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The cometary outbursts at large heliocentric distances

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Abstract. A model is presented explaining changes in cometary brightness during an outburst at large heliocentric distances. It is shown that a combination of the following effects can explain the main characteristics of outburst at large heliocentric distances: the specific exothermic processes in cometary nucleus (as the HCN polymerisation and the crystallization of the water amorphous ice, connected with the ejection of the large quantities of dust) and the sublimation of CO or CO_2 from the comet's nucleus. The obtained results are in good agreement with observations.

Key words: comets: general – comets: individual: P/Schwassmann - Wachmann 1

1. Introduction

Cometary outbursts are among the most interesting phenomena in the evolution of comets. During the outburst the brightness of a comet increases by several magnitudes. Many comets undergo outbursts of brightness during their evolution. Some well-known comets such as Ikeya-Seki (1965 VIII), P/Schwassmann-Wachmann 1 (1925 II) and P/Halley (1986 III) belong to this group of comets. Generally, a cometary spectrum has two components: continuous and emissive. The continuous component is produced by dust and ice particles in the comet head, which reflect and disperse solar light. The emissive component is created by molecules and atoms in the cometary head and tail. The relation between the continuous and the emissive components depends strongly on the heliocentric distance of comet. We can say that, at great distances, the comet only reflects and disperses solar light. During the comet's approach to the Sun the emissive components gain a greater and greater role. Observations generally show that most comets at distances greater than 4 AU do not show outburst activity. But there are exceptions. Comet Humason (1962 VIII) underwent an outburst at a heliocentric distance of 6 AU, P/Halley flared up at 14.3 AU heliocentric distance. The most famous example of the activity of comets at large heliocentric distances is P/Schwassmann-Wachmann 1. This comet has a near-circular orbit situated between the orbits of Jupiter and Saturn. The eccentricity of its orbit is e ≈ 0.13, and its heliocentric distance varies from ≈ 5.5 AU to ≈ 7.5 AU during its orbital period of ≈ 16.0 yr. Usually, its luminosity is about 18–19 mag. Many astronomers collected and reduced observations of this comet (e.g. Richter 1954; Whipple 1980; Andrienko & Vashchenko 1981; Hughes 1990). Normally P/SW 1 looks like a blurred disk. Sometimes a central dense region can be seen. The comet has outbursts 1–2 times a year. At the beginning of an outburst, within a few hours or days, the star-like bright nucleus is formed while the brightness of the comet increases appreciably. The nucleus expands with a velocity of 100–400 m/sec forming a structure like a planetary disc. Next, it is transformed into a cometary halo with its surface brightness decreasing with distance from the center.

The spectrum of the comet is due mainly to scattered and reflected sunlight; only weak emission of CO^+ is observed (Cochran et al. 1980). After the onset of the outburst the maximum reached luminosity is several stellar magnitudes (2–5, exceptionally 9) brighter than the value at quiescence. In the period of maximum brightness the central cloud has a radius about 300 000 km. After a few days the comet returns to its initial state, its shape and luminosity become as they were prior to the onset of outburst. In principle, outbursts of the other comets take a similar course. Many authors have tried to explain these interesting phenomena by various mechanisms and models (Huebner & Weigert 1966; Fernández 1990; Prialnik & Bar-Nun 1992; Rettig et al. 1992; Williams et al. 1993; Cabot et al. 1996) but none of these has been definitely confirmed and accepted. All these models agree that the cause of the cometary outburst is a sudden and strong release of energy. Different mechanisms are proposed as to the source of this energy. Two mechanisms seem most probable: the transformation of amorphous ice into cubic ice (Patashnik et al. 1974; Smoluchowski 1981) or chemical processes such as the polymerization of HCN (Rettig et al. 1992). Both these processes are strongly exothermic and give satisfactory values for the amount of observable energy released during the outburst (Patashnik et al. 1974; Rettig et al. 1992). The earlier papers about cometary outbursts did not take all important characteristics of the studied phenomenon into account, such as the amount of the sudden increase in brightness. The aim of this paper is to call attention to the possibility of explaining the values of certain characteristics of outbursts, such as

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the increase in brightness and time interval of this phenomenon under the assumption that these two mechanisms are the cause of outbursts.

2. The model of outburst

We shall consider comets at large heliocentric distances ($\sim$ 7 AU) where sublimation of H_2O ice is negligible in comparison with the sublimation of more volatile species which are likely to be CO_2 or CO. For simplicity, we assume that the cometary nucleus is an ice-snowball with radius R_n. The nucleus includes ice of water, dust and stones. Besides, a nucleus can include species like CO or CO_2. Probably, there are two kinds of chemical compounds like CO and CO_2 in cometary nuclei. The first kind are gases trapped in the amorphous water-ice matrix, and the second kind are gases frozen into ices (Schmitt et al. 1989). The dominant component of a comet nucleus is water ice, in amorphous or crystalline form. Generally, the authors agreed that the original comet's water ices should be amorphous because they were formed at low temperatures and pressures. The water vapour condensing to amorphous ice can trap large quantities of molecules of other gases (CO, CO_2). These facts were confirmed experimentally by Bar-Nun et al. (1985, 1987). In propitious conditions, the gases trapped in the amorphous ice can be released from it, when a phase transition from amorphous H_2O ice to the crystalline ice (Bar -Nun & Owen 1995) is taking place. If a comet approaches the Sun, its nucleus, heated by the solar radiation, loses its ice species through sublimation when the evaporation temperature is reached. So, cometary ices, CO or CO_2, sublimate from the nucleus and carry away dust from its surface. In this way under normal conditions in the 'inactive phase', the nucleus is surrounded by a halo containing gas and dust. The optical depth of this halo is small. The grains of dust accumulating on the surface of nucleus are too big to be able to leave the nucleus with sublimating volatile gases. For those grains the gravitional force coming from the nucleus exceeds the molecular drag force coming from the molecules of the sublimating gases bumping against the grains. Based on these assumption is easy to show (Dobrovolsky 1966, Delsemme & Miller 1971) that the size limit a_m below which dust particles can be carried outward by sublimating cometary gases is proportional to the vaporization rate of the nucleus. For both species, CO and CO_2, the rate of sublimation is a very slowly-changing function of the heliocentric distance of the comet in the range of 0.2 to 10 AU (Houpis & Mendis 1981a) and therefore the size limit a_m is very weakly dependent on the heliocentric distance for the comets considered. Below, this problem will be considered in greater detail. The mantle of the nucleus contains water ice and dust which are weakly volatile at this heliocentric distance, i.e. it is simply a very dirty ice. The mantle has a porous structure and more volatile species can sublimate from under its surface and permeate through the mantle out of the nucleus. However, the mantle generally reduces the sublimation rate. Therefore only a small part of the surface of the nucleus (that outside the mantle) shows full sublimating activity. The spectra of comets in the visible and in the near-IR indicate a black body temperature of about 6000 K, corresponding to scattered sunlight. The colour of the scattered light is neutral or a slightly red at wave lengths of 0.36 to 2.2 μm (Grün & Jassberger, 1990). Generally, Rayleigh scattering is not observed in cometary spectra and this indicates that the relative number of dust grains with a diameter much smaller than these wavelengths is negligible. However, we will assume that the scattering properties of the dusty comet halo are characterized by an average effective Bond albedo of dust grains and in our further calculations we will assume for simplicity that the brightness of the cometary halo is proportional to the cross-sectional area of all the dust grains. Consequently, at large heliocentric distance the total area reflecting and dispersing sunlight is equal to the cross-section of dust particles and nucleus. We shall consider the behaviour of the comet assuming that apart from amorphous water ice, carbonoxide and carbondioxide ices existing in nucleus, a small fraction of the nucleus contains polymers of HCN. Even before the return of P/Halley, HCN (Huebner et al. 1974) and CH_3CN (Ulich & Conklin 1974) were detected in Comet Kohoutek (1976f). Also, the results from the P/Halley encounter suggest the presence of HCN, among other organic compounds (Schloerb et al. 1987). Estimates of HCN in comets and in the interstellar medium vary from 0.1% H_2O (Schloerb et al. 1987) to 4% (d'Hendecourt et al. 1986; Tegler et al. 1993). Rettig et al. (1992) have shown that HCN polymerisation in the nuclei of inhomogeneous comets is a possible source for outbursts but under the very optimistic assumption that they take place in comet regions with 4% concentration of HCN. The energy released by polymerization of HCN is 1.85×10^{11} ergs g^{-1}. This value corresponds to the release of approximately 1.85×10^8 ergs g^{-1} and 7.4×10^9 ergs g^{-1} in regions with minimum 0.1% and maximum 4% known concentration of HCN, respectively. The surface temperature for a CO_2-dominated comet is higher than that for a CO-dominated comet. This is because CO is more volatile than CO_2. If the sublimation is controlled by CO, then the temperature will be between 30 and 45 K for a heliocentric distance of from 0.2 to 10 AU; if it is controlled by CO_2 the temperature will be in the range of from 85 to 115 K for the same range of heliocentric distances (Houpis & Mendis 1981a).

The fundamental question in the explanation of the mechanism of cometary outburst is what initiates it. In our model we propose the following scenario: polymerization of HCN can be started by accidental absorption of UV solar photons by HCN molecules situated on the surface of the nucleus or by a chain reaction of free radicals (Rettig et.al. 1992). The energy released by the polymerization of HCN raises the temperature of that part of the nucleus sufficiently to initiate the phase transition of H_2O. The latter reaction can deliver a basic quantity of outburst energy: at 140 K the amorphous water ice undergoes a phase transition to the cubic ice. It is easy to show that for a comet with specific heat ≈ 0.25 cal g^{-1} K^{-1} approx. 10^9 ergs g^{-1} of energy are needed to raise the temperature of the nucleus ice to 140 K when CO is the dominating sublimating species while $\approx 5.4 \times 10^8$ ergs g^{-1} are needed when CO_2 dominates. Thus, the energy of HCN polymerisation is probably quite sufficient to initiate the phase transition of H_2O ice. The transformation of amorphous ice with density of about $2.3\,\mathrm{g\,cm^{-3}}$ into cubic ice with a density of $0.94\,\mathrm{g\,cm^{-3}}$ must induce severe strains that would cause cracks, erode the amorphous layer and pulverize the ice (Patashnick et al., 1974). Simultaneously the propagation of a heat wave created by the transformation of ices into the nucleus can lead to the release of trapped volatiles, such as CO and CO_2, and to a sudden rise in the sublimation of this species in the layer of the nucleus just below the surface. In this way the gas can concentrate just below the surface of the nucleus. Once the pressure of cometary vapours becomes greater than the tensile strength of cometary mantle material the nucleus throws off its outer layer. This specific crystallization of amorphous ice into cubic ice releases 8.4×10^8 ergs $\mathrm{g^{-1}}$ of energy. On the other hand the typical quantity of mass lost by the comet during it outburst is $\approx 10^{11}$ g. This means that, assuming that the mass lost by the nucleus is coming from the destroyed outer layer which undergoes crystallization, $\approx 8.4 \times 10^{19}$ ergs of energy are released by the outburst of comet. These results are consistent with observable standard values of energy released during the outburst which is around 10^{19} ergs. We assume that the cloud of dust and dirty-ice particles created in this way, consists of spherical grains with radii between a_{min} and a_{max}. These particles creating the cometary dust-ices halo are characterized by a distribution function $f(a)$ such that the value of $f(a)$ defines the relative number of particles of a given radius a. We will consider the motion of dust particles in the cometary head when a comet is situated at a relatively large heliocentric distance (6 to 8 AU). Then, the assumption that the gas particles have mean free paths much longer than the grain size seems very reasonable. A simple model of the cometary gas-dust interaction assumes that the gas particles collide elastically with the dust. If, additionally, we neglect the radiation pressure and the solar gravity in the head of the comet, then the equation of motion for the particles can be written in the form (Dobrovolsky 1966; Grün & Jessberger 1990):

$$\frac{4\pi}{3} a^3 \rho_d \frac{\mathrm{d}v_d}{\mathrm{d}t} = \pi a^2 \frac{C_D}{2} \rho_g (v_g - v_d)^2 - \frac{4\pi}{3} a^3 \rho_d M_N \frac{G}{R^2} \tag{1}$$

where a, ρ_d, v_d and ρ_g, v_g are the dust particle radius, density and velocity, and gas density and velocity, respectively. In this equation M_n denotes the mass of the nucleus, R – the distance between the particles and the center of comet and G is the gravitational constant, C_D is the drag coefficient which, for free molecular flow, can be taken as equal to 2. The first term on the right-hand side of the equation describes the force exerted by vapour particles bumping the dust particle, the second one denotes the gravitation of the nucleus. After simple algebraical transformations, denoting $v_d = \dot{R}$ and $\frac{\mathrm{d}v_d}{\mathrm{d}t} = \ddot{R}$ we can rewrite Eq. (1) in the following form:

$$\ddot{R} = -\frac{\alpha \dot{R} - \beta \dot{R}^2 + \gamma}{R^2} \tag{2}$$

where

$$\alpha = \frac{3\dot{Z}\mu m_0 R_N^2}{2a\rho_d}\,, \quad \beta = \frac{\alpha}{2v_g}\,, \tag{3a}$$

$$\gamma = GM_N - \frac{\alpha v_g}{2} \tag{3b}$$

$$v_g = \sqrt{\frac{\kappa k T}{\mu m_o}} \tag{3c}$$

In Eqs. (3) $\dot{Z}$ is the rate of gas molecule production ($\mathrm{cm^{-2}\,s^{-1}}$) by sublimation, μ is its gramme-molecular mass, m_0 is the atomic mass unit. The ratio of specific heats, c_p and c_v, of sublimated gases is denotes by κ, T is their temperature, and k is the Boltzmann constant. In Eq. (3c), we have assumed after Houpis & Mendis (1981c) that the sonic velocity is reached by gas very near the surface of nucleus. This value seems a sensible compromise between two approaches to the cometary gas effusion. The first, for pure effusion in vacuum, assumes that the gas flows away from nucleus with a radial velocity which is in the range of thermal gas velocity (Dobrovolsky 1966; Huebner & Weigert 1966). The second (Finson & Probstein 1968a, 1968b), is based on the fluid dynamics equations and may give velocities greater than the velocity of sound. However, if the pure effusion approach gives too small gas velocities, the fluid dynamics approach is likely to give too large gas velocities (Delsemme & Miller 1971). From Eqs. (2),(3) we can obtain the size limit a_m e.g. the maximum radius of particles which can be carried outward from the comet by the sublimation of CO or CO_2. By taking in Eq. (2) $\ddot{R} = 0$ and $\dot{R} = 0$ for $R = R_n$, we can work out that:

$$a_m = \frac{9\dot{Z}\mu m_o v_g}{16\pi G R_n \rho_n \rho_d}\,; \tag{4}$$

As we see, the size limit is proportional to the speed of cometary species sublimation. For the analysed range (6 AU–8 AU) of heliocentric distances from Eq. (4) we have a_m in the range 10^{-3} m for both kinds of comet. The model presented here is based on the assumption that ejected dust and ice in the cometary halo increases the total area reflecting the sunlight. Additionally, the surface of the active sublimation region may increase during the outburst and, in this way, the cometary brightness may increase further. According to Pogson's law, the change in comet brightness Δm caused by these effects is approximately defined as follows:

$$\Delta m \approx -2.5 \log \frac{A_n S_n + A_d S_d(t) + A_d S_e}{A_n S_n + A_d S_d(0)} \tag{5}$$

Here A_n and A_d denote the albedo of nucleus and cometary dust respectively. We assume that the albedo of the nucleus and the albedo of the ejected particles from the destroyed layer of the mantle have values in the same range. In Eq. (5) $S_n = \pi R_n^2$ denotes the cross-section of the comet nucleus, $S_d(0)$ and $S_d(t)$ are the total cross-sections of the dust particles which have been raised by sublimating gases and remain the head of comet at the moment of inactive phase and at that of the outburst, respectively. The total cross-section of ejected dirty-ice particles and dust particles during the outburst is denoted by S_e.

Then the total mass and cross-section of these particles are given as:

$$M_e = \frac{4}{3}\pi\rho_d \int_{a_{min}}^{a_{max}} f(a) a^3 \mathrm{d}a\,, \tag{6a}$$

$$S_e = \pi \int_{a_{min}}^{a_{max}} f(a) a^2 \mathrm{d}a \, . \tag{6b}$$

Therefore, we have:

$$S_e = \frac{3M_e}{4\rho_d} \frac{\int_{a_{min}}^{a_{max}} f(a) a^2 \mathrm{d}a}{\int_{a_{min}}^{a_{max}} f(a) a^3 \mathrm{d}a} \tag{7}$$

The production rate of the gas due to sublimation can be expressed in following form:

$$\dot{M}_g = 4\eta S_n \dot{Z} \mu m_0 \tag{8}$$

where η is defined as the ratio of the active sublimation area of the nucleus to its total surface. The molecules of sublimating gases remain in the head of the comet with radius R_h while the interval of time equal to $\frac{R_h}{v_g}$ and the global mass of gas that exists in the head is given by:

$$M_g = 4\eta S_n \dot{Z} \mu m_0 \frac{R_h}{v_g} \tag{9}$$

If the dust-to-gas mass ratio is denoted by χ, then the total mass of the dust that exists in the head of the comet and has been raised by sublimating gases is equal to χM_g. Using similar calculations to those for Eq. (7), we can get the total dust cross-section in the following form:

$$S_d = \frac{3\eta\chi \dot{Z} \mu m_0 R_h}{\rho_d v_g} \frac{\int_{a_{min}}^{a_{max}} f(a) a^2 \mathrm{d}a}{\int_{a_{min}}^{a_{max}} f(a) a^3 \mathrm{d}a} \tag{10}$$

We chose the jump in the brightness Δm as the main characteristic of a cometary outburst. Using Eqs. (5), (7) and (10) we can obtain the change in comet brightness. On the basis of Eqs. (2), and (3a,b,c), we can estimate the expansion velocity of dust halo of the comet and the time t of the stay of the ejected particles in the comet's head and the time interval of the outburst connected with them.

3. Results

The table presented below contains the results of numerical calculations of Δm, where r denotes the heliocentric distance of the comet expressed in AU. The value of the rate of sublimation $\dot{Z}$ is assumed according to Houpis & Mendis (1981b). The assumed value of ejection mass M_e is in accordance with the observations. The calculations were performed for a few realistic values: $\eta = 0.1$ and $R_h = 10^5$ km in "inactive" phase and $\eta = 0.2$, $R_h = 3 \cdot 10^5$ km during the outburst, $\chi = 0.5$, $a_{min} = 10^{-6}$m and $a_{max} = 10^{-3}$ m.

The calculations were done for varying distribution functions $f(a)$ with the dust particle radius as variable a. We used power functions, ($f(a) = A_1 a^{-4.2}$), gaussian functions ($f(a) = A_2 \exp(\frac{-(a-a_o)^2}{2\sigma^2})$) and logarithmic-normal distributions functions ($f(a) = A_3 a^{-1} \exp(\frac{-(ln(a)-m)^2}{2\sigma^2})$). In the formula for the gaussian normal distribution function a_o and σ denotes the average radius of dusty grains and dispersion respectively, in the formula for the logarithmic normal distribution functions m and σ denote some parameters of that distribution, which for its known average radius and dispersion can be easily estimated. From the normalized conditions, after simple integrations we get the constants A_1, A_2, A_3. Numerical tests showed, that the jump in cometary brightness depended on the average radius a_0 and the dispersion σ. Differences between the two results obtained from Eq. 5 for different functions $f(a)$ which have the same values, a_0 and σ, are negligible. This result was to be expected (Gronkowski & Maciejewski 1990). According to the power distribution function the assumed value of the middle radius and dispersion are ≈ 1.45 μm and $\approx 0.74\,\mu$m, respectively. In the model presented the final expansion velocity of the dust halo is approximately equal to $55\,\mathrm{m\,s^{-1}}$ at a heliocentric comet distance of 6 AU and $36\,\mathrm{ms^{-1}}$ at 8 AU, if sublimation is controlled by CO_2.

For a CO-dominated comet this velocity is equal to $66\,\mathrm{ms^{-1}}$ and $55\,\mathrm{ms^{-1}}$, respectively. The obtained values of the dust outflow velocity are in good agreement with observations. For comets such as P/SW 1, P/Halley, P/Hale-Bopp these velocities are typically a few tens of meters per second. The value of the time t is highly dependent on the radius of particles; t is a rising function of particle diameter. For a CO_2-dominated comet and grains with diameter 10^{-6} m, $t \sim$ 63–96 days, while for a CO-dominated comet, $t \sim$ 53–63 days. For dust particles with radius near to a_m the time t is practically unlimited.

Table 1. The variation of Δm with the ejected mass M_e. In deriving Δm the assumed radius of the cometary nucleus is 5 km, $\rho_n = 0.2$ g/cm^3, $\rho_d = 0.5$ g/cm^3, $A_n = A_d$ = 0.04.

		CO_2		CO	
r (AU)	M_e (g)	$\dot{Z}$ (mol cm^{-2} s^{-1})	Δm (mag)	$\dot{Z}$ (mol cm^{-2} s^{-1})	Δm (mag)
6	10^{10}	$4.72 \cdot 10^{15}$	−1.99	$2.32 \cdot 10^{16}$	−1.96
	10^{11}		−2.35		−2.06
	10^{12}		−3.81		−2.76
7	10^{10}	$2.83 \cdot 10^{15}$	−2.01	$1.70 \cdot 10^{16}$	−1.96
	10^{11}		−2.55		−2.10
	10^{12}		−4.27		−2.95
8	10^{10}	$1.66 \cdot 10^{15}$	−2.06	$1.29 \cdot 10^{16}$	−1.96
	10^{11}		−2.82		−2.14
	10^{12}		−4.78		−3.14

4. Conclusion

There have been many models for the comet outbursts at large distances from the Sun. Among those our model seems to be very realistic. The comet outburst is initiated by accidental polymerization of HCN, which leads to a sufficient rise of nucleus temperature to start a phase transition of amorphous ice into the crystallic cubic form. This reaction produces a major fraction of the outburst energy. Part of this energy can lead to the release of trapped volatiles, such as CO or CO_2 and a sudden rise of the rate of sublimation of these species. On the other

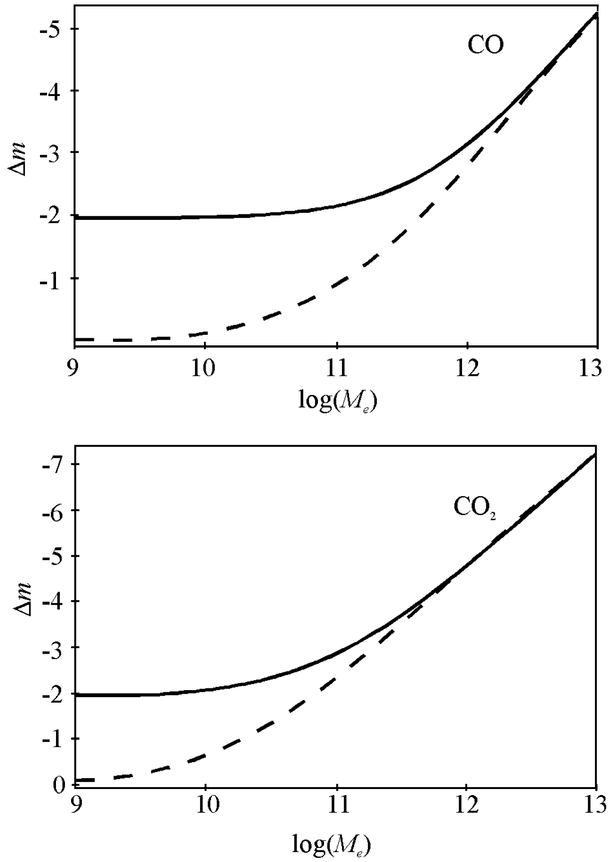

Fig. 1. The jump Δm in cometary brightness with ejected mass M_e for comets (at 8 AU heliocentric distance) with sublimation controlled by CO and by CO_2. The dashed line corresponds to the ratio of active nucleus area during outburst with $\eta = 0.1$, solid line corresponds to $\eta = 0.2$.

hand the transformation of water ice induces severe strains that erode and pulverise the surface layer of nucleus. These phenomena, together with the sublimation of cometary gases in the below-surface layer of the nucleus, induce the nucleus to throw off the surface layer. In this way ejected ice and dusts increase the total area that reflects the sunlight, and finally, strongly increase the brightness of the comet. Simultaneously, layers of nucleus rich in sublimated species are being exposed. This also leads to the increase of the cometary luminosity. From the table we can conclude that the jump in brightness obtained in this model is in very good agreement with observations. The well known P/Schwassmann-Wachmann 1 comet increases its brightness during outburst activity by 4–8 mag, comet Humason (1962 VIII) had a flare of 6 mag at heliocentric distance $\sim$ 6 AU in 1964 and P/Halley had an outburst of $\sim$ 5 mag on February 12, 1991 at heliocentric distance 14.3 AU. The obtained values of t are greater than the duration time of the outburst observed (Hughes 1990), but the calculations were performed assuming that the dust grains started from the nucleus with zero initial velocity ($\dot{R} = 0$ for $R = R_n$). On the other hand, if we assume, for example, that at the start $\dot{R} = 100\ \mathrm{ms}^{-1}$, then estimated values of $t \sim$ 35 days are comparable with the real values for the course of the outburst (for P/SW 1 $t \sim 50$ days, Andrienko & Vashchenko, 1980). Three results are quite clear:

1) the value of Δm is highly dependent on the ejected mass (see Fig. 1),
2) the jump in brightness increases with the heliocentric distance of the comet,
3) the duration of the outburst increases with the heliocentric distance of the comet.

These facts are confirmed in the statistical sense by observations of many comets during their outbursts (Andrienko & Vashchenko, 1981). Additionally, we can see that the outburst flares for comets which have their sublimation controlled by CO_2 are more rapid than for comets with sublimation controlled by CO. If we assume that the causes of comet outbursts at large heliocentric distances are polymerisation of HCN and crystallisation of amorphous ice as suggested here, then we obtain results which are in very good agreement with observations. Of course our calculations apply to comets that derive the main part of their luminosity from reflexion, i.e. comets with dust dominated coma. In any case, the present model gives a good explanation of the main characteristics of cometary outbursts at large heliocentric distances.

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