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A new method for determining the mass ejected during the cometary outburst – Application to the Jupiter-family comets

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ABSTRACT

In the present article, we propose a new method of mass estimation which is ejected from a nucleus of a comet during its outburst of brightness. The phenomena of cometary outburst are often reported for both periodic and parabolic comets. The outburst of a comet brightness is a sudden increase in its brightness greater than one magnitude, average by 2–5 mag. This should not be confused with explosions such as outbreak of a bomb. The essence of the phenomenon is only a sudden brightening of the comet. Long-term observations and studies of this phenomenon lead to the conclusion that the very probable direct cause of the many outbursts is the ejection of the some part of surface layer of a comet's nucleus and an increase in the rate of a sublimation (Hughes (1990), Gronkowski (2007), Gronkowski and Wesołowski (2015)). The purpose of this article is presentation of a new simple method of the estimation of the mass which is ejected from the comet's nucleus during considered phenomenon. To estimate the mass released during an outburst, different probable coefficients of extinction for cometary matter was assumed. The scattering cross-sections of cometary grains were precisely calculated on the basis of Mie's theory. This method was applied to the outburst of a hypothetical comet X/PC belonging to the Jupiter-family comets and to the case of the comet 17P/Holmes outburst in 2007.

1. Introduction

The phenomenon of cometary outbursts of brightness has attracted interest of astronomers in the first half of last century. Then in 1927 two German astronomers Friedrich Karl Arnold Schwassmann and Arthur Arno Wachmann discovered the comet probably at one of its numerous outbursts. This comet was later named as 29P/Schwassmann–Wachmann (hereafter 29P/SW). The essence of this phenomenon is the unexpected increase of cometary luminosity by at least one magnitude, on average 2–5 magnitudes. It should be emphasized that this should not be confused with a physical explosion such as for example a bomb explosion. Outbursts of comets are an intriguing and interesting manifestation of the physical activity of this class of cosmic bodies. This phenomenon is repeatedly reported both for periodic and parabolic comets. However, the most well-known representative of comets undergoing explosion is 29P/SW. Therefore, many astronomers around the world have been looking for the causes the cometary outbursts up till now (Richter, 1954; Hughes, 1990; 1991; Cabot, 1996; Enzian, 1997; Groussin et al., 2004; Trigo-Rodriguez, 2008a; 2008b; 2010; Ivanova, 2011; 2012). A typical outburst of the 29P/SW brightness is as follows (Richter (1954); Hughes (1990); Gronkowski and Wesołowski (2015), and literature therein). Initially, in a calm phase, the comet looks like a very faint diffuse coma with a slight central condensation. Suddenly in a few hours the object becomes stellar-like and its brightness increases rapidly. The inner coma of a comet expands with the velocity of the order of 100–400 ms^{-1} forming a structure like planetary disc. Afterwards the shape of the cometary coma is mostly spherical or oval, sometimes asymmetrical. During the outburst, the spectrum of a comet is mainly scattered sunlight. During the duration of the phenomenon under consideration, the total mass emitted into the space from the comet nucleus is of the order of 10^6–10^9 kg. After a few - several dozen days, the appearance of a comet returns to its initial state and no changes of the comet orbit as the consequence of the outburst are observed. It is worth noting that the outburst of brightness of other comets have a similar course.

In the literature dealing with comet outbursts, a number of different mechanisms are being discussed to clarify and understand this phenomenon. The most frequently discussed mechanisms and hypothesis are briefly described below:

1) The pressure mechanism.
   Whitney (1955) suggested that vapours released as a result of sublimation of chemical compounds such as CH_4, CO or CO_2 which are more volatile than H_2O, could concentrate in the subsurface regions

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of the nucleus of a comet. If the vapour pressure surpasses tensile strength of the cometary material, then the surface layers can be destroyed and rejected. On the one hand the large amount of cometary material are thrown away into the head of the comet. On the other hand the regions which are reach in fresh cometary snows are exposed. These phenomena lead to the increase of the total speed of sublimation from the comet. Finally the outburst of the brightness of the comet can be observed.

2) The collision mechanism.
Sekanina (1972) stated that the outburst of 29P/SW could be caused by its impacts with interplanetary boulders. In fact, the velocity of such impactors in relation to SW 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, such a collision is not highly probable Gronkowski (2004a, 2004b). Surely, impacts of 29P/SW with other small bodies can sporadically occur and trigger outbursts of this comet. However this mechanism cannot be the main source of its outbursts.

3) The solar wind.
The famous comet 1P/Halley (hereafter 1P/H) has undergone an unexpected outburst of brightness on February 12, 1991 at 14.3 au heliocentric distance. Several dozen days earlier in December 1990 and January 1991 large solar flares up were observed. 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. They calculated that flux of solar wind arrived the 1P/H nucleus on 12 February. Then impacted on the cometary nucleus shock wave could destroy its surface crust. By that means volatile ices placed below the surface of nucleus were exposed on the solar radiation. Initiated in this manner intense sublimation of a comet could be seen as a jump in its brightness.

4) The polymerization of HCN.
On the basis of knowledge about an existence of polymers in comets Retting (1992) suggested the possibility of cometary outbursts as result of the polymerization of HCN. A probable scenario of the outburst can be described in the following way. Polymerization can start on the surface of the cometary nucleus by an accidental absorption of UV photons or high-energy solar photons by HCN molecules. This reaction can also be initiated by the free radical chain reaction. The polymerization of HCN releases the energy which is equal to 1.8510^7 J/kg. One can easily show that the latent heat of the polymerization of HCN is large enough to rise the temperature of a part of the cometary nucleus from of about 100 K to temperature of about 140 K when the transformation of amorphous water ice is practically immediate. The last reaction can provide the main amount of the released during the outburst energy. The described about both reactions i.e. the polymerization and the phase transition probably lead to destruction of a part of surface layers of the cometary nucleus. At a last resort the nucleus rejects cometary material into the space and the outburst can be observed.

5) The crystallization of amorphous water ice.
Nuclei of comets were created at low temperature and low pressure. Under these conditions, the water vapour freezes and changes into an amorphous form. Therefore, initially the comet ice was probably amorphous. This state it is not stable: amorphous water ice can be transformed by phase transition into a crystalline cubic form. The rate of transformation of amorphous ice into a crystalline form depends strongly on the temperature. It starts slowly at about 120 K, but above 140 K it is practically immediate Schmitt (1989). The transformation is strongly exothermic. The heat generated during this process results in quick sublimation of CO and CO_2 molecules. This leads to a significant increase in the matter in the comet's head and, as a last resort, it is possible to observe the outburst of brightness. (Prialnik and Bar-Nun (1992); Meech (2009); Rosenberg and Prialnik (2010); Kossacki and Szutowicz (2011, 2013)).

6) The idea of numerous cavities in comets.
Gronkowski and Wesołowski (2015) proposed a new model explaining the source of a comet outburst. This model is based on the hypothesis that a comet can contain below a surface of the nucleus numerous caves and niches filled with gas under pressure Ipatov and A'Hearn (2011). This hypothesis is a conclusion from the analysis of particle dynamics ejected from Comet 9P/Tempel after collision with Deep Impact Impactor. In favourable conditions the surface layers above the hollows can be destroyed. This leads to the exposure of the deeper layers of the nucleus for solar radiation. As a consequence, the sublimation rate is rapidly increasing, which can lead to the outbursts of the comet's brightness.

7) The melting of cometary ice.
This attempt to explain the brightness of comets at large distances from the Sun is based on the idea that large amounts of CH_4 in the form of a solid can be entrapped in some cavities and niches below a surface of the comet's nucleus. (Miles et al. (2016); Miles (2016a, 2016b)). Under favourable conditions, solid CH_4 may start to melt and absorb large amounts super active gases such as CO and N_2. Subsequently, the absorbed gases release significant amounts of heat their enthalpy dissolution. This leads to further melting of the matter inside the comet's nucleus. The phenomenon of gas dissolution is the most active near the solid-liquid interface, where the solvent temperature is low and the solubility in the gas is highest. The nucleus layer containing paraffinic hydrocarbons is softened under the influence of heat released. At some point the pressure of trapped gases in the cavity can destroy the layer which covers it. This leads to the rapid release of dissolved gases, mainly CO. Eventually, the comet's brightness it may take place.

The mechanisms mentioned above were also collected and discussed by Hughes (1991) and Gronkowski and Wesołowski (2016). Of course, the cited mechanisms are not the only ones known in the literature. However, it should be noted that none of the well-known mechanisms fully explains all morphological features of cometary outbursts. It is likely that a change in the comet's brightness may be a combination of several mechanisms that may occur simultaneously. The authors of various hypotheses about cometary outbursts agree that the direct reason for the comet brightening is the rejection of some part of the surface layer of the nucleus. This exposes the subsurface layers rich in cometary water ice, resulting in a significant increase in the sublimation rate of the comet. It is noteworthy that considered phenomenon is often observed for both periodic and parabolic comets. The most famous representative of comets undergoing flares of brightness is the already mentioned comet 29P/SW. Especially often the phenomenon is observed for comets belonging to Jupiter-family comets (hereafter JFCs). Comets belonging to this family meet the Tisserand criterion which has the following shape:

$$T_J = \frac{a_J}{a_c} + 2\cos(i)\sqrt{(1-e^2)\frac{a_c}{a_J}}, \tag{1}$$

here T_J stands for the Tisserand dynamical parameter with respect to Jupiter, a_J is the semimajor axis of Jupiter orbit ($a_J = 5.2$ au), a_c, i and e mean the semimajor axis of a comet orbit, its inclination and an eccentricity , respectively. According to Belton (2014a, 2014b) the Tisserand parameter T_J, and orbital inclination i fulfil the conditions: $2.4 \le T_J \le 3.1$ and $0^\circ \le i \le 31^\circ$. We note that the most spectacular throughout the whole history of astronomy was the outburst of comet 17P Holmes (hereafter 17P/H) in 2007. The comet 17P/H moves along an elliptical orbit with an eccentricity of $e = 0.4326$, the perihelion of the orbit is approximately equal to $q = 2.05$ au and its aphelion is equal to $Q = 5.18$ au. The orbital period is equal to $P = 6.89$ years. Due to its orbit parameters the 17P/H is include to the JFCs. On the night of 23/24 October 2007, the 17P/H was at a heliocentric distance of 2.47au. The brightness of the comet at this distance should be approximately