THE OUTBURST TRIGGERED BY THE COLLISION OF THE DEEP IMPACT MODULE WITH COMET TEMPEL 1, AND CAVITIES IN COMETS.

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1. Introduction: In 2005 the impact module of the Deep Impact (DI) spacecraft collided with Comet 9P/Tempel 1. Based on analysis of images of the cloud of ejected material made during the first 13 min after the impact, we studied [1,2] the time variations in the rate and velocities of ejection of observed particles (mainly with diameter d<3 μm). These variations differed from those for the model based on theoretical studies of impact events and can give information about composition of the comet.

2. Triggered DI outburst: Analysis of maxima or minima of plots of the time variations in distances R of contours of constant brightness from the place of ejection (at R>1 km, i.e. outside of regions of saturated pixels) allowed us to estimate the characteristic velocities of particles at several moments in time t_e of ejection after impact for $t_e \leq 115$ s [1-2]. Other approaches for estimates of the velocities were also used. All these estimates are in accordance with the same exponential decrease in characteristic velocity (with exponent about -0.7). Analysis of time variations in the size of the bright region of ejected material allowed us also to estimate the time variations in the relative amount of ejected particles. At t_e~10 s, the morphology of the ejecta (e.g. the location and brightness of the brightest pixel) changed, and the rate r_{te} of ejection of observed material increased. Between 1 and 3 seconds after the impact and between 8 and 60 seconds after the impact, more small bright particles were ejected than expected from crater excavation alone. An outburst triggered by the impact could cause such a difference. The sharp (by a factor of 1.6) decrease in the rate of ejection at $55<t_e<72$ s could be caused by a decrease in the outburst that began at 10 s.

Our studies did not allow us to estimate accurately when the end of ejection occurred, but they do not contradict a continuous ejection of material during at least the first 10 minutes after the collision. The duration of the outburst (up to 30-60 min) could be longer than that of the normal ejection, which could last only a few minutes. Our research testifies in favor of a model close to gravity-dominated cratering. We studied the motion of small particles with velocities greater than the escape velocity. These particles constituted a small part of all ejected material.

3. Peculiarities of the DI ejection: Conditions of ejection of material from Comet Tempel 1 were different from those for experiments and theoretical models. The great difference in projectile kinetic energy introduces challenges when scaling the laboratory results to DI conditions, e.g. some materials will vaporize that otherwise would remain in solid or liquid form. Holsapple and Housen concluded [3] that for the normal cratering mechanism only a negligible amount of mass ejected had velocities of the order of 100's of m/s, and velocities of 100's of m/s that were observed are due to the particles which were accelerated by vaporization of ice in the plume and fast moving gas. Our estimates showed [2] that it is more probable that the increase of velocities of particles by gas during their motion inside the region with radius of a few km from the place of ejection probably did not exceed a few m/s at initial velocity greater than 20 m/s.

A few other differences of the DI ejection from experiments are the following: gravity on the comet (0.04 cm/s^2) is much smaller than that on the Earth (9.8 m/s^2), and masses of projectiles in experiments were small. Diameters of particles that made the main contribution to the brightness of the DI cloud are considered to be less than 3 μm, and sizes of sand particles in experiments were much larger (~100 μm) than those of the observed DI particles.

Besides the outburst, the differences between theoretical estimates [4] and observed velocities are partly caused by that in the theoretical model all particles ejected at the same time had the same velocities and were ejected at the same distance from the place of impact. In our opinion, at the same time DI particles could be ejected with different velocities and at different distances from the center of the crater.

4. Cavities with dust and gas under pressure: The outburst ejection could have come from the entire surface of the crater, while the normal ejection was mainly from its edges. The 'fast' outburst could be caused by the ejection of material from the cavities that contained the material under gas pressure. The 'slow' outburst ejection could be similar to the ejection from a 'fresh' surface of a comet and could take place long after the formation of the crater.

Analysis of observations of the DI cloud and of outbursts from different comets testifies in favor of the proposition that there can be large cavities, with material under gas pressure, below a considerable fraction of a comet's surface. Internal gas pressure and material in the cavities can produce natural and triggered outbursts and can cause splitting of comets. The upper edge of the cavity excavated at t_e~10 s could be located a few meters under the surface of Comet Tempel 1.

5. Outbursts from different comets: Observed outbursts from different comets testify in favor of the existence of cavities with gas under pressure and the relatively close location of the cavities to the surface of a comet. The triggered DI outburst was one of many other outbursts of comets. The DI spacecraft observed natural outbursts from Comet Tempel 1.

Outbursts from comets caused by internal processes could last for weeks or months, much longer than for the DI outburst caused by the impact. Prialnik et al. concluded [5] that the outburst of Comet 1P/Halley could take place during a few months when the comet moved at a distance greater than 5 AU from the Sun. They supposed that crystallization of amorphous ice in the interior of the porous nucleus, at depths of a few tens of meters, caused the release of gas. The role of crystallization of amorphous ice in bursts of comet activity was discussed in several other papers. Boehnhardt concluded [6] that if the gas pressure cannot be released through surface activity, the tensile strength of the nucleus material can be exceeded and fragmentation of the comet occurs.

The total mass of material ejected at the 2007 October 24 outburst of Comet 17P/Holmes (~1-4 % of the nucleus mass of the comet, i.e. $(1\text{-}3)\times10^{11}$ kg) was much greater than that at the DI collision. Schleicher concluded [7] that production of OH decreased by a factor of 200-300 during 124 days after the outburst of Comet 17P/Holmes in 2007, but it was still greater than before the outburst. It shows that the ejection of material from a 'fresh' surface of a comet can make a noticeable contribution to the total ejection from the comet for many days. Schleicher suggested [7] that the explosion occurred at greater depth in Holmes than in other comets. Reach et al. supposed [8] that the explosion of Comet 17P/Holmes was due to crystallization and release of volatiles from interior amorphous ice within a subsurface cavity: once the pressure in the cavity exceeded the surface strength, the material above the cavity was propelled from the comet.

Belton et al. concluded [9] that natural outbursts on Comet 9P/Tempel 1 were caused by that at some depth the stress of gas overwhelmed the strength and overburden pressure of cometary material. Comet nuclei are assumed to be of porous structure. For example, Richardson et al. considered [4] that the bulk density of Comet Temple 1 is ~0.4 g cm^{-3}. Sources of gas that can fill cavities and pores in comets include the crystallization of amorphous ice and the sublimation at 'internal' surfaces [10].

The above examples and the observation of the DI triggered outburst testify in favor of that cavities containing particles and gas under pressure can be located below a considerable fraction of a comet's surface. At a triggered outburst caused by a collision, the duration of the outburst can be short because most of the material under pressure can leave the excavated cavity quickly. Duration of some natural outbursts can be much longer.

Cometary activity of asteroid 7968 Elst-Pizarro, also known as Comet 133P/Elst-Pizarro, could be caused by the same internal processes as the triggered or natural outbursts from Comet Tempel 1, but its solid crust could be much thicker than that of Comet Temple 1. In 1996, 2002, and 2007, the object Elst-Pizarro had a comet tail for several months. The asteroid orbit of this object is stable [11]. Based on studies of the orbital evolution of Jupiter-crossing objects [12-13], Ipatov and Mather supposed [14] that the object Elst-Pizarro earlier could be a Jupiter-family comet, and it could circulate its orbit also due to non-gravitational forces.

Hsieh et al. concluded [15] that activity of Comet 133P/Elst-Pizarro was consistent with seasonal activity modulation and took place during hemisphere's summer, when the comet received enough heating to drive sublimation. We suppose that there could be natural outbursts during the 'summer', and they could be one of the sources of observed activity of the comet. It could be possible that vaporized material formed under the crust moved outside through narrow holes for a long time. There can be a lot of ice under the crust of the object Elst-Pizarro, and this ice produced a comet tail after the crust had been damaged in some way (e.g. due to high internal pressure).

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