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Impacts experiments onto heterogeneous targets simulating impact breccia: Implications for impact strength of asteroids and formation of the asteroid families

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ABSTRACT

A series of impact experiments onto solid decimeter-sized cylinders made of porous gypsum admixed with approximately 1 cm-sized pebbles have been performed. The target densities and their heterogeneous structures could be representative of those of the asteroids Ida, Eros and many others, because asteroid sub-surface could be the consolidated boulders made by self-compaction and/or by impact compaction. Impact velocities in the experiments ranged from 2.0 km/s to 6.7 km/s (collision velocity in the asteroid main belt is approximately 5 km/s). It was found that the slope of the cumulative number distribution of post-impact fragments strongly depends on the specific energy of the impact. The presence of pebbles strongly influences the impact strength of the target as well as the size distribution of the post-impact fragments. Results of the experiments presented here are aimed at identifying the analogy between the laboratory results and the damage of small asteroids or their catastrophic disruption after impacts.

1. Introduction: asteroids vs. laboratory targets

We studied experimentally the impact damage (cratering or breakup) of heterogeneous samples. Experiments and their interpretation were aimed at looking for the analogies between the laboratory-scale and the asteroidal scale of the impact events. Particularly, this program was intended to model the results of impacts onto small asteroids. Here 'small' means asteroids with sizes of the order of hundreds of meters or a few kilometers at most. For such sizes the cohesion forces within the asteroidal matter are predominant or they are of the same order as the self-gravity forces.

Space missions during their flyby, orbiting, and even landing provide huge amount of important data concerning physics of asteroids and their surface features. The asteroids could be "small monolithic objects, bigger fractured objects or gravitational aggregates, as well as porous and nevertheless robust objects formed of cohesive material" (Lavasseur-Regourd et al., 2006). Table 1 lists sizes and densities (if available) of the asteroids whose surfaces have been photographed. To date there are only eleven of those. Diversity and heterogeneity of surface features on individual asteroids, as well as the differences between the surfaces of particular asteroids, are clearly visible. The photographs of Eros (mission NEAR Shoemaker, landed in February 2001; see e.g. Chapman et al., 2002) and that of Itokawa (mission MUSES-C, known as Hayabusa, that landed and collected Itokawa dust samples in 2005; see e.g. Dombard et al., 2010; Michikami et al., 2008; Miyamoto, 2013) show the surfaces covered by stones of very different sizes spanning from small gravel to large boulders. There are no reasons to suppose that the bulk composition of these asteroids as well as of the others is uniform and made from one type of material of fixed physical parameters e.g. mechanical strength, granulation, density and porosity. Summarizing the present knowledge concerning bulk properties of asteroids one it is known that the asteroidal density belongs to a large interval (1000–3500) kg m^{-3} and their porosity could be even as high as ~0.6 and as low as zero (Britt and Consolmagno, 2001; Britt et al., 2002). Unfortunately, densities of the asteroids are only established with large error margin. For only four asteroids, namely Vesta, Eros, Itokawa, and Lutetia density is known with precision better than 10%. The large interval of possible density values and the variety of the observed surface properties allow considerable flexibility in the choice of materials to be used for the laboratory targets as the asteroidal analogs in the impact experiments. In this work the targets were porous solid mixture made of the basalt pebbles consolidated by

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Table 1
Asteroids (ordered by their size) whose surfaces were photographed. *Asteroid classes*: C – chondritic, E – eucrite, S – silicate, V – Vesta class. *Abbreviations*: MB – Main Belt Asteroid, NEA – Near Earth Asteroid, fb – flyby, orb – orbiter. *References*: (1) Fujiwara et al. (2006). (2) Richter et al. (2001). (3) Keller et al. (2010). (4) Duxbury et al. (2004). (5) Chapman et al. (1996). (6) Krasinsky et al. (2002). (7) Petit et al. (1997). (8) Yeomans et al. (2000). (9) Yeomans et al. (1997). (10) Pätzold et al. (2011). (11) Russell et al. (2012).

Asteroid	Class	Dimensions and radius of a sphere with the similar volume (km)	Density (kg m^{-3})	The best resolution (m/px)	Mission, year of the main data acquisition
25143 Itokawa	S, NEA Mars crosser	0.5 × 0.3 × 0.2 ~0.16 (1)	1900 ± 130 (1)	~1 (1)	MUSES-C, 2005; orb
9969 Braille	Q, NEA Mars crosser	2.1 × 1 × 1 ~1.3 (2)	3900 (2)		Deep Space 1, 1999; fb. Images from the distance 14,000 km
2867 Steins	E, MB	6.67 × 5.81 × 4.47 2.65 (3)	n.a.	80 (3)	Rosetta, 2008; fb
5535 Annefrank	S, MB	6.6 × 5.0 × 3.4 4.4 (4)	n.a.	185 (4)	Stardust, 2002; fb
951 Gaspra	S, MB	18.2 × 10.5 × 8.9 6.1 (5)	2700 estimate (6)	54 (5)	Galileo, 1991; fb
243 Ida	S, MB	53.6 × 24.0 × 15.2 15.7	2600 ± 400 (7)	31–38	Galileo, 1993; fb
Dactyl Ida sat.	S, MB	1.6 × 1.4 × 1.2	n.a.		Galileo, 1993; fb
443 Eros	S, NEA	34.4 × 11.2 × 11.2 16.8	2670 ± 30 (8)	2	NEAR, 2000; orb
253 Mathilde	C, MB	66 × 48 × 44 26.4	1300 ± 200 (9)	230	NEAR, 1997; fb
21 Lutetia	C, MB	132 × 101 × 76 ~50	3400 ± 300 (10)	61	Rosetta, 2010; fb
4 Vesta	V, MB	262.7 (11)	3456 ± 1% (11)	25	Dawn, 2011; orb

gypsum: the hard basalt pebbles are surrounded by porous gypsum matrix of low strength. Basalt is the material discovered on asteroids (Pieters et al., 2005; Moskovitz et al., 2008).

Experimental works aimed to study the impact cratering and/or disruption of the asteroids and the icy satellites can be divided in several groups depending on the parameters of primary interest. The types of experiments are listed below according to different parameters characterizing the target that potentially simulates an asteroid or a small satellite. Some representative references are included. The targets are:

- Loose or sintered granular and uniform (homogeneous) – made of one component, e.g. loose sand (Stöffler et al., 1975), sintered snow (Arakawa and Yasui, 2011).
- Loose, complex (homogeneous or heterogeneous) – made of two or more components, e. g. granular mixtures of ices and minerals (Arakawa et al., 2000).
- Solid, uniform – made of one component, e.g. basalt (Fujiwara et al., 1977; Davis and Ryan, 1990), carbon dioxide ice (Burchell et al., 1998, 2005), water ice (Arakawa, 1999; Leliwa-Kopystynski et al., 2008), gypsum (Okamoto and Arakawa, 2009), sintered glass beads (Machii and Nakamura, 2011), pumice (Flynn et al., 2013).
- Solid, complex – made of two or more components, e.g. ice and silicate (Arakawa et al., 2002), targets made from meteorites (Flynn and Durda, 2004; Lipman et al., 2010; earlier Flynn et al., 1999, studied mechanical properties of chondrite meteorites focusing their research on disruption of asteroids), glass beads dispersed in gypsum matrix (Yasui and Arakawa, 2011). The present work belongs to this group.

The difference between 'loose' and 'solid' targets may not be clearly defined since the strength of mutual cohesion of grains depends on many factors, predominantly on their composition, ambient temperature and pressure that control sintering process. However, loose targets are far from the topic of the present work, so they are mentioned here only for completeness. A target prepared from two different materials cemented to each other seems to be a reasonable possibility (from the continuum of the other ones) for the simulation of well-consolidated heterogeneous asteroids. Note that the meaning of 'homogeneity' or 'heterogeneity' depends on the scale of inclusions or other non-uniformities vs. the scale of the object. The above classification does not take into account the properties of the impactor. In most cases the impactor plays only the role of a source of energy that is abruptly delivered to a very small fraction of the target body (point-like when compared with the target size).

Extrapolation of the decimeter-scale laboratory results onto the kilometer scale of an asteroid requires extreme caution. For example, an interpretation of the results of impact experiments onto the targets made from gypsum mixed with glass beads (Yasui and Arakawa, 2011) leaves a margin of uncertainty. They are appropriate for impacts onto individual chondrites, but not necessarily for an asteroid as a whole since a chondrite-bearing asteroid (C-type or Carbonaceous) is not a large chondrite-like monolith but rather a conglomerate of chondrites. If so, impact cratering and/or impact disruption of the two-component targets can be considered as an analog of asteroid damage by impacts.

2. Experiments

2.1. Guns

Experiments were performed at the impact facilities of the Sagamihara campus of JAXA (Japan Aerospace Exploration Agency) and of Kobe University. They are described elsewhere (Dohi et al., 2012). Velocities of the impactor were calculated from the measured time of flight on the distance of approximately 5 cm, close to the impact chamber. The impact velocities were within the following ranges:

- *JAXA two-stage light-gas gun*: v_{imp} = 2.0–6.7 km/s.
- *Kobe University gun*: $v_{imp} \sim 2.5$ km/s.

2.2. Impactors

Spherical nylon impactors were used for all shots. They were slightly different in size for the two guns used: