LOCATION OF THE UPPER BORDERS OF THE CAVITIES EXCAVATED AFTER THE DEEP IMPACT COLLISION. S. I. Ipatov [1,2,*], [1] Department of Physics, Catholic University of America, Washington DC, 20064, USA; [2] Space Research Institute, Moscow, Russia; [*] Present address: Alsubai Establishment for Scientific Studies, Doha, Qatar; siipatov@hotmail.com.

1. Introduction: In 2005 the impact module of the Deep Impact (DI) spacecraft collided with Comet 9P/Tempel 1 [1]. Based on analysis of the images made during the first 13 minutes after this impact, Ipatov and A'Hearn [2] studied the process of ejection of material and concluded that, besides the normal ejection, there was a triggered outburst of small particles. The outburst was considerable at t_e~8-60 s after the impact (it could began at t_e~1 s). It was supposed [2] 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).

Based on the time of the beginning of excavation of the main cavity (t_e≈8 s) obtained by Ipatov and A'Hearn [2] and on the diameter of the DI crater, in Section 5 we estimate the distance d_{cavDI} between the pre-impact surface of Comet Tempel 1 and the upper border of the main excavated cavity. Such estimates allow one to better understand the distances between surfaces of comets and upper borders of cavities with dust and gas under pressure.

2. Triggered Deep Impact Outburst: Hosapple and Housen [3] supposed that ejected particles could be accelerated by the dust-gas interaction. Such acceleration could be important during time intervals of about several hours. Ipatov and A'Hearn [2] made their conclusions basing on analysis of variations in brightness in images made during the first 13 minutes and considering distances *R* from a place of ejection between 1 and 10 km. They concluded that particles could not increase their velocities by more than a few m s^{-1} during not more than a few minutes, when the particles moved at *R* between 1 and 10 km. Ipatov and A'Hearn analyzed the brightness of the DI cloud at such distances and did not consider a plume base at *R*<1 km as Richardson et al. [4]. In many DI images, the region corresponding to *R*<1 km consisted mainly of saturated pixels.

In our opinion, it is difficult to explain the time variations in the brightness of the DI cloud at 1<*R*<10 km without consideration of the triggered outburst with velocities of about 100 m s^{-1}. Several authors (e.g., [4]) suppose that variation in brightness of the DI cloud was caused by variation in particle size distribution due to striking a layered target. We 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 (e.g., why at the same time ~10 s there was the jump of the direction from the place of ejection to the brightest pixel of the cloud image by 50^o, the increase of the rate of ejection of small particles, and the increase of brightness of the brightest pixel; why at time of ejection t_e~60 s there was the sharp decrease in the rate of ejection of small particles, why at time after the impact *t*~60 s the direction from the place of ejection to the brightest pixel in an image returned to that at 1<*t*<12 s, why mean ejection velocities of observed particles were almost the same at t_e~10-20 s, etc.).

3. Diameter of the Deep Impact Crater: Based on studies of ejecta plume, Richarson et al. [4] concluded that a transient crater of not more than 85–140 m (but not less than 22–26 m) diameter, formed in not more than 250–550 s. Estimates of the crater diameter made by Busko et al. [5] on the basis of analysis of DI images were about 150–200 m. Schultz et al. [6] obtained a little wider range for the diameter: 130–220 m.

Peter Schultz analysed photos made by the Stardust spacecraft on February 14, 2011 and concluded (http://www.universetoday.com/83335/nasa%E2%80%99s-stardust-discovers-human-made-deep-impact-crater-on-comet-tempel-1/) that the diameter of the DI crater is about 150 m. Richardson supposes that there is an approximately 50 meter diameter depression that most likely represents the DI crater.

On the image made by the Stardust spacecraft (http://stardustnext.jpl.nasa.gov/Multimedia/popups/Tempel1ImageSite.html), the diameter of the brightest part of the ring zone of ejected material around the crater is about 90-100 m. The diameters of the inner and outer edges of the ring zone are ~60-70 m and ~130-140 m, respectively. The ring zone may correspond to ejected material, and the diameter of an excavation zone might not exceed 100 m.

4. Formation of Craters: It is considered (e.g., [7]) that ejected material originates from an excavation cavity which has a geometry distinct from a transient crater. The excavation cavity and the transient crater have the same diameter d_{tc}, but the depth d_{he} of the excavation cavity is ~0.1d_{tc} (d_{he}/d_{tc} can be in the range [0.09, 0.17]), or about one-third of the transient crater depth, and, in the case of simple bowl-shaped craters, about one-half of the depth of the final apparent crater. For example, d_{he}~10 m at d_{tc}=100 m. For theoretical models (e.g., [3]), during the most time of crater formation (except for initial and final stages), a diameter d_c

of a crater at time t_e elapsed after the impact is proportional to t_e^γ, where γ is about 0.25-0.4. In their table 4, Holsapple and Housen [3] considered models at $0.29 \le \gamma \le 0.36$. According to fig. 12 in [8], d_c grows faster at the initial stage (which duration is usually less than $0.1T_e$, where T_e corresponds to the end of the stage of proportionality of d_c to t_e^γ), but practically did not grow at a final stage.

5. Cavities Containing Dust and Gas under Pressure in Comet 9P/Tempel 1: Ipatov and A'Hearn [2] concluded that outburst and excavation of a large cavity began at ~8 s after the DI collision. Supposing d_c to be proportional to t_e^γ, we can estimate the lower limit of the depth d_{cavDI} of the DI crater at the time of the beginning of excavation of the main cavity t_{eb}=8 s as $d_{cavmin}=d_{he}\times(t_{eb}/T_e)^\gamma$.

For t_{eb}=8 s and T_e=400 s, the value of $(t_{eb}/T_e)^\gamma$ is equal to 0.31, 0.21, and 0.38 at γ equal to 0.3, 0.25, and 0.4 respectively. For smaller T_e, the value of $(t_{eb}/T_e)^\gamma$ is greater. For example, for γ=0.3 this value and d_{cavDI} are greater by a factor of $2^\gamma \approx 1.23$ at T_e=200 s than those at T_e=400 s. Based on the above estimates, we can suppose that d_{cavmin} was probably not less than 3 m at d_{tc}=100 m. During the intermediate stage of crater formation (when diameter d_c of a crater is proportional to t_e^γ), time usually increases by more than a factor of 10 (see fig. 12 in [8]). Therefore, during the time interval $[0.1T_e, T_e]$ (we consider T_e as the time that corresponds to the end of the stage of proportionality of d_c to t_e^γ) d_c increases by a factor of 10^γ, where 10^γ is 1.8-2.5 at $0.25 \le \gamma \le 0.4$. These estimates show that at T_e>80 s the value of d_{cavDI} does not exceed $d_{he}/10^\gamma$ m, which is about $(0.4\text{-}0.56)d_{he}$ (e.g., $d_{he}/10^\gamma \le 5.6$ m at d_{tc}=100 m and d_{he}/d_{tc}=0.1). Summarizing the above estimates, we can conclude that the most probable estimate of d_{cavDI} is about 3-4 m at diameter of a transient crater d_{tc}=100 m. It is easy to estimate d_{cavDI} for other values of d_{tc}, taking into account that d_{cavDI} is proportional to d_{tc} (e.g., d_{cavDI}~5-6 m at d_{tc}=150 m, and d_{cavDI}~2-3 m at d_{tc}=50 m). Estimates of d_{cavDI} are approximate because we do not know exact values of d_{tc}, T_e, and γ. The above estimates are not changed if we take into account that γ changes with time in the limits discussed above.

The excavated cavity could be located at some distance from the center of the DI crater (not below its center). 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 a crater at the beginning of excavation of the cavity. On the other hand, due to 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}.

The largest cavity excavated after the DI collision could be relatively deep because a considerable excess ejection lasted during ~50 s (at $8<t_e<60$ s). This ejection probably was from the same cavity because the direction from the place of ejection to the brightest pixel in images made at $12<t<60$ s was quite different from the direction at t<12 s and t>60 s, and one of `rays of ejection` (i.e., rays of more bright material in the DI cloud with a vertex at the place of ejection) disappeared at 60 s. Existence of `rays of ejection` in DI images made at $t\approx$13 min testifies in favor of the ejection of particles from cavities at $t_e\approx$10 min. Ejection of slower-moving particles from a `fresh` surface of the DI crater could continue for more than 10 min.

For small cavities/cavity excavated at t_e=1 s, the depth of a crater could be smaller by a factor of $\ge 8^\gamma$ (8^γ is about 2) than that at t_e=8 s and could be ~1-2 m.

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 [9]). 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.

6. 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 3-5 meters below the pre-impact surface of the comet. 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 by Kossacki and Szutowicz [10]. 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.

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