressure which is coming from the electromagnetic solar radiation, (d) solar tidal force and, (e) rocket-force which is product of asymmetrically sublimation of H_2O from the particles (Kelley et al. 2013). *However, we assume that the considered grains* do not show sublimation at large heliocentric distance. *At such heliocentric distances* only the first two forces are dominating. The question of cometary particles dynamics is widely described in literature (see e.g.: Dobrovolsky 1966; Keller 1990; Jones 1995; Crifo et al. 2005; Molina 2010; Molina and Moreno 2011; Rubin et al. 2011; Tenishev et al. 2011; Combi et al. 2012; Fougere et al. 2012, 2013). The equation of the motion for particles situated at a distance R from the center of a centaur nucleus can be expressed in the following form:

$$m\ddot{R} = \frac{C_{\mathrm{D}}}{2}\pi a^2 \rho_{\mathrm{g}}(\dot{R} - v_{\mathrm{g}})^2 - \frac{\mathrm{G}M_{\mathrm{N}}m}{R^2} \tag{14}$$

The first term on the right side of Eq. (14) represents the drag force and the second term stands for the gravitation of the centaur. We use the following notation: m, $\ddot{R}$, C_{D}, ρ_{g}, $\dot{R}$, v_{g}, G, M_{N}, the mass of dust-ice grains, the second derivative of distance R in respect to the time t, the modified free-molecular drag coefficient for spherical grain of radius a, the density of the gas, *the first time-derivative of distance* R, the velocity of the gas molecules, the gravitational constant and the mass of a centaur nucleus, respectively. The modified-molecular drag coefficient C_{D} [Eq. (14)] is expressed as follows (Crifo et al. 2005 and literature therein):

$$C_{\mathrm{D}} = \frac{2s^2+1}{s^3\sqrt{\pi}}\exp(-s^2) + \frac{4s^4+4s^2-1}{2s^4}\mathrm{erf}(s) + \frac{2\sqrt{\pi}}{3s}\sqrt{\frac{T_{\mathrm{gr}}}{T_{\mathrm{g}}}}. \tag{15}$$

Here T_{gr} and T_{g} denote the *grains and gas temperature, respectively*. For simplicity we assume that $T_{\mathrm{gr}} = T_{\mathrm{g}}$. The factor s is given by the following formula:

Fig. 6 The brightness jump Δm for 95P/Chiron during its outbursts as the function of ejected mass M_{ej} and the parameter $\eta(t_1)$. The parameter $\eta(t_1)$ represents the ratio of the active sublimation area of the nucleus to its total surface during the inactive phase [see also explanations to Eq. (10)]. The calculations were done for the model of heterogeneous grains which are built from three spheres [model (c)] and for three assumed heliocentric distances which are the same as in Fig. 2. Additionally, it is assumed that the radius of the 95P/Chiron is equal to $R_N = 120\,\text{km}$ (as the arithmetic mean of different values which are given in literature) and its albedo is equal to $A = 0.11$ (Groussin et al. 2004). After Brown and Luu 1998 (and literature therein) we take for the effective radius of the 95P/Chiron coma $R_{coma} = 50{,}000$ km. It has been assumed that the centaur is in the heliocentric distances: **a** perihelion q, **b** average d_{av} and **c** aphelion Q

$$s = |v_g - \dot{R}| / \sqrt{(2k_B T_g)/(m_g)}; \tag{16}$$

where k_B denotes Boltzmann's constant, and m_g stands for the gas molecules mass. We assume that the velocity of the gas molecules fulfils the conditions (Molina 2010): $v_g = \sqrt{(2k_B T_g)/(\pi m_g)}$. After some algebraical transformations the Eq. (14) can be transformed into the following form which is useful for analytical as well as numerical calculations:

$$\ddot{R} = \frac{A\dot{R}^2 + B\dot{R} + C}{R^2} \tag{17}$$

where factors A, B, C are expressed as:

$$A = -\frac{3C_D \dot{Z} \mu m_0 R_N^2}{8 a \rho_{gr} v_g}, \tag{18}$$

$$B = \frac{3C_D \dot{Z} \mu m_0 R_N^2}{4 a \rho_{gr}}, \tag{19}$$

$$C = -\frac{3C_D \dot{Z} \mu m_0 R_N^2 v_g}{8 a \rho_{gr}} - GM_N. \tag{20}$$

Here: $\dot{Z}$, R_N, ρ_{gr} denote the rate of *CO sublimation from the centaurs, the radius* of its nucleus and the density of the grains. Other symbols have the same meaning as previously. Using the following relationship:

$$\ddot{R} = \frac{d\dot{R}}{dR} \cdot \frac{dR}{dt} = \dot{R} \cdot \frac{d\dot{R}}{dR}, \tag{21}$$

we can Eq. (17) rewrite in the form of:

$$\int_{v_0}^{v_\infty} \frac{\dot{R}\, d\dot{R}}{A\dot{R}^2 + B\dot{R} + C} = \int_{R_N}^{R_\infty} \frac{dR}{R^2} \approx \frac{1}{R_N}. \tag{22}$$

The following notations are used: v_0, v_∞, R_∞ the grains ejection velocity, the halo expansion velocity at large distance from the nucleus and the radius of the halo, respectively. *On the*

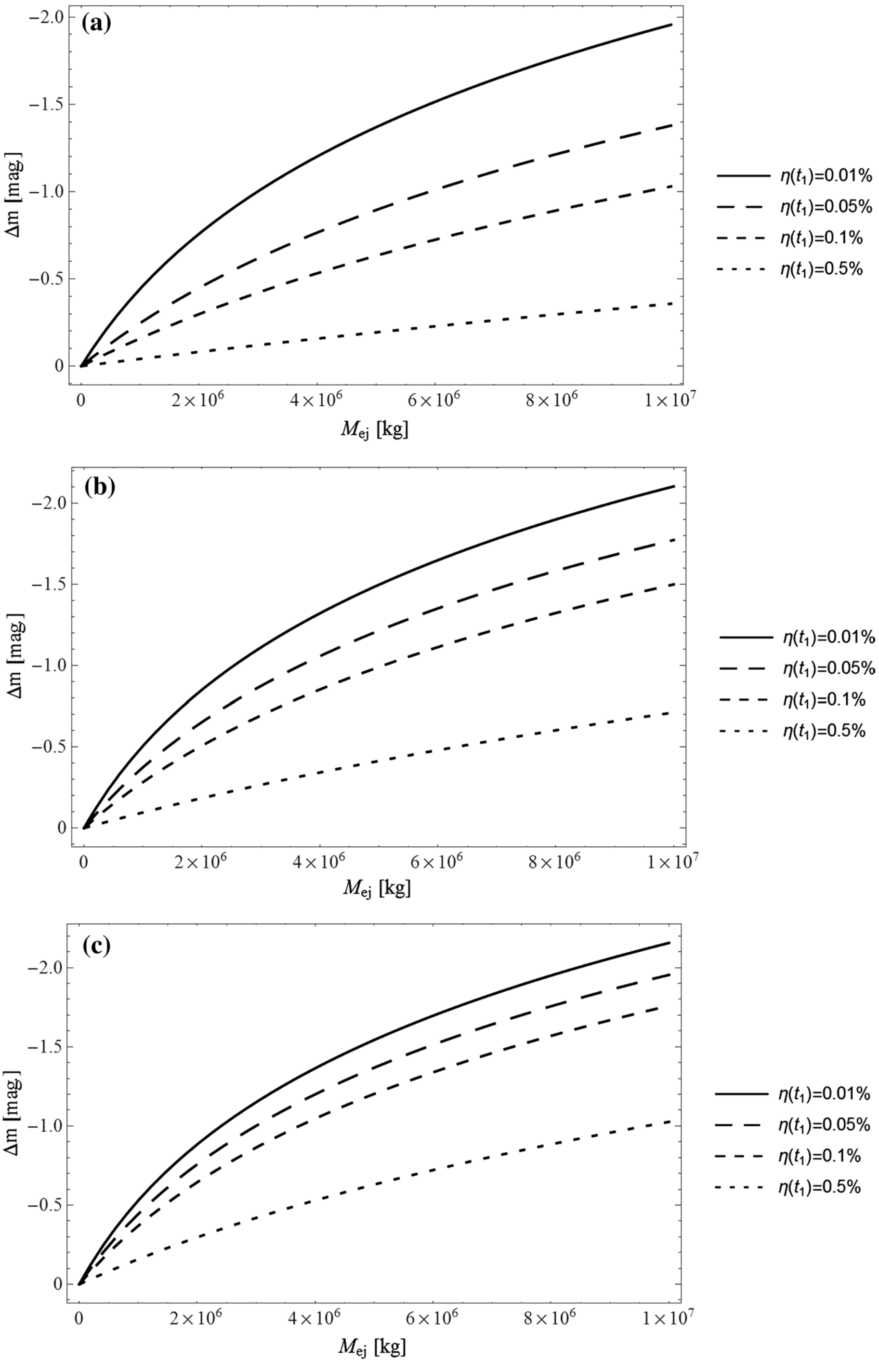

(a)
(b)
(c)
Δm [mag]
M_{ej} [kg]
−2.0
−1.5
−1.0
−0.5
0
2×10^6
4×10^6
6×10^6
8×10^6
1×10^7
$\eta(t_1)$=0.01%
$\eta(t_1)$=0.05%
$\eta(t_1)$=0.1%
$\eta(t_1)$=0.5%

Fig. 7 The jump in the brightness of the hypothetical X/PC centaur as the function of the parameter $\eta(t_1)$ ▶ and the ejected mass M_{ej}. Calculations were done for its three heliocentric distances: **a** perihelion q, **b** average d_{av} and **c** aphelion Q

right-hand side of Eq. (22) we have used the approximation $R_\infty >> R_N$. Long-term observations lead to the conclusion that the halo expansion velocities during comets outbursts range from several dozen to several hundred meters per second. Based on this fact we can obtain from Eq. (22) the particles ejecta velocities v_0. We note that numerical calculation of halo expansion velocity were done for the centaur 29P/SW. *This object was chosen by the fact that* its outburst activity is most accurately known. The results of numerical calculations are given in Table 2. It is easy to see that the obtained values of the halo expansion v_∞ are compatible with the results of the long-term observations of the cometary outbursts.

4 Remarks, Conclusions

The problem about the source of comets and centaurs outburst activity at *large heliocentric distance is a very* intriguing question for astrophysicists. This *issue was approached using the example* of the 95P/Chiron and hypothetical object XP/C. The numerical simulations show that the CO pressure in both objects along their entire orbits is large enough to cause the destruction of the surface layers of these objects to a depth of a few meters. The proposed scenario of the outburst is as follows: in a subsurface cavity CO, which comes from the sublimation of the walls of the cavity or reaches it from the deeper layers of the nucleus of the centaur through the porous material of its interior. In this way, the gas pressure in the cavity may increase and at some point can overcome the sum of the effective weight of the layer above the cavity (per unit area) and the large-scale tensile strength [see Eq. (1)]. Therefore, the outer nucleus layer covering the cavity is destroyed. Its remnants, in the shape of a cloud of cometary-like ice-dust particles, are ejected into space. At the same time, subsurface nucleus layers rich in volatiles are exposed. Then the rate of sublimation of the centaur nucleus with these newly exposed subsurface layers increases significantly. All of this causes that the total number of ice-dust grains that remain in the temporary atmosphere and reflect solar light increases dramatically. Eventually, an outburst of centaur's brightness can be observed. It should be noted that a number of numerical simulations have been made concerning the changes in brightness of the centaurs in question. They have shown huge similarities in the activity of comets and centaurs. The most important ones are listed below.

1. The main factor which determines the amplitude of the outburst is the quantity of the mass M_{ej} ejected from the centaur's nucleus.
2. The jump in the amplitude of the centaur's brightness is greater when the initial part of the nucleus *which was in active sublimation is smaller*. It is a consequence of the fact that the fixed quantity of ejected mass M_{ej} has larger scattering cross-section, in comparison with the same parameter of mass included in its coma in inactive phase, when the value of $\eta(t_1)$ is smaller.
3. The jump in the centaur brightness is an increasing function of its distance from the Sun. This conclusion was foreseen, because the rate of sublimation is a decreasing function of the centaur's heliocentric distance. It results from the fact that the same amount of

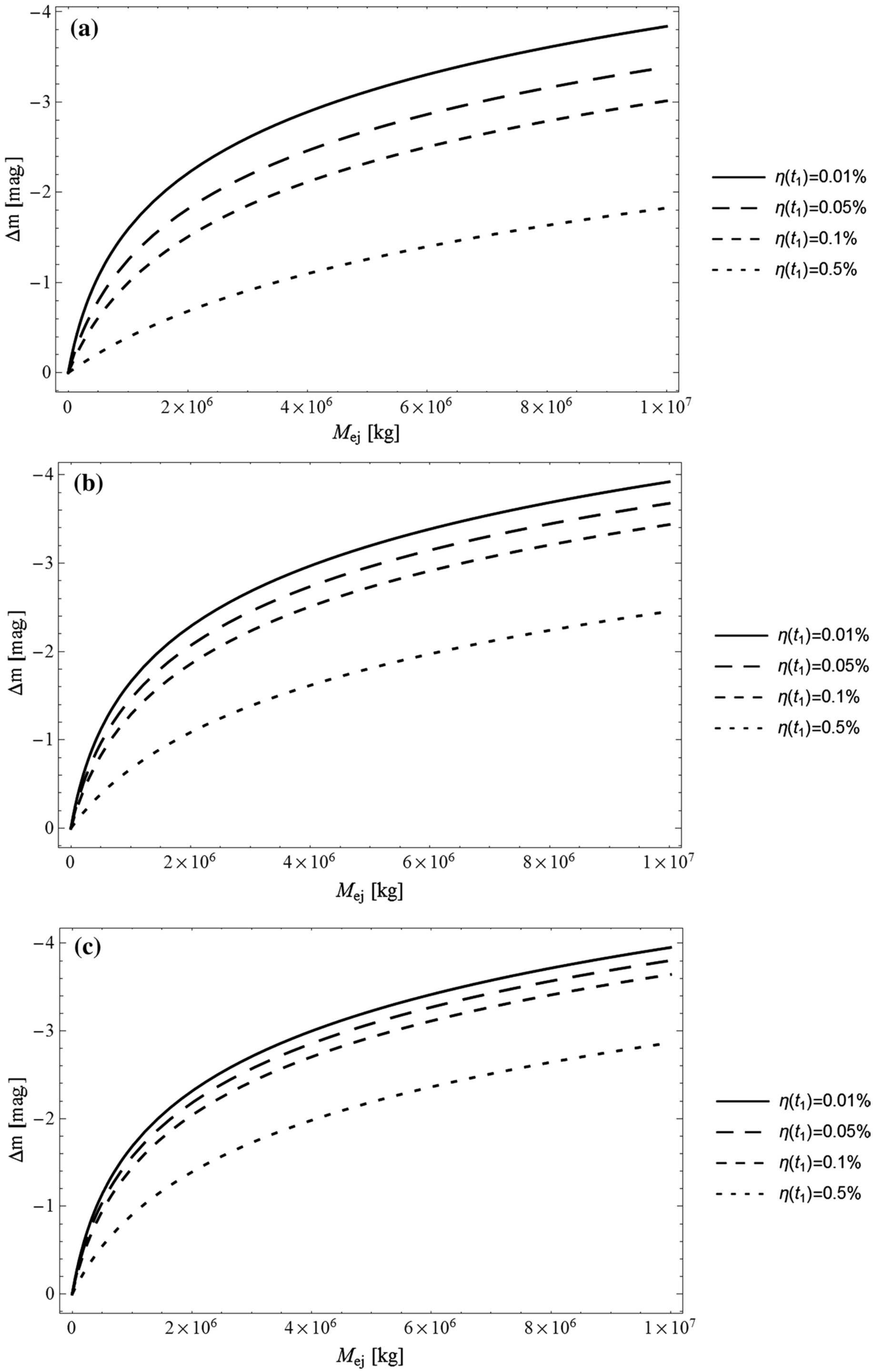

(a)
Δm [mag.]
−4
−3
−2
−1
0
0
2×10^6
4×10^6
6×10^6
8×10^6
1×10^7
M_ej [kg]
η(t_1)=0.01%
η(t_1)=0.05%
η(t_1)=0.1%
η(t_1)=0.5%
(b)
Δm [mag.]
−4
−3
−2
−1
0
0
2×10^6
4×10^6
6×10^6
8×10^6
1×10^7
M_ej [kg]
η(t_1)=0.01%
η(t_1)=0.05%
η(t_1)=0.1%
η(t_1)=0.5%
(c)
Δm [mag.]
−4
−3
−2
−1
0
0
2×10^6
4×10^6
6×10^6
8×10^6
1×10^7
M_ej [kg]
η(t_1)=0.01%
η(t_1)=0.05%
η(t_1)=0.1%
η(t_1)=0.5%

Table 2 The expansion velocity v_∞ of a cometary halo as the function of the assumed density of grains ρ_{gr} and the ejection velocity of the cometary particles from the nucleus v_0 for the comet 29P/SW. It is assumed that the radius of cometary grain is equal to $a = 10^{-6}$ m

v_0(m/s)	v_∞(m/s)				
	ρ_{gr}(kg m^{-3})				
	500	1000	1500	2000	2500
0	13.29	11.70	10.99	10.58	10.32
50	53.10	52.29	52.04	51.92	51.85
100	113.26	106.33	104.36	103.42	102.88

cometary mass ejected to the halo compared to *the mass placed over there, during an inactive phase, has relatively bigger scattering* cross-section for a larger heliocentric distance.

Finally, it should be emphasized that the issue of the strong activity of comet 29P/SW, which also belongs to the centaur family, is a separate problem. There are many hypotheses trying to explain its activity on the basis of different mechanisms. Authors often use the idea that the probable source of its outbursts is the transformation of amorphous water ice into the cubic crystalline form. Such a way of explaining the causes of the phenomenon under consideration seems to be trustworthy and attractive for the following reasons:

1. The orbit of *the comet is placed at a unique distance* from the Sun because the heliocentric distance 6 AU is situated at the very edge of the amorphous water ice stability zone.
2. The orbit of comet 29P/SW is placed also at the edge of the sublimation of water-ice zone.
3. The radius of 29P/SW nucleus is large enough for the amorphous water ice to survive inside the comet until now.

Summarizing, the unique location of 29P/SW orbit in the solar system and the unique large size of its nucleus can be responsible for the atypical activity of the comet.

On the other hand, this hypothesis has at least two weak points. The first one is related to the question that there is no assurance that amorphous ice has survived up to date in this comet. The second one is related to the problem that the transformation of cometary *amorphous water ice, which can contain a mixture of other chemicals compounds, is not necessarily* highly exothermic. Taking these uncertainties into account a few authors proposed an alternative models of outbursts for centaur 29P/SW. The first one was given by Cowan and A'Hearn (1982). In that paper the proposed model for 29P/SW outburst is based on the simple equilibrium vaporization of CO_2 or CO which were suddenly exposed on the comet nucleus. The second model was proposed by Hartmann (1993). According to Hartmann, regolith on the surface of the comet nucleus may contain trapped gas. Under favourable conditions, this fact can cause an outburst. A few other issues are worth noting.

Firstly, a thorough analysis of attempts to explain the phenomenon of explosions leads to the conclusion that none of them satisfactorily explains all aspects of the phenomenon under consideration.

Secondly, CO is still under active sublimation in the whole region of the solar system, where the orbits of centaurs are located.

Thirdly, the model for the outbursts of centaurs/comets proposed in the present paper uses similarly to the paper by Gronkowski and Wesołowski (2015) the idea of numerous cavities in comets. In other words, the approaches to the issue of centaurs outbursts presented in these two papers should be seen as an attempt to avoid the aforementioned difficulties and ambiguities associated with other, older hypotheses.

Fourthly, the idea of existence of cavities under the surface of comet nuclei has gained stronger support through the results of Rosetta space mission to comet 67P/Churyumov–Gerasimenko. The cameras on board of Rosetta recorded many pits on the surface of the comet's nucleus. These pits are probably the result of collapse of the upper surface layers of the comet's nucleus which covered the cavities located under its surface (Vincent et al. 2015).

To sum up, proposed scenario for the outburst seems to be realistic; the model gives some physical characteristics of the outburst which are consistent with the observations of real phenomena taking place at large distances to the Sun. It is worth emphasizing that our model is not limited to the case of centaur 95P/Chiron and XP/C object. It can also explain some outbursts of centaur/comet 29P/SW. This could be expected in advance. It seems reasonable that, in general, the sublimation of different volatile ices would trigger the destruction of nuclei surface. In support of our model we should note that according to the paper by Filonenko and Churyumov (2006), statistically, the outbursts of brightness during different appearances of given periodic comet to the Sun occur at similar heliocentric distances. This fact is compatible with our model. Indeed, if a sublimation of fixed type of ice induces outbursts of a fixed comet, then during different approaches to the Sun the same comet should show outburst activity at similar heliocentric distances. It should be emphasized that, the purpose of this work does not to completely exclude other hypotheses. It seems to be likely that outbursts may have different causes. The presented paper does not intend to consider all possible causes of cometary outbursts at large heliocentric distances. Only one potential model has been examined. The calculations which were carried out were based of many assumptions and approximations. Taking into consideration many uncertainties related to the physical characteristics of centaurs/comets, the numerical results obtained in the current paper should be interpreted rather as qualitative. However, the proposed model for the outbursts of brightness for centaurs/comets at large heliocentric distances seems to be realistic and probable.

Acknowledgements The authors would like to express their gratitude to the anonymous reviewer for very helpful comments that have considerably improved the manuscript. This work was supported by the Centre for Innovation and Transfer of Natural Sciences and Engineering Knowledge at the University of Rzeszów.

References

J. Agarwal et al., Evidence of sub-surface energy storage in comet 67P from the outburst of 2016 July 03. MNRAS **469**, S606 (2017)

C.F. Bohren, D. Huffman, *Absorption and Scattering of Light by Small Particles* (Wiley, New York, 1983)

W.R. Brown, J.X. Luu, Properties of model Comae around Kuiper Belt and Centaur objects. ICARUS **135**, 415 (1998)

S.J. Bus, M.F. A'Hearn, E. Bowell, S.A. Stern, (2060) Chiron: evidence for activity near aphelion. ICARUS **150**, 94 (2001)

M.T. Capria, A. Coradini, M.C. De Sanctis, R. Orosei, Chiron activity and thermal evolution. Astron. J. **119**, 3112 (2000)

M.R. Combi, V.M. Tenishev, M. Rubin, N. Fougere, T.I. Gombosi, Narrow dust jets in a diffuse gas coma: a natural product of small active regions on comets. Astrophys. J. **749**, 29 (2012)
H. Campins et al., The color temperature of (2060) Chiron: a warm and small nucleus. Astrophys. J. **108**, 2318 (1994)
J.J. Cowan, M.F. A'Hearn, Vaporization in Comets; outbursts from Comet Schwassmann–Wachmann 1. ICARUS **50**, 53 (1982)
J.F. Crifo, G.A. Loukianov, A.V. Rodionov, V.V. Zakharov, Direct Monte Carlo and multifluid modeling of the circumnuclear dust coma. Spherical grain dynamics revisited. ICARUS **176**, 192 (2005)
B.J.R. Davidsson, Y.V. Skorov, On the light-absorbing surface layer of cometary nuclei. I. Radiative transfer. ICARUS **156**, 223 (2002)
O.V. Dobrovolsky, Comets **159**, 186 (1966). (**Nauka, Moskov, in Russian**)
R. Duffard et al., New activity of chiron: results from 5 years of photometric monitoring. ICARUS **160**, 44 (2002)
N. Fougere, M.R. Combi, V. Tenishev, M. Rubin, B.P. Bonev, M.J. Mumma, Understanding measured water rotational temperatures and column densities in the very innermost coma of Comet 73P/Schwassmann–Wachmann 3 B. ICARUS **221**, 174 (2012)
N. Fougere, M.R. Combi, M. Rubin, V. Tenishev, Modeling the heterogeneous ice and gas coma of Comet 103P/Hartley 2. ICARUS **225**, 688 (2013)
V.S. Filonenko, K.I. Churyumov, New peculiarities of cometary outburst activity. Adv. Space Res. **38**, 1940 (2006)
S. Fornasier et al., TNOs are cool: a survey of the trans-neptunian region. VIII. Combined Herschel PACS and SPIRE observations of nine bright targets at 70–500 μ m. Astron. Astrophys. **555**, 2215 (2013)
S. Fornasier et al., The Centaur 10199 Chariklo: investigation into rotational period, absolute magnitude, and cometary activity. Astron. Astrophys. **568**, 11 451 (2014)
P. Gronkowski, The search for a cometary outbursts mechanism: a comparison of various theories. Astron. Nachr. **328**, 126 (2007)
P. Gronkowski, Large cometary grains—their destruction and changes in the luminosity of comets. Mon. Not. R. Astron. Soc. **397**, 883 (2009)
P. Gronkowski, The outbursts of the comet 29P/Schwassmann–Wachmann 1: a new approach to the old problem. Astron. Nachr. **335**, 124 (2014)
P. Gronkowski, M. Wesołowski, A model of cometary outbursts: a new simple approach to the classical question. Mon. Not. R. Astron. Soc. **451**, 3068 (2015)
O. Groussin, P. Lamy, L. Jorda, Properties of the nuclei of Centaurs Chiron and Chariklo. Astron. Astrophys. **413**, 1163 (2004)
M. Gunnarsson, Icy grains as a source of CO in comet 29P/Schwassmann–Wachmann 1. Astron. Astrophys. **398**, 353 (2003)
J.I. Hage, J.M. Greenberg, A model for the optical properties of porous grains. Astrophys. J. **361**, 251 (1990)
O. Hainaut, A. Smette, R.M. West, Periodic Comet Halley (1986 III), IAU Circular No. **5189** (1991)
W.K. Hartmann, Physical mechanism of comet outbursts—an experimental result. ICARUS **104**, 226 (1993)
D.W. Hughes, Cometary outbursts—a review. Q. J. R. Astron. Soc. **31**, 64 (1990)
D.W. Hughes, Comets in the Post-Halley Era, in *Comets in the Post-HalleyEra*, vol. 2, ed. by R.L. Newburn, M. Neugebauer Jr., J. Rahe (Kluwer, Dordrecht, 1991), p. 825
S.I. Ipatov, M.F. A'Hearn, The outburst triggered by the Deep Impact collision with Comet Tempel 1. Mon. Not. R. Astron. Soc. **414**, 76 (2011)
S.I. Ipatov, Location of upper borders of cavities containing dust and gas under pressure in comets. Mon. Not. R. Astron. Soc. **423**, 3474 (2012)
D. Jewitt, The persistent coma of Comet P/Schwassmann–Wachmann 1. Astrophys. J. **351**, 277 (1990)
D. Jewitt, The active centaurs. Astrophys. J. **137**, 4296 (2009)
J. Jones, The ejection of meteoroids from comets. Mon. Not. R. Astron. Soc. **275**, 773 (1995)
H.U. Keller, in *Physics and Chemistry of Comets*, vol. 21, ed. by W.F. Huebner (Springer, Berlin, 1990)
M. Kelley et al., A distribution of large particles in the coma of Comet 103P/Hartley 2. ICARUS **222**, 634 (2013)
E. Kührt, Temperature profiles and thermal stresses in cometary nuclei. ICARUS **60**, 512 (1984)
C. Kowal, T. Gehrels, Slow-moving object Kowal. IAUC **3129**, 1 (1977)
A. Li, J.M. Greenberg, A unified model of interstellar dust. Astron. Astrophys. **323**, 566 (1997)
H.W. Lin et al., Pan-STARRS 1 observations of the unusual active centaur P/2011 S1(Gibbs). Astron. J. **147**, 114 (2014)
J.X. Luu, Cometary activity in distant comets—Chiron. Astron. Soc. Pac. **105**, 946 (1993)
K.J. Meech, M.J.S. Belton, The atmosphere of 2060 Chiron. Astrophys. J. **100**, 1323 (1990)

A. Molina, The importance of nucleus rotation in determining the largest grains ejected from comets. Rev. Mex. Astron. Astrofis. **46**, 323 (2010)
A. Molina, F. Moreno, Leonid meteoroids: reconciliation of cometary outgassing theory and electrophonic sound data. Astron. J. **141**, 148 (2011)
T. Mukai, Analysis of a dirty water-ice model for cometary dust. Astron. Astrophys. **164**, 397 (1986)
R.L. Newburn, H. Spinrad, Spectrophotometry of seventeen comets. II—the continuum. Astron. J. **90**, 2591 (1985)
D. Prialnik, M. Podolak, Radioactive heating of porous comet nuclei. ICARUS **117**, 420 (1995)
W.T. Reach, J. Vaubaillon, C.M. Lisse, M. Holloway, J. Rho, ICARUS **208**, 276 (2010)
P. Rousselot, 174P/Echeclus: a strange case of outburst. Astron. Astrophys. **480**, 543 (2008)
M. Rubin et al., Monte Carlo modeling of neutral gas and dust in the coma of Comet 1P/Halley. ICARUS **213**, 655 (2011)
J.D. Ruprecht et al., 29 November 2011 stellar occultation by 2060 Chiron: symmetric jet-like features. ICARUS **252**, 271 (2015)
S.A. Stern et al., Numerical simulations of particle orbits around 2060 Chiron. Astrophys. J. **107**, 765 (1994)
L.V. Tambovtseva, L.I. Shestakova, Cometary splitting due to thermal stresses. Planet. Space Sci. **47**, 319 (1999)
G. Tancredi, H. Rickman, J.M. Greenberg, Thermochemistry of cometary nuclei. 1: the Jupiter family case. Astron. Astrophys. **286**, 659 (1994)
V.M. Tenishev, M.R. Combi, M. Rubin, Numerical simulation of dust in a cometary coma: application to Comet 67P/Churyumov–Gerasimenko. Astrophys. J. **732**, 104 (2011)
R.M. West, A photometric study of (2060) Chiron and its coma. Astron. Astrophys. **241**, 635 (1991)
S. Wyckoff, Overview of comet observations, in *Comets*, ed. by L.L. Wilkening (The University of Arizona Press, Tucson, 1982), pp. 3–55
J.B. Vincent et al., Large heterogeneities in comet 67P as revealed by active pits from sinkhole collapse. Nature **523**, 67 (2015)