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Cavities in comets

S.I. Ipatov (1,2,*)
(1) Space Research Institute, Moscow, Russia (siipatov@hotmail.com), (2) Catholic University of America, Washington DC, USA, (*) Present address: Alsubai Est. for Scientific Studies, Doha, Qatar

Abstract

The distance between the pre-impact surface of Comet 9P/Tempel 1 and the upper border of the largest cavity excavated during ejection of material after the collision of the impact module of the *Deep Impact* spacecraft with the comet is estimated to be about 5-6 meters if the diameter of the transient crater was about 150-200 m. This result suggests that the cavities containing dust and gas under pressure located a few meters below surfaces of comets can be frequent.

1. Introduction

In 2005 the impact module of the *Deep Impact* (*DI*) spacecraft collided with Comet 9P/Tempel 1. Ipatov and A'Hearn [3] analyzed images of the cloud of material ejected after this collision. Based on analysis of the images captured during the first 13 minutes, they studied the process of ejection of material and concluded that, in addition to the normal ejection, there was a triggered outburst of small (micron-sized) particles. Some excess ejection was observed beginning at 1 s. The outburst was considerable 8-60 s after the impact. It increased the duration of the ejection and the mean velocities of observed small ejected particles (compared with the normal ejection). The mean velocities (~100 m s^{-1}) of small observed particles were almost constant with time elapsed, t_e, since the impact for $10<t_e<20$ s. Ipatov and A'Hearn [3] supposed that the outburst was caused by the ejection of material from cavities containing dust and gas under pressure. Velocities of such `fast` outburst particles could be mainly ~100 m s^{-1} (such velocities were obtained at various observations of the leading edge of the *DI* cloud).

Ipatov and A'Hearn [3] analyzed the sky brightness mainly at the distances from the place of ejection at which most observed material did not fall back on the comet. I suppose that the model of a layered target plays some role in explanation of the variation of brightness of the *DI* cloud, but it cannot explain all details of such variation (for example, why at t_e~10 s there was simultaneously the jump in the direction from the place of ejection to the brightest pixel in an image of the *DI* cloud by 50°, the increase in the rate of ejection of small particles, and the increase in the brightness of the brightest pixel; why at t_e~60 s there was a sharp decrease in the rate of ejection of small particles, why at t_e~60 s the direction from the place of ejection to the brightest pixel returned to the direction which had been at $1<t_e<12$ s, why the mean ejection velocities of observed particles were almost the same at t_e~10-20 s, etc.). Schultz et al. [5] analyzed images of Comet Tempel 1 made by Stardust and concluded that the diameter d_{tc} of the DI transient crater was about 200 m. Some authors support smaller values of d_{tc} (up to 50 m). The diameter of the brightest part of the ring zone of ejected material around the observed crater is about 100 m.

2. The cavity excavated by the Deep Impact collision

Ipatov and A'Hearn [3] concluded that outburst and excavation of a large cavity began at t_{eb}~8 s. During the intermediate stage of crater formation (when the diameter d_c of a crater is proportional to t_e^{γ}), t_e usually increases by more than a factor of 10. Therefore, during the time interval $[0.1T_e, T_e]$ (where T_e is the time of formation of the crater), d_c increases by a factor of 10^{γ}, where 10^{γ} equals to 2, 1.8, and 2.5 at γ equal to 0.3, 0.25, and 0.4, respectively. These estimates show that at $t_{eb}=8$ s and $T_e>80$ s (this inequality is fulfilled for the *DI* crater) the maximum value, d_{cavmax}, of d_{cavDI} does not exceed $d_{he}/10^{\gamma}+d_{h1}$, which is in the range $[0.4d_{he}+d_{h1}, 0.56d_{he}+d_{h1}]$, that is $d_{cavmax}\le 0.056d_{tc}+d_{h1}$ at $d_{he}/d_{tc}=0.1$ (the limits are smaller for greater T_e), where d_{he} is the depth of a transient crater. At the initial stage of crater formation, the real growth of the depth of the crater is greater by d_{h1} than that at d_c proportional to t_e^{γ}. The difference d_{h1} was considered to be about 1 m.

Supposing the diameter d_c of a growing crater to be proportional to t_e^γ also at the initial stage, Ipatov [1] estimated the lower limit of the depth, d_{cavDI}, of the *DI* crater at the time, t_{eb}, of the beginning of excavation of the main cavity as $d_{cavmin}=d_{he}\times(t_{eb}/T_e)^\gamma$, At $d_{he}=0.1d_{tc}$, the value of d_{cavmin} equals $d_{cmn}=0.1d_{tc}\times(t_{eb}/T_e)^\gamma$. At t_{eb}=8 s, the values of d_{cmn} for three values of γ are presented in Table 1. The real value of d_{cavDI} is greater by d_{h1} than d_{cmn}. At T_e=80 s and γ=0.3, the value of $0.05d_{tc}+d_{h1}$ ($d_{cavmax}\le 0.05d_{tc}+d_{h1}$ for γ=0.3) is greater by about 2 and 5 m than the values of d_{cavDI} presented in Table 1 for d_{tc}=100 m and d_{tc}=200 m, respectively.

Based on the obtained values of d_{cavDI}, it is concluded that the distance between the pre-impact surface of the comet and the upper border of the main excavated cavity is about 5-6 m for the estimates (150-200 m) of the diameter of the *DI* transient crater presented by Schultz et al. [5]. The estimated distance is 4 m for the diameter of 100 m. The excavated cavity could be located at some distance from the centre of the *DI* crater (i.e. not directly below its centre). Therefore, the distance d_{cavDI} between the pre-impact surface of the comet's nucleus and the upper border of the cavity could be smaller than the depth of the crater at the beginning of excavation of the cavity. On the other hand, as a result of cracks caused by the impact, the outburst from the cavity could begin before excavation of its upper border, and consideration of cracks can increase the estimate of d_{cavDI}.

Table 1: The distance, d_{cavDI}, between the pre-impact surface of the comet and the upper border of the cavity excavated at t_{eb}=8 s.

d_{tc} [m]	100	200
T_e [s]	330	660
d_{cmn} [m] for γ=0.25	3.9	6.6
d_{cmn} [m] for γ=0.3	**3.3**	**5.3**
d_{cmn} [m] for γ=0.4	2.3	3.4
d_{cavDI} [m]	**4**	**6**

The distance between the pre-impact surface of Comet 9P/Tempel 1 and the upper border of the largest excavated cavity equal to about 4-6 m, and sizes of particles inside the cavities of a few microns are in good agreement with the results obtained by Kossacki and Szutowicz [4]. These authors made calculations for several models of the explosion of Comet 17P/Holmes. They concluded that the nonuniform crystallization of amorphous water ice itself is probably not sufficient for an explosion, which could be caused by a rapid sublimation of the CO ice leading to a rise of gas pressure above the tensile strength of the nucleus. In their models, the initial sublimation front of the CO ice was located at a depth of 4 m, 10 m, or 20 m, and calculations were finished when the CO pressure exceeded the threshold value 10 kPa. It was shown that the pressure of CO vapor can rise to this value only when the nucleus is composed of very fine grains, a few microns in radius.

The porous structure of comets provides enough space for sublimation and testifies in favor of existence of cavities. Natural outbursts were observed for several comets (see references in [2]). Similarity of velocities of particles ejected at the triggered and natural outbursts shows that these outbursts could be caused by similar internal processes in comets.

3. Conclusions

The upper border of the largest cavity excavated during ejection of material after the collision of the impact module of the *Deep Impact* spacecraft with Comet 9P/Tempel 1 could be located at a depth of about 4-10 meters below the pre-impact surface of the comet (at diameter of a transient crater about 100-200 m). This depth is in accordance with the depth (4-20 m) of the initial sublimation front of the CO ice in the models of the explosion of Comet 17P/Holmes considered in [4]. Our studies testify in favor of that cavities with dust and gas under pressure located a few meters below surfaces of comets can be frequent.

References

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