Cometary outbursts – the post-Deep Impact outlook on collisions as possible causes

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ABSTRACT

The possibility of impacts between comets belonging to the Jupiter Family and other small bodies orbiting in the main asteroid belt, and the consequences in relation to cometary activity are discussed. The probability of such events and the jumps in cometary brightness caused by impacts are examined. The results are compared with the results of the Deep Impact mission to Comet 9P/Tempel 1. The main conclusion of this paper is in agreement with previous findings, namely that an impact mechanism cannot be the main cause of the outburst activity of comets.

Key words: comets: general – comets: individual: Comet 9P/Tempel 1 – meteors, meteoroids – minor planets, asteroids.

1 INTRODUCTION

Outbursts of brightness are frequently reported for both periodic and parabolic comets. Such outbursts are the result of a sudden increase of cometary activity, manifested in a strong emission of gas and dust. During an outburst, the brightness of the comet increases suddenly by 2 to 3 mag on average, and then decreases exponentially over a few or several days (Richter 1954; Cabot, Enzian & Klinger 1996; Hughes 1991; Filonenko & Churyumov 2006). Many authors have tried to explain this phenomenon, considering various mechanisms and sources. Recently, Filonenko & Churyumov (2006) examined 180 outbursts of 129 comets. Their main conclusion is that there is no clear dependence of the appearance of outbursts on the heliocentric distance of a comet. The distribution of outburst number in relation to the heliocentric distance shows a specific structure: narrow local maxima are separated by narrow local minima for a wide range of heliocentric distances (fig. 2 and table 1 in their paper). Furthermore, there is no clear dependence of the amplitudes of outbursts on their frequency. In light of the above-mentioned statistical characteristics of outbursts and the results of research published in the last decade (Enzian, Cabot & Klinger 1997; Gronkowski & Smela 1998; Gronkowski 2002, 2005) it seems that there is more than one cause of outbursts and variations of cometary brightness. One of the proposed hypotheses is an impact mechanism. The results of the recent successful Deep Impact mission to Comet 9P/Tempel 1 (hereafter T1) have given us an opportunity to revise our knowledge of this subject. The main aim of this paper is therefore a discussion of the outburst impact hypothesis, taking into account the results of the Deep Impact mission.

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2 THE JUMP IN COMETARY BRIGHTNESS INDUCED BY IMPACT

This paper considers the possibility of an outburst in a comet that is relatively ‘old’, i.e. one in which the nucleus consists of a mixture of water-ice in crystalline form and dust. Numerical calculations will be carried out for a comet that belongs to the Jupiter family of comets. Such a comet has an orbit that is close enough to the Sun for the nucleus to reach high enough temperatures for its original material, i.e. the amorphous water-ice, to be converted into the crystalline form. It is assumed that the nucleus of the considered hypothetical comet has a shape similar to the nucleus of 1P/Halley, but its average radius is equal to \( R_n = 2 \, \text{km} \). The comet moves along an elliptical orbit that has a semimajor axis \( a = 4 \, \text{au} \), eccentricity \( e = 0.513 \) and inclination \( i = 12.5^\circ \). The choice of such values for the average radius of the nucleus \( R_n \) and the parameters of the orbit \( a, e, i \) is a consequence of the averaging of well-known radii of cometary nuclei (Tancredi et al. 2000) and of elements of orbits (Marsden & Williams 2003) of comets belonging to the Jupiter family (hereafter JF).

The problem of the impacting interaction of comets with other small bodies has recently been studied by (Gronkowski 2004b), who showed that cometary outbursts can be triggered by impacts with bodies that have sizes in the range of one metre. We now have the opportunity to make use of the results of the Deep Impact mission to T1 to shed further light on this subject. The approach presented in this paper therefore uses conclusions deduced from the T1 mission. On 4 July 2005, observatories on the Earth and in space recorded an unprecedented collision of Deep Impact with the nucleus of T1. An impacting spacecraft whose weight was \( m_s = 372 \, \text{kg} \) and whose velocity relative to T1 was \( v_s = 10.3 \, \text{km s}^{-1} \) excavated a crater on the surface of the nucleus from which \( M_0 \approx 10^6 \, \text{kg} \) of cometary material was released and raised into the coma (Meech et al. 2005; A’Hearn et al. 2005).
3 THE PROBABILITY OF IMPACTS OF COMETS WITH OTHER INTERPLANETARY BODIES ORBITING IN THE SOLAR SYSTEM

We should expect that the most favourable conditions for cometary impacts with other interplanetary small bodies will be in the inner Solar system near the plane of the ecliptic. There are two reasons for this. The essence of the first is that bodies belonging to the Solar system have a strong tendency to move on orbits that are near the plane of the ecliptic. The second is that the highest observed volume concentration of small bodies in the Solar system is in the main asteroid belt. The spatial density of bodies belonging to the main asteroid belt has a maximum near the ecliptic plane at a heliocentric distance equal to $R_0 = 2.8$ au. This is why, in order to simplify numerical calculations, the main asteroid belt is simulated as a circular torus with a radius equal to $R_0$. A circular section of such a torus has a radius equal to $r_{\text{esc}} = 0.7$ au. The choice of the values $R_0$ and $r_{\text{esc}}$ results from the analysis of data related to the spatial density of bodies orbiting in the main asteroid belt (Dohnanyi 1972, http://ssd.jpl.nasa.gov/?histo_a_ast).

In the numerical calculations, the size distribution function $N(r)$ of bodies belonging to the main asteroid belt given by Bottke, Nolan & Greenberg (1995) was used. The probability of collisions between a comet and small impactors belonging to the main asteroid belt will be calculated based on the assumption that the spatial density of such bodies is a two-dimensional Gaussian that is normal in relation to a radial distance $R = R_0$ measured from $R_0 = 2.8$ au and in relation to the distance $z$ from the plane of the ecliptic. This means that we assume that the spatial density of impactors has the following form:

$$n(R, z) = A \exp \left[ -\frac{(R - R_0)^2}{2\sigma^2(R)} \right] \exp \left[ -\frac{z^2}{2\sigma^2(z)} \right].$$

Here $A$, $\sigma(R)$ and $\sigma(z)$ denote a constant and adequate standard deviations. These parameters can be obtained from the normalization conditions. We assume that $\beta$ per cent of all bodies belonging to the main asteroid belt are included in the torus. The numerical calculations were carried out for $\beta = 90$, 95 and 99 per cent, respectively. The total probability of an impact $n_{\text{col}}$ (i.e. frequency of collisions) of the nucleus of a comet with another small body moving in the main asteroid belt can be calculated in a similar way to the method given in Beech (2001) and Beech & Gauer (2002), according to the formula

$$n_{\text{col}} = \int \int p_i (dN(r)/dr) (R_0 + r)^2 dr.$$

Here $N(r)$ is the size distribution function of the impacting bodies. We assume that the limits of the integration are equal to $r_1 = 0.5$ m and $r_2 = 2.0$ m because we want to know how probable are impacts that can generate real outbursts of cometary brightness. In this equation $R_0$ denotes the radius of a cometary nucleus, and $p_i$ is an intrinsic probability. The intrinsic probability $p_i$ was calculated according to the method outlined by Steel & Baggeley (1985). It should be emphasized that in the literature the mass distribution function $f(m)$ of small bodies orbiting in the Solar system with a shape $f(m) = A m^{-\beta}$ $dm$ is also considered. Here $m$ stands for the mass of a body, $A$ is a constant that can be obtained from a normalization condition.

Table 2. The total frequency of collisions $n_{\text{col}}(s)$ of comets that belong to the JF with small bodies during their passage through the main asteroid belt as a function of the mass index $s$. It is assumed that the radii of impactors are in the range from 0.5 to 2.0 m.

<table>
<thead>
<tr>
<th>$s$</th>
<th>90</th>
<th>95</th>
<th>99</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.63</td>
<td>0.829</td>
<td>1.025</td>
<td>1.361</td>
</tr>
<tr>
<td>1.73</td>
<td>0.244</td>
<td>0.302</td>
<td>0.400</td>
</tr>
<tr>
<td>1.83</td>
<td>0.071</td>
<td>0.087</td>
<td>0.116</td>
</tr>
<tr>
<td>1.93</td>
<td>0.020</td>
<td>0.025</td>
<td>0.033</td>
</tr>
<tr>
<td>2.03</td>
<td>0.006</td>
<td>0.007</td>
<td>0.009</td>
</tr>
</tbody>
</table>

For small-scale collisions in which the mass of the impactor is very small in comparison with the mass of the target, the ejected from the crater mass $M_{\text{cr}}$ is proportional to the kinetic energy of the impactor $E_{\text{imp}}$ via a crater excavation coefficient $\alpha$: $M_{\text{cr}} \approx \alpha E_{\text{imp}}$ (Peit & Farinella 1993). The parameter $\alpha$ depends on the material properties of the target and the impactor, and is in the range from $10^{-3}$ to $4 \times 10^{-4}$ s$^2$ m$^{-2}$ (Stöffler et al. 1975; Dobrovolskis & Burns 1984). The velocity of the impactor relative to the hypothetical comet considered in this paper is given by the formula given in Opik (1963). Its mass $m_{\text{imp}}$ is determined via the assumed radius $r_{\text{imp}}$ and the density $\rho_{\text{imp}}$. It is therefore easy to determine the mass ejected after an impact from the following relationship: $M_{\text{ej}} = M_0(4\pi \rho_{\text{imp}} r_{\text{imp}}^2 v_{\text{imp}}^2)/(3m_r v_r^2)$. These briefly presented approaches to the estimation of the quantity of the cometary mass that is ejected by an impact are the basis for estimating the jump in the brightness of the comet. The calculations were carried out in a similar way to those in Gronkowski (2002, 2004a). In these papers, numerical problems related to the calculation of the jump in the cometary brightness $\Delta m$ induced by the ejection of mass from the nucleus are described. The results of the calculations are presented in Table 1. Here it should be noted that grains and meteoroids released by a calm sublimation of cometary snows have a different size distribution from that of the material ejected by a crater-producing event. The Deep Impact project shows that cometary material ejected after an impact contains a large number of small grains in comparison with the material released by sublimation. After the impact the coma of T1 was dominated by micrometre grains of size in the range 0.5 to 1 $\mu$m (Meech et al. 2005; Hughes 2006). For this reason, the numerical calculations whose results are presented in Table 1 were performed for small assumed values of the average radius of the grains ejected after impact, namely $a_{\text{m}} = 0.75 \mu$m. In this paper the values of cometary physical characteristics in all numerical calculations are the same as in Gronkowski (2004a,b). Other cases are as specified in the tables. From Table 1 it can be concluded that the obtained simulated jumps in cometary brightness are very realistic and similar to the observed ones if the impactors have radii in the range 0.5–2.0 m.
and $s$ denotes a mass distribution index. There are some uncertainties related to the value of $s$; however, it is often assumed that $s = 11/6$ (Dohnanyi 1969; Paolicchi 1994). In the face of these uncertainties we assume that $s = 1.83 \pm 0.2$. The results of calculations for impactors that can potentially induce real cometary outbursts for the observed $N \approx 150$ comets belonging to the JF are presented in Table 2. From Table 2 we can conclude that the probability of cometary collisions with impactors that have sizes in the range of 1 m is indeed low. For $s = 1.83$ this probability is in the range of 0.1 per year for 150 objects! Even under the most favourable but unrealistic assumption of $s = 1.63$ it is in the range of one per year. We therefore conclude that impacts of comets with bodies orbiting in the main asteroid belt cannot be the main mechanism for inducing cometary outbursts.

4 DEEP IMPACT MISSION RESULTS AS A TEST OF THE CORRECTNESS OF COMPUTATIONS

The recent Deep Impact mission has provided us with many detailed images of the nucleus of T1. We therefore have an opportunity to compare the theoretical results of calculations associated with cometary impacts with the number of real impact craters visible on the surface of T1. A comet like T1 usually loses $\Delta h = 0.2$ to 0.5 m of surface material at each perihelion passage, according to an integration of the rate of sublimation of cometary ice along the orbit of the comet. The density of the nucleus T1 is estimated to be of the order of 600 kg m$^{-3}$ (A’Hearn et al. 2005). For such a quasi-solid target we can therefore estimate the diameters of craters excavated after impact according to the formula (Housen et al. 1979) $D \approx KE^{0.25} g^{1/6} / \kappa$. Here $E$ denotes the kinetic energy of the impactor, $g$ denotes the gravitational acceleration of the target, $K = 6.75 \times 10^{-2}$ (expressed in cgs units), and the coefficient $\kappa$ is in the range of a unit. Because the kinetic energy $E$ of impactors is a function of, among other things, its radius, we can express the radius of impactors by means of the diameter of the excavated crater $D$. In the pictures of the nucleus of T1 the smallest visible craters have a diameter equal to 40 m (A’Hearn et al. 2005). In this way we can estimate the minimum radius of an impactor $r_{\text{min,crat}}$ that makes visible craters. Because at each perihelion passage a comet loses a thickness $\Delta h$ of its surface material, a crater decreases in diameter $D$ by $\Delta D = \mu \Delta h$. Here the parameter $\mu = h/D$ denotes the ratio depth/diameter of the crater. It is generally assumed that $\mu \approx 0.2$ (Fernández 1981). Therefore the number of visible impact craters on the cometary nucleus surface is a result of a trade-off between the gradual disappearance of the previously excavated craters and the formation of craters during each passage through the main asteroid belt. Omitting the details we give a final formula for the total number of visible craters on the surface of a cometary nucleus:

$$n_{\text{crat}} = \sum_{i=0}^{i_{\text{max}}} n(r_{\text{min,crat}} + i \Delta h, r_{\text{max}}).$$

Here $n(r_{\text{min,crat}} + i \Delta h, r_{\text{max}})$ denotes the number of collisions in the $i$th orbit before the present moment. It is equal to the number of collisions with impactors that have radii in the range of $r_{\text{min,crat}} + i \Delta h$ to $r_{\text{max}}$. The index $i_{\text{max}}$ fulfills the condition $i_{\text{max}} = (r_{\text{max}} - r_{\text{min,crat}}) / \Delta h$.

The next component of the sum in equation (3) were calculated in a similar way to the frequency of collisions presented in the last section (equation 2). In the calculations, the elements of the T1 orbit given by Marsden & Williams (2003) were used: $a = 3.12$ au, $e = 0.519$ and $i = 10.5$. The results of the calculations for comet T1 are presented in Table 3. In the calculations it was assumed that $\Delta h = 0.2$ m for $\Delta h = 0.5$ m the obtained values are circa twice smaller). After the analysis of images of T1 (http://deepimpactumd.edu/gallery/ITS_PressRelease2.html) and extrapolation of the results from the visible part of the nucleus to the whole object we conclude that the total number of visible craters is equal to about 50.

Comparing this value with Table 3, it can be seen that our theoretical calculations are in general quantitatively correct. However, the results of the analysis of the images of T1 are consistent with the results of calculations for a relatively small distribution mass index in the range from 1.63 to 1.73. The calculations for the most frequently assumed value of $s = 1.83$ give too small a number of impactors is a function of $s$, among other things, a function of the orbital elements of a comet. Other things, a function of the orbital elements of a comet. The calculations were carried out for the present orbital parameters. Thirdly, when we take into consideration the many uncertainties in the nature of comets, the obtained values of $n_{\text{crat}}$ should be interpreted as qualitative, not quantitative, ones.

In order to explain the above-mentioned discrepancy, some numerical tests were carried out. Potentially we can expect fairly large changes in the obtained results if we change the values of free parameters such as the density of the cometary nucleus $\rho_a$, the thickness of surface material that is lost by the nucleus of the comet at each perihelion passage $\Delta h$, the parameters $K$ and $\kappa$ in Housen’s formula for the diameter of excavated craters, and parameters in the Gaussian distribution of impactors (see equation 1). Numerical simulations have shown that the obtained results are most likely to change if the parameters $\Delta h$, $K$ and $\kappa$ change. The changes of the other parameters are less important. We should keep in mind that if we assume, for example, that $\Delta h = 0.1$ m and that the mass distribution index is equal to $s = 1.83$, the obtained results are consistent with the results of the Deep Impact mission. In other words, the total number of calculated visible craters is approximately 50 with a precision of about ±20 per cent. This result confirms in some way the viability of the method presented here for calculating the probability of cometary impacts in the main asteroid belt.
5 CONCLUSIONS

The potential collisions of comets with small bodies as causes of outbursts of cometary brightness have been examined. The calculations leading to estimations of jumps in the cometary brightness and the probability of such collisional events have been reviewed. To conclude, impacts between comets and small bodies can sometimes occur and can lead to changes in the brightness of comets. However, the impact mechanism is a possible but a marginally probable explanation of cometary outbursts. Much more probable and real causes of the considered phenomenon are related to the internal structure and the physicochemical processes that occur in the interior of cometary nuclei. This is a clear conclusion from the Deep Impact mission. Indeed, a few days before impact, the spacecraft observed periodic spikes in the luminosity of T1. These outbursts occurred during a local sunrise, and clearly were not induced by impacts, but by internal processes occurring inside the cometary nucleus. A detailed analysis of Deep Impact data will be helpful in explaining these events; this should be the aim of future work.

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