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A Review of Cometary Outbursts at Large Heliocentric Distances

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Abstract The outbursts of comets, sudden large increases in their luminosity, are still very interesting and mysterious signs of activity of this celestial bodies. Most of the cometary outbursts are taking place at heliocentric distances where sublimation of water ice plays an important role in the activity of comets. However, the phenomenon is also observed far away from the Sun (i.e. $\simeq$5–20 au) where the sublimation of water ice is negligible and the activity of comets is dominated by more volatile chemicals. Not only typical comets show 'cometary-like' activity but also Centaurs. In addition to the long-term changes in brightness related to heliocentric distances and short-periodic variations connected with the rotation of the nucleus, they also exhibit a random variations in luminosity which are similar to the cometary outbursts. Paper presents an overview of the most likely hypotheses and models which try to explain this phenomenon.

Keywords Comets · General comets · Individual · The comet-like 95/P Chiron

1 Introduction

The 29P/Schwassmann–Wachmann 1 comet (hereafter 29P/SW1) was discovered on the photographs by the two Germans astronomers Arnold Schwassmann and Arno Arthur Wachmann on November 1927. Probably, it took place at the maximum of one of its outbursts. Two exceptional peculiarities of this Centaur put 29P/SW1 apart from comets in general. Firstly, the orbit of this comet is an exception as far as cometary orbits are concerned. 29P/SW1 moves along the quasi-circular orbit with current eccentricity $e \approx 0.044$ and semimajor axis $a \approx 6$ au. The orbit of 29P/SW1 is placed near the ecliptic plane

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between orbits of Jupiter and Saturn. Secondly, despite relatively large distance from the Sun this comet shows an unexpected outbursts activity, over a dozen per year. The brightness flares up of comets are very interesting and intriguing signs of their activity. It is generally known that an outburst of a comet is a sudden and unexpected increase in its brightness. We note that general physical characteristics of the 29P/SW1 outbursts is detailed presented in the paper by Gronkowski and Wesołowski (2015) (hereafter Paper 1). It should be emphasized that substantially outbursts of other comets take a similar course. The outbursts of brightness are frequently reported for periodic as well as parabolic comets. Most comets are outburst active at heliocentric distances $d < 5$ au, i.e. where it is possible sublimation of H_2O. Therefore, by the term large heliocentric distance in this paper, we understand the distance $d > 5$ au. In other words, it is the distance from the Sun, for which the sublimation of H_2O ice is negligible. We will focus on the behaviour of comets at the range of heliocentric distances $\simeq$5–20 au. Another comet that was active at large heliocentric distance was the comet Humason C/1961 R1 (Humason). In 1964 this object underwent large flare-up of about 6 m at the distance from the Sun equal to 6 au (Wyckoff 1982). The famous comet 1P/Halley (hereafter 1P/H) showed strong outbursts of about 6 m on February 12, 1991 at heliocentric distance 14.3 au (Hainaut et al. 1991; West 1991). Also a dozen Centaurs show comet-like activity at the large heliocentric distance even >10 au. Some of them also exhibit outbursts of brightness. We note that Centaurs are the transitional population, between the distant, frigid stable bodies resided in the Kuiper Belt and the quickly sublimating, disintegrating comets which are placed in the relatively hotter inner regions of the solar system. Centaurs definition is as follows (Jewitt 2009).

1. The perihelion distance, q, and the semimajor axis, a, of Centaurs orbits, fulfil the following conditions: $a_J < q < a_N$ and $a_J < a < a_N$, respectively, where $a_J = 5.2$ au is the semimajor axis of Jupiter orbit and $a_N = 30$ au is the semimajor axis of Neptune orbit.
2. The orbits of Centaurs are not in 1:1 mean motion resonance with any planet.

At this point it is worth recalling that the largest recorded outburst of comet brightness in the all history of astronomy took place on October 2007. Then the comet 17P/Holmes brightened about 15 mag up in 2 days (Montalto et al. 2008; Moreno et al. 2008). However, this phenomenon is beyond our interest because it took place relatively close to Sun at a heliocentric distance about 2.4 au. Some authors use statistical methods in order to find the potential correlation between frequency of cometary outbursts and the solar activity, a heliocentric distance of a comet in a moment of outburst, its distance from the ecliptic plane etc. (Richter 1954; Pittich 1971; Filonenko and Churyumov 2006). There are two main conclusions that we should keep in mind. If selective effects of comet discovery and observation are taken into account then there is not a clear dependence of frequency of cometary outbursts on the heliocentric distance and the solar phase cycle. Also a dependence of outbursts on a position of a comet relatively to the plane of an ecliptic is problematic. Probably a lot of cometary outbursts are not detected. It is the result of the fact that the vast majority of outbursts are detected visually. It is very difficult to estimate the magnitude of an active comet near perihelion to better than 0.5 m. Therefore a chance to recorded an outburst is only when its amplitude is more than about 1.5 m. Lots of astronomers have tried to explain this phenomenon by various mechanisms and sources. The detailed discussion of majority attempts of explanations of cometary outbursts presented up to 1990s was given by Hughes (1991). Nevertheless, none of these hypotheses have been finally confirmed and accepted. In the light of the results of researches which were published in the last decades (Prialnik and Bar-Nun 1992; Enzian et al. 1997;

Filonenko and Churyumov 2006; Gronkowski 2005, 2007), it seems that there is not one source of considered phenomenon. It is possible that these phenomena have different causes. Cometary outbursts still remain intriguing, mysterious phenomena in the evolution of comets. The aim of this paper is to provide an overview of the most reliable hypotheses and models which try to explain the causes of cometary outbursts at large heliocentric distance.

2 The Outbursts of Comets at Large Heliocentric Distances: A Search for the Causes of a Phenomenon

2.1 Pioneering Hypotheses

The discovery of the comet 29P/SW1 initiated the long-standing speculations connected with the source of cometary outbursts at large heliocentric distances. The first hypothesis attempted to explain the source of this phenomenon by internal causes such as sublimation of chemical compounds more volatile than H_2O (Whitney 1955), chemical reactions (Donn and Urey 1956) or the influence of the solar wind (Dobrovolsky 1966). We should note that nowadays these hypotheses have rather a historical meaning.

Sekanina (1974) stated that the outburst of 29P/SW1 could be caused by its impacts with interplanetary boulders. In fact, the velocity of such impactors in relation to SW1 is typically in the range of 10 km/s. That is why the kinetic energy of a boulder with a mass 10^5 kg is in the range of 10^{12} Js. This value is comparable with the typical energy of the cometary outbursts. However, in the light of the papers by Gronkowski (2004a, b) collisions of meteoroids with comets are very poor probable. Generally, besides this there is other strong argument against impact hypothesis. Problem is related to the size distribution function of small interplanetary bodies which circulate in the solar system. This function is such that if one large meteoroid strikes a comet at some point in time, then we should expect that a few smaller meteoroids hit a comet in the same period of time. Therefore, for example if we observe at some moment in time the outburst with the 5 m, than we would observe in the same season of time a few with the amplitude 4 m, and more 3 m and much more outbursts with 2 m. Practically we have not observed such time distribution of cometary outbursts. In this way we conclude that impacts cannot be cause of outbursts of comets in general way.

At that time when the briefly presented above hypotheses originated the physical characteristics of comets material were not well-known in comparison with our present knowledge. Several years ago results of modern laboratory experiments simulating physical conditions in cometary nuclei were not known at all. Also the first hypotheses were formulated at the time when computer simulations were not used or they just came into being. That is why the first hypotheses tried to make use of analytical not digital computational calculations on the one hand. Since then the digital technique have become common place and helpful. On the other hand pioneering hypotheses were not base on laboratory experiments and that is why they often had only speculative character. The space missions and broadly carried out laboratory experiments in the last 30 years considerably improved our knowledge about comets. The results of such laboratory experiments as well as the results of theoretical considerations and computer simulations connected with the physical evolution of comets have been broadly published (e.g. Prialnik and Bar-Nun 1992; Tancredi et al. 1994; Prialnik and Podolak 1995, 1999; Enzian et al.

1997; Orosei et al. 2001; Capria et al. 2003). Different speculations and hypotheses about the source of the 29P/SW1 outbursts which originated during last several years use the knowledge about physics of comets which previously was completely unknown. Thus they are much more realistic and credible than the results of majority previous pioneering researches in this field. They are shortly reviewed below.

2.2 Polymerization of HCN

Based on the analysis of the comet 1P/Halley observations in 1986, Rettig et al. (1992) suggested the possibility of cometary outbursts as result of the polymerization of HCN. However, our knowledge about physical and chemical structure of comets is still far from completion and that is why the polymerization of HCN outbursts model has some uncertainties. For example, we do not know exactly how the structure of other comets and Centaurs is similar to the structure of 1P/H. There are some of ambiguities connected with this hypothesis, and it is hard to accept it as a general cause of outbursts activity of comets and Centaurs at large heliocentric distances.

2.3 The Solar Wind

The famous comet 1P/Halley has underwent an unexpected outburst of brightness on 12 February 1991 at 14.3 au heliocentric distance. The luminosity of this object increased by more than 5 mag and an extended coma developed (West 1991). Several days earlier in December 1990 and January 1991, large solar flares were observed. Therefore, Intrilligator and Dreyer (1991) postulated that a shock wave which was a consequence of these solar flares could reach the surface of the 1P/H nucleus. This hypothesis, however, has been subjected to criticism by Weissman (1991). If this hypothesis is valid, then it is hard to understand why earlier in 1986 when the 1P/H was much closer to the Sun the outbursts did not occur, while many of solar flares were observed.

2.4 The Amorphous Water Ice

The most common hypothesis related to the source of the cometary brightness outbursts is hypothesis which is based on the idea of amorphous ice. Probably the original comets water ice should be amorphous because comets were formed at low temperatures and very low pressure. Under these physical conditions, this form of ice is the thermodynamically preferred structural form of water. The water vapour which condenses to amorphous form can trap some quantities of molecules of other gases like carbon monoxide and carbon dioxide. The amorphous water ice is not stable and it can transform into the crystalline form. This reaction is strongly exothermic. The transformation releases latent heat $L^{cr}_{H_2O} = 9 \times 10^4$ J/kg from pure amorphous water ice. The tempo of this irreversible crystallization reaction depends strongly on the temperature of ice. Generally, the crystallization slowly starts at the rate of around 120 K, but over $T_{cr} = 137$ K is rapid (Schmitt et al. 1989). This is the main mechanism, which releases gases such as CO or CO_2 trapped in an amorphous water ice matrix. Scenario of cometary outburst based on this idea can be briefly presented as follows. If a 'new' comet approaches the Sun, the surface of its nucleus is gradually more and more heated by the solar radiation. Consequently, the heat wave penetrates the undersurface layers of the nucleus. If a temperature of a some part of the nucleus increases high enough, the phase transition begins. Conversion of amorphous water ice into crystalline form does not occur continuously but in stages separated by increasing intervals of time. The depth in the cometary nucleus reached by front of transformation depends on the ambient temperature which rises all the time. It is a consequence of the fact that cometary nucleus is continuously heated by the solar radiation. Therefore, in the subsequent crystallization steps thickness of the crystalline layer of the nucleus grows (e.g. Herman and Podolak 1985; Prialnik and Bar-Nun 1987, 1990; Espinasse et al. 1991, 1993; Tancredi et al. 1994). It is possible that the 'new' comet which has small enough perihelion distance and a small nucleus, can convert in the first approach to the Sun all water ice from the amorphous to the crystalline state. The transformation of amorphous water ice into cubic crystalline form which has a little bit different density must cause lots of strains and finally leads to erosion and pulverization of this part of a cometary nucleus which has undergone crystallization. Consequently, the surface layer of the nucleus cracks and the subsurface layers of the cometary nucleus rich in sublimated species are being exposed. These all phenomena lead to the increase in the total area in the head of the comet which reflects the sunlight. Consequently we can observe the outburst of the cometary brightness. The idea of amorphous water ice in comets became the basis to explain the outbursts of several real comets (see next subsections). This idea was also used several times in order to explain the activity of the comet 29P/SW1 (e.g. Klinger et al. 1996; Enzian et al. 1997; Gronkowski 2005). The idea of the crystallization of amorphous water ice around the source of cometary outburst activity explanation is still used and improved. Below, there is presented its application to explanation regarding the activity of three comets.

2.5 Outburst of the Comet 1P/Halley at Heliocentric Distances 14 AU

On the basis of the idea of amorphous ice, one can explain above-mentioned distant outburst of the comet 1P/Halley. The outburst lasted on a timescale of months. Such behaviour of this comet can be explained by conversion of amorphous water ice into crystalline form in the interior of the porous nucleus, at depths of a few tens meters (Prialnik and Bar-Nun 1992). Then one can show that strong outgassing results from the release of trapped gas during crystallization of the water ice. Here should be emphasized that carried out numerical simulations showed that the point on the cometary orbit where the outgassing reaches its maximum depends essentially on the realistic assumed values of the porosity and the pore size of cometary material. Then the transformation of amorphous ice can take place at heliocentric distances between 5 and 17 AU. It should be noted that the duration of an outburst is the most difficult to determine. It depends on the pore size and on mechanical properties of the cometary material. Therefore, it may vary over three orders of magnitude. However, the calculated duration of outburst may be of the order of month for assumed suitable choice of cometary parameters.

2.6 The Case of the Distant Activity of the Comet C/1995 O1 Hale–Bopp

This comet was discovered at 7.4 au on 23 July 1995 (Hale and Bopp). Immediately after its discovery, it turned out that it is extremely active comet. It had an unusually bright coma at a heliocentric distance of about 7 au. Jewitt et al. (1996) noticed a very strong flux of CO molecules, which increased significantly. Such behaviour of the comet is unlikely to have resulted from surface sublimation of CO ice as a consequence of insolation. Ice of CO should have been depleted from surface of nucleus much earlier in the orbit of the comet. It results from the fact that at 7 au the surface temperature of cometary nucleus is already above 100 K. This value is considerably higher than the sublimation temperature of CO. The activity of this comet has been studied in detail by Prialnik (1999). It was assumed that a porous, spherical nucleus with the radius 20 km consists of dust and gas-laden amorphous water ice. This model takes into account the following effects: transformation of amorphous water ice and release of occluded gas, condensation, sublimation and flow of gases through the pores, changing pore sizes, and flow of dust grains. The initial values of pore size, porosity, emissivity and dust grain size were varied in order to match the observed activity. The obtained strong increase in the activity of the nucleus occurs at a large heliocentric distance pre-perihelion. The increase in the CO fluxes and in the rate of dust emission is in the range of a few magnitude. This is due to the start of crystallization in outer layer of nucleus, deepening down to a few meters below the surface of the cometary nucleus. This process is accompanied by release of the trapped CO.

On the basis of the results of calculations, it can be concluded that the emission of H_2O molecules surpasses the emission of CO molecules at a heliocentric distance of 3 au. Then the cometary activity is mainly determined by the behaviour of the dust. If dust can create a mantle, then sublimation of water does not increase strongly towards perihelion. On the contrary, if most of the dust is ejected from the surface of comet's nucleus, then activity of comets increases rapidly. Finally the outbursts of cometary outburst can be observed. Note that essentially similar model of the comet C/1995 O1 Hale–Bopp activity has been proposed by Capria et al. (2002).

2.7 Activity of the 2060 Chiron (95/P Chiron)

As it was already mentioned, many Centaurs at large heliocentric distances show cometary-like activity. Objects belong to this class, include, among others, 2060 Chiron, 174P/Echeclus and 101199 Chariklo (Rousselot 2008; Jewitt 2009; Fornasier et al. 2014). In addition to the long-term changes in brightness related to heliocentric distances and short-periodic variations connected with the rotation of the nucleus, they also exhibit a random variations in luminosity which are similar to the cometary outbursts. The most famous representative of this class is Chiron. Chiron was detected by Kowal (1977). Since its discovery, the evolution of its orbit has been investigated and extrapolated backward and forward in time. It is worth to note that Chiron's orbit seems to be chaotic and the results of studies of various authors lead to conflicting conclusions (Prialnik et al. 1995 and literature therein). Some authors suggest that Chiron is a young object in the inner solar system, but they are also authors who think that Chiron was earlier short-period comet. By using archive observations, Marcialis and Buratti (1993) concluded that since its discovery (and even before), Chiron was showing reduction in brightness until 1985. Subsequently from 1985, Chiron increased steady brightness until 1989, and then a further darkening was observed. After its discovery, the first observed episode related to coma formation occurred in 1978 during the middle of the decline in brightness. The second episode, in 1989, when the coma reached large dimensions about 230,000 in diameter, coincided with its maximal brightness. It should be noted that even near aphelion Chiron underwent a major outburst that lasted several years. Prialnik et al. (1995) proposed the model which explains the cometary-like activity of Chiron. Model is based on the assumption that nucleus of Chiron is spherically symmetric, porous and fast rotates. Numerical calculations produce results very consistent with observations if one assumes that nucleus contains of 60 % dust and 40 % amorphous ice, occluding a fraction 0.1 % of CO, and it has a low emissivity (0.25). The optimal combination of these parameters is based on a number of numerical simulations. In the last cited paper it is shown that the conversion of amorphous water ice into crystalline form started close to aphelion. Next the CO production rate slightly decreased when Chiron approached the Sun from aphelion. This result is consistent to enigmatic fading of Chiron between heliocentric distance 18–14 AU in years 1970–1985. Obtained emission rates of CO are explained by release of trapped gas. It is worth to note that proposed model reproduced also the estimated surface (colour) temperatures at different points of the orbit as derived by Campins et al. (1994). The model of Chiron activity has also been proposed by Capria et al. (2000). Similarly to the described above model, the cometary activity of Chiron is explained by CO trapped in amorphous water ice. But now it accepts the possibility of existence of CO very close to the surface of the Chiron nucleus. This means that recently only Chiron moves on the current orbit.

2.8 The Idea of Numerous Cavities in Comets

Recently Gronkowski and Wesołowski (2015) have proposed a new model of cometary outbursts at large heliocentric distances. This model is based on an idea of Ipatov and A'Hearn (2011). This idea is a conclusion from the analysis of the dynamics of particles ejected from Comet 9P/Tempel after collision with the Deep Impact impactor. The authors of this idea concluded that there are large cavities a few metres below the surface of comet nuclei. These cavities contain material under high gas pressure. In suitable conditions, the surface layers over the cavities can be thrown away and the deeper layers of the nucleus exposed. Finally, an outburst of the comet may be observed. It is assumed that comets nucleus is spherical in shape and the main its 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. The carbon monoxide is still active throughout the range 5–20 au of heliocentric distances. Therefore, it appears unlikely that CO could survive on the surface of the comet nucleus in considered region of the solar system. It can exist only inside the cometary nucleus. The key assumption of the model is that nucleus of comet contains common large cavities located at a certain depth below its surface. In the interior the nucleus CO could sublimate into cavities. Three processes: evaporation, condensation and outflow of CO through the porous wall of the cavity should be taken into account. From the set of equations which are described above-mentioned processes, one can conclude that the pressure in the cavity may gradually increase over time. This is the result of CO sublimation. At a certain moment of the time, it reaches a kind of equilibrium state when the rate of CO sublimation into cavity is equal to the rate of the CO outflow from the cavity. Then CO pressure in cavity reaches its maximum value. The nucleus layer placed over cavity is going to break if the pressure of CO exceeds 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 and Wesołowski 2015). Numerical calculations give the maximum values of CO pressure which are sufficient for the destruction of the cavity cover layer for all range of considered heliocentric distances. In this way, the interior of cavities, which could be rich in volatile ices, can be exposed to the solar radiation. Then the tempo of sublimation from a comet can increases considerably. Finally the outburst of cometary brightness can be observed. The obtained values of the jump in the cometary brightness are in agreement with observations of real cometary outbursts at large heliocentric distances. However, the proposed model seems to be realistic at least for the comets that have extensive orbits with large perihelion distances. However, we must bear in mind that the included in the model method of calculating of the amplitude in the jump of cometary brightness may be applied to the objects which have halos dominated by water ice–dust grains. It means that this method can be used for comets which produce the dominant part of their radiance from the reflection of the solar light. Here a two issues must be noted. Firstly, presented above model is consistent with the latest space ESA/Rosetta results. The active pits have been recorded on the surface of the comet Churyumov–Gerasimenko nucleus. It is believed that the pits are a sign of endogenic cometary activity and are not impact craters. It has been argued that pits can be related to outbursts processes (Vincent et al. 2015). In other words pits might be the remains of the destroyed cometary cavities. Secondly, this model assumes that 10 kPa is a lower limit for the tensile strength of cometary material on a decametre scale. Such tensile strength value received Reach et al. (2010) based on analysis of the outbursts of the comet 17P/Holmes on 2007. However, this value is far higher than what has been measured on the comet 67P/Churyumov–Gerasimenko by Groussin et al. (2015). Therefore, for comets, which have much lower strength than 10 kPa is to be expected that the destruction of the cavities will take place much farther from the Sun. It is also possible that the reason for the cometary outburst can be a sublimation less volatile than that proposed in the paper by Gronkowski and Wesołowski (2015)—probably H_2O. The recorded pits on the surface of the comet 67P/Churyumov–Gerasimenko in a sense, reinforce this conclusion.

2.9 Melting of Cometary Ices

Quite recently, in the current year it has been published a very interesting and unconventional model of outbursts and quiescent activity of the 29P/SW1 and other comets at large heliocentric distances (Miles et al. 2016; Miles 2016a, b). The scenario of outburst is outlined in the following way. Some cometary ices as a solid CH_4 are trapped under pressure in the interior of the nucleus of the comet and are located beneath the crust of stabilization. At a certain moment in time they begin to melt and absorb large quantities of supervolatile gases, such as CO and N_2. Then absorbed gases liberate considerable heat via their enthalpy of solution. This process induces further melting inside the cometary nucleus. The proposed gas–solute process is most active near the solid–liquid interface, where the solvent temperature is lowest and gas solubility is highest. The crust of stabilization containing paraffinic hydrocarbons softens under the influence of heat. Then the pressure trapped underneath gases can destroy it. The sudden release of gases provokes the explosive ex-solution of dissolved gases, principally CO. This latter process results in lifting dust and cometary debris into space, and leads to cometary brightness outburst.

3 Remarks, Conclusions

The problem about the source of cometary outburst activity at large heliocentric distance is very intriguing question of cometology. Initially this issue was considered mainly based on the example of the comet 29P/SW1 which belongs to the Cantaurs. There is no clear answer to the question of what initiates its outbursts of brightness. On the one hand it seems that the probable source of this phenomenon is the transformation of amorphous water ice into the cubic crystalline form. This approach seems to be trustworthy and attractive from at least a few reasons. Firstly, it is consistent with the observed values of main characteristics of the considered phenomena. Secondly it makes use of the fact that the orbit of this Centaur is placed in the unique heliocentric distance from the point of view of activity of comets. The heliocentric distance 6 au is situated at the very edge of the amorphous water ice stability zone. Also 29P/SW1 is placed at the edge of the sublimation of crystalline water ice zone. Additionally, it must be emphasized that the radius of its nucleus is large enough so the amorphous water ice could survive in the interior of its nucleus up to now. Perhaps unique place in the solar system and unique large dimension of the nucleus 29P/SW1 are responsible for its atypical activity. Most published in the last two decades model uses the idea of amorphous ice and is based on the numerical analysis of the thermodynamic evolution of comets. The behaviour of cometary nucleus is obtained by using the set of equations which describe mass and energy conservation, heat conduction, amorphous–crystalline transition of water ice, radioactive heat production, the gas diffuse through the pores, dust mantles formation etc. They take into account the temporal evolution of the basic physical parameters characterizing the comet. The optimal choice of these parameters allows to create models, which results are consistent with the observations of the activity of real comets. This approach seems to be the most versatile and having the greatest use. Apart from such approach to the issues under consideration, there are models and hypotheses based on some specific phenomena such as: the solar wind, the idea of large numbers of cavities in comets, cometary collisions with other small bodies orbiting in the solar system, etc. Likely the latter approach can explain only some outbursts of comets at a great distance from the Sun. At the end a two issues must be noted.

Firstly, continuously up to date advanced analytically and numerically valuable papers are published which use the idea of amorphous ice (Prialnik 1999, 2010; Rosenberg and Prialnik 2010; Meech et al. 2009; Kossacki and Szutowicz 2011, 2013; Hillman and Prialnik 2012; González et al. 2014). Secondly, several decades generations of astronomers attempted to explain the phenomenon of cometary outbursts at large heliocentric distances by various mechanisms and sources. On the basis of presented in the current paper different approaches to the considered question, we can conclude that it seems very real that there is not one cause of this phenomenon. Probably in favour of conditions, cometary outbursts can have different sources or combinations of several reasons triggering this phenomenon. However, still the most widespread models are those that use the idea of crystallization of water ice.

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