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Laboratory modelling of an active space experiment using railgun as a launch device

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ABSTRACT

Laboratory modelling of active space experiments is described. To accelerate an impactor, a specially developed electromagnetic railgun capable of accelerating 10-mg cubic impactors to velocities of up to 5.5 km/s was used. As targets, different materials, such as ice and moon-like regolith, were employed. To simulate a collision with a comet, a hypervelocity impact on water ice targets with different densities was performed. To simulate an impact on the Moon's surface, a special method for preparation of regolith targets with the compositions corresponding to the Moon's surface materials was developed. The impact experiments with regoliths of different densities were carried out.

1. Introduction

The problems connected with protection of spacecrafts against ballistic exposure to "space debris" or meteoroids are widely discussed in scientific literature [1,2]. A rich variety of information is available in literature about the distribution of space debris in orbits in accordance with the size and mass and the number of the objects being tracked [3]. All the sources are of the opinion that space debris presents a real threat for orbital stations [4], and its amount will be increasing owing to active exploitation of the low Earth orbits and mutual collision of space debris objects and particles. Today, the space debris control is limited to debris monitoring with optical and radar techniques and developing methods for protection of space vehicles against collisions with high-velocity damaging elements [2,5–7]. The theoretical models used for the space vehicle shield design need to be developed in conjunction with experiments on the hypervelocity impact. In the study reported here a laboratory railgun was used for accelerating the impactor. Another application of laboratory hypervelocity impact techniques stays in addressing fundamental problems of Cosmophysiques of the structure of space objects without atmosphere (comets, asteroids, moons), which is studied in hypervelocity impact response and ejecta spectrum analysis. To get information on these issues, active space experiments (LCROSS, Deep Impact) have been conducted [8,9]. Laboratory experiments in which different target materials were used for impact studies have also been performed. In order to interpret the results of these experiments, it is necessary to build theoretical models and to carry out calculations of the processes of hypervelocity impact on different materials (ice, regolith, silicates) with different initial densities. The construction of a theoretical model and numerical calculations of the phenomena that accompany a high-speed collision of bodies from different materials is not an easy task. It requires the knowledge of the phase diagram and the equation of the state of the matter in a wide range of variation of parameters and the development of an adequate calculation scheme.

This paper describes laboratory modelling of the hypervelocity impact processes similar to those in active space experiments. The experiments involved the use of mm-size mg-mass plastic impactors which were accelerated up to a 5.5 km/s velocity. To accelerate the impactor, a “compact” railgun of the original design developed and built at Ioffe Institute was used [10–12]. This railgun used a plasma armature [13] to accelerate a solid body in the railgun channel. As compared with the light-gas guns, such a hypervelocity impact experiment is much cheaper and a shorter time is needed to prepare the experiment.

The materials that were used as targets in our experiments were ice cubes in the Deep impact experiment modelling and regolith-like material in LCROSS modelling. The impactor in all the experiments was a 2×2×2 mm^3 cube made from polycarbonate.

2. Deep Impact experiment simulation

The goal of the Deep Impact active space experiment was to investigate the process of collision of the space impactor with Comet Tempel 1. The crater growth rate and final crater morphology gave important information

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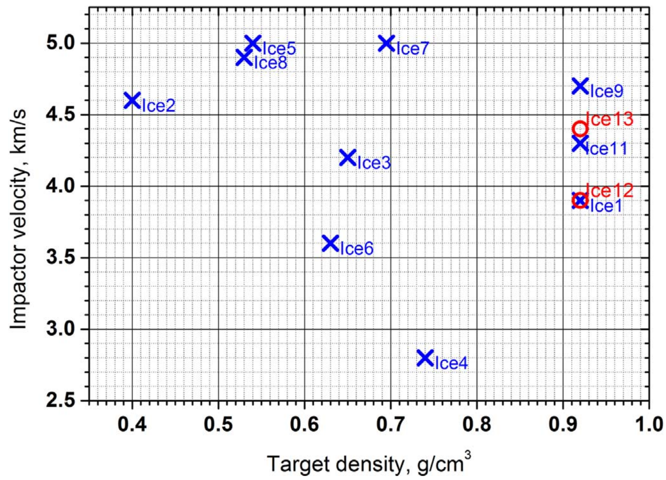

Fig. 1. Parameters of the experiments. The labels near the crosses and circles in the diagram correspond to the experiment ID. The crosses indicate the experiments with normal incidence, the circles mark the experiments with tilted incidence (the angle is 30^o).

on the nature of the upper surface of the comet [9].

To simulate in laboratory the effects similar to the Deep Impact experiment, the processes of crater formation that accompany high-speed impacts of plastic cubes on a massive ice target (because Comet Tempel 1 consists mainly of ice) were studied. At present there are a number of theoretical and experimental invevestigations of hypervelocity impact on ice targets [14–16]. The difference between our experiments and the experiments reported in [14,15] is that we used ice targets with different densities at different temperatures. The density of the ice target was varied in our case from 0.4 to 0.92 g/cm^3. The density of 0.92 g/cm^3 corresponded to the transparent water ice with few bubbles.

Fig. 1 shows the diagram in the “target density - impactor velocity” coordinates which gives information on the experiments which were conducted (the labels near the crosses and circles in the diagram correspond to the experiment ID). In the majority of our experiments the impact at normal incidence was investigated, but in several experiments a tilted impact of the ice cube was used. The angle between the impactor velocity vector and the normal to the target surface was 30^o. These experiments are marked in Fig. 1 by red circles.

The ice target in the form of a parallelepiped or cylinder with typical sizes of 10–15 cm was placed at a distance of 40–50 cm from the railgun muzzle. A system of thin-film sensors of the original design [17] that allowed registration of impactor speed with a high accuracy (better than 1%) was installed on the path from the impactor to the target. The frame sequence of the burst of the products ejected from the collision zone during the spallation process was recorded by a high-speed camera on the background of a matte screen illuminated by a flash lamp. We also managed to obtain the frame sequence of the dynamics of the fracture zone inside the target for transparent ice targets with an ice density of 0.92 g/cm^3 (Fig. 2 shows two frames from this sequence). By analyzing the frame sequence from the high-speed video it was found that the ice fracture exhibited a nonmonotonic behavior, and the crack expansion zone was much larger than the final crater sizes.

To fix the size and shape of the resulting crater in the target, a special technology of crater casting with a gypsum plaster immediately after the experiment was developed. The obtained casts were measured with a special micrometer. The ice target temperature remained unvaried due to fact that the experiment was performed during a very short time. The target was set on the impactor path immediately before the experiment, and a plaster cast was obtained immediately after the experiment. Fig. 3 shows plaster casts of the craters for all the experiments. It is evident that the craters have different sizes and volumes.

Let us consider in more detail some crater samples obtained in our impact experiments. As an example, Fig. 4 shows photos of plaster casts of the craters for two experiments Ice5 and Ice8.

The crater shape graphs corresponding to Fig. 4 are presented in Fig. 5. It is clearly seen that there is a noticeable difference in the shapes and in the volumes of the target material ejected in the Ice5 and Ice8 experiments. It is important to note that the initial conditions in the Ice5 and Ice8 experiments, i.e., the impact velocity and target density were nearly the same. The only difference was different target temperatures before the impact (t(Ice5) =−10 °C, t(Ice8) =−2 °C). However, as one can see from Figs. 4 and 5, the shapes and volumes of the craters appreciably differ. The crater volume was more than twice higher for the target with a higher temperature. In our opinion, this can be explained by the fact that several phases coexist on the phase diagram of ice in this temperature region.

So our experiments demonstrate that it is impossible to predict the crater shape and volume without knowing all ice parameters (not only density).

3. Moon’s surface impact simulation

The simulation of the phenomena that accompany a high-speed collision with the Moon’s surface with a specific energy release power of up to 10^8 W/cm^2, which corresponds to meteorite velocities of 2–5 km/s, was performed. The Moon has a 65-km thick crust which is covered with a loose detritus, i.e., a regolith layer the thickness of which ranges from 3 to 15 m [18]. On the surface, regolith is a weakly bound material having grains with an average size much smaller than 1 mm and a considerable number of different rock fragments with larger

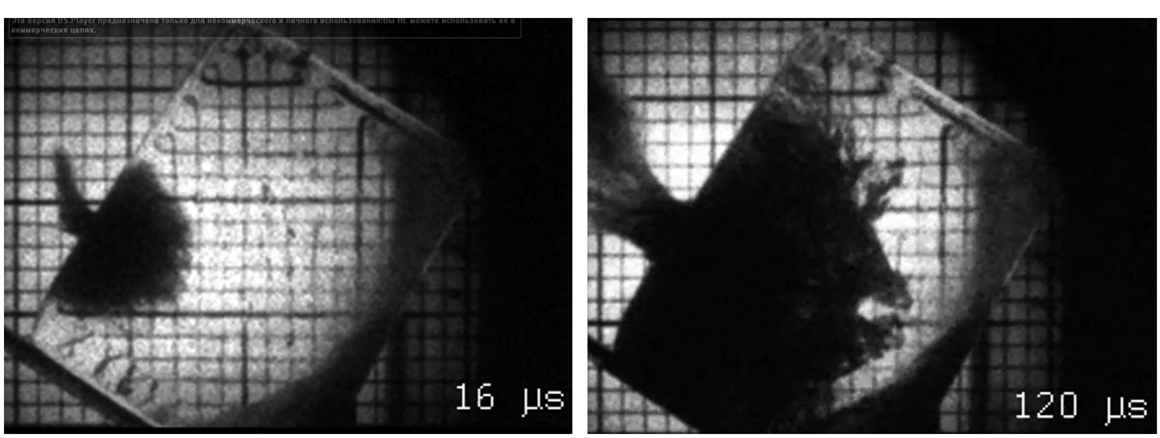

Fig. 2. Two frames from the high-speed filming of the fracture zone evolution inside the target for transparent ice targets with an ice density of 0.92 g/cm^3.