Icarus 264 (2016) 316–330

Contents lists available at ScienceDirect

Icarus

journal homepage: www.journals.elsevier.com/icarus

Fragment shapes in impact experiments ranging from cratering to catastrophic disruption

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ARTICLE INFO

Article history:
Received 11 May 2015
Revised 20 September 2015
Accepted 23 September 2015
Available online 8 October 2015

Keyword:
Impact processes
Collisional physics
Asteroids
Asteroid Itokawa

ABSTRACT

Laboratory impact experiments have found that impact fragments tend to be elongated. Their shapes, as defined by axes *a*, *b* and *c*, these being the maximum dimensions of the fragment in three mutually orthogonal planes ($a \geqslant b \geqslant c$), are distributed around mean values of the axial ratios $b/a \sim 0.7$ and $c/a \sim 0.5$. This corresponds to a:b:c in the simple proportion 2:$\sqrt{2}$:1. The shape distributions of some boulders on Asteroid Eros, the small- and fast-rotating asteroids (diameter <200 m and rotation period <1 h), and asteroids in young families, are similar to those of laboratory fragments created in catastrophic disruptions. Catastrophic disruption is, however, a process that is different from impact cratering. In order to systematically investigate the shapes of fragments in the range from impact cratering to catastrophic disruption, impact experiments for basalt targets 5–15 cm in size were performed. A total of 28 impact experiments were carried out by firing a spherical nylon projectile (diameter 7.14 mm) perpendicularly into the target surface at velocities of 1.60–7.13 km/s. More than 12,700 fragments with $b \geqslant 4$ mm generated in the impact experiments were measured. We found that the mean value of c/a in each impact decreases with decreasing impact energy per unit target mass. For instance, the mean value of c/a in an impact cratering event is nearly 0.2, which is considerably smaller than c/a in a catastrophic disruption ($\sim$0.5). The data presented here can provide important evidence to interpret the shapes of asteroids and boulders on asteroid surfaces, and can constrain current interpretations of asteroid formation. As an example, by applying our experimental results to the boulder shapes on Asteroid Itokawa's surface, we can infer that Itokawa's parent body must have experienced a catastrophic disruption.

1. Introduction

In laboratory impact experiments, the shapes of fragments from catastrophic collisions defined by axes *a*, *b* and *c*, these being the maximum dimensions of the fragment in three mutually orthogonal planes ($a \geqslant b \geqslant c$), have been found to behave in a very regular way (see the pioneering work of Fujiwara et al., 1978). The axial ratios are distributed around mean values of the axial ratios $b/a \sim 0.7$ and $c/a \sim 0.5$, i.e. corresponding to a:b:c in the simple proportion 2:$\sqrt{2}$:1. The data indicate a general property of collisional fragments, which is repeated with great regularity in widely different experimental conditions such as projectile velocity, target shape, composition and strength (Fujiwara et al., 1978; Matsui et al., 1982, 1984; Bianchi et al., 1984; Capaccioni et al., 1984, 1986; Durda et al., 2015).

The shape distributions of small asteroids less than tens of kilometers in diameter are considered to be similar to distributions obtained for fragments generated in laboratory impact experiments (Fujiwara et al., 1978; Capaccioni et al., 1984, 1986). The shapes of most asteroids can be inferred from the observed light curve amplitude. For instance, Szabó and Kiss (2008) have determined the shape distribution of 11,735 asteroids based on the Sloan Digital Sky Survey Moving Object Catalog. In particular, they have researched eight prominent asteroid families. Nearly one-third of all asteroids belong to families (Zappalà et al., 1995) that are believed to be a result of collisional disruption of parent asteroids (O'Brien and Greenberg, 2005). In young families, the shape distributions of asteroids are very similar to the distributions obtained for fragments generated in laboratory impact

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http://dx.doi.org/10.1016/j.icarus.2015.09.038
0019-1035/

experiments. In old asteroid families, on the other hand, the shape distributions of asteroids are more spherical as impact-related phenomena occur (impact reshaping and impact-induced seismic activity are dominant processes in the late evolution of asteroid shapes). The shapes of larger asteroids are also more spherical due to self-gravitational effects (e.g., Capaccioni et al., 1984).

Michikami et al. (2010) investigated the shapes of boulders with sizes of 0.1–220 m on Asteroid 433 Eros using a few arbitrarily selected images taken by the NEAR spacecraft. Moreover, the shapes of small and fast-rotating asteroids (diameter < 200 m and rotation period < 1 h), which are natural fragments from previous impact events among asteroids, were inferred from archived light curve data taken by ground-based telescopes. The results show that the shape distributions of laboratory fragments are similar to those of the boulders on Eros and of the small and fast-rotating asteroids. One has to bear in mind, however, that almost all of the data about fragment shapes in the laboratory were obtained from catastrophic disruption.

The shapes of fragments in non-catastrophic disruption such as impact cratering would be different from those in catastrophic disruption (e.g., Lange and Ahrens, 1981) because the strength of the shock wave in the target is relatively weak and only the surface of the target is broken. Lange and Ahrens (1981) carried out impact experiments for water ice targets (at temperatures of 81 K and 257 K) in order to investigate the correlation among the shape of fragments, temperature and the degree of fragmentation (cratering, erosion, disruption, and total fragmentation). Their results show that the shapes of fragments in a weak disruption at 257 K are different from those in a catastrophic disruption. Therefore, the shapes of fragments are considered to reflect the degree of fragmentation of the target.

Although the experiment of Lange and Ahrens (1981) is the only laboratory experiment to research the shapes of fragments from non-catastrophic to catastrophic disruption, the data currently available are not sufficient to develop a comprehensive model that includes impact phenomena among asteroids. This is mainly for the following three reasons.

(1) Because Lange and Ahrens' study focused on the collisional interaction of icy planetary bodies, the impact velocities in the experiments are low (0.14–1 km/s) compared with the average impact velocity ($\sim$5 km/s) in the asteroid main belt. Of course, the dynamic disruption of silicate bodies is also different from those of icy bodies.
(2) Unfortunately, the data of the fragment shapes in impact cratering were not shown, although Lange and Ahrens carried out the impact experiments in the entire range from impact cratering to catastrophic disruption. As a reason, we think that the total number of fragments counted in impact cratering is very small, because in each shot only very few (several tens of) fragments were counted. In general, for the impact experiments using targets of similar size, fewer fragments are produced in impact cratering than in heavier disruptions.
(3) The shapes of fragments in the case of weak disruption (non-catastrophic disruption) are different in 257 K and 81 K ice targets. The fragment shapes in 81 K ice targets are similar to those for catastrophic disruption of basalt targets, and are independent of the degree of fragmentation. On the other hand, the shapes of fragments in 257 K ice targets depend on the degree of fragmentation. That is, in the case of 257 K ice targets, the shapes of fragments in a strong (catastrophic) disruption are similar to those for catastrophic disruption of basalt targets, while those in a weak disruption (many plate-like shaped fragments are seen) are different from those for a catastrophic disruption of basalt targets. The difference of the results in 81 and 257 K targets may be (according to the suggestion of the authors) due to the fact that it is difficult to produce the 81 K targets without numerous cracks and air bubbles. Lange and Ahrens (1981) pointed out that the growth rate in 81 K ice was much faster than that in 257 K ice, thus causing the 81 K targets to contain significantly more cracks and air bubbles. Indeed, their 81 K ice targets were much weaker than the 257 K ice targets. These cracks and air bubbles would affect the resulting shapes of the fragments. Therefore, we are confident that only a comparison of the data of 257 K ice targets with our experimental data is meaningful.

In this study, in order to investigate the shapes of fragments in the entire range from impact cratering to catastrophic disruption, impact experiments into silicate (basalt) targets with various sizes were carried out. The research described here is intended to constrain current interpretations of asteroid formation.

2. Experimental method

2.1. Target properties

The samples used as targets were fine-grained and very homogeneous basalts from Linxi, Inner Mongolia. The optical microscopic image of a thin section of the basalt is shown in Fig. 1a. The lath-like crystals are micro-phenocrysts plagioclase and their

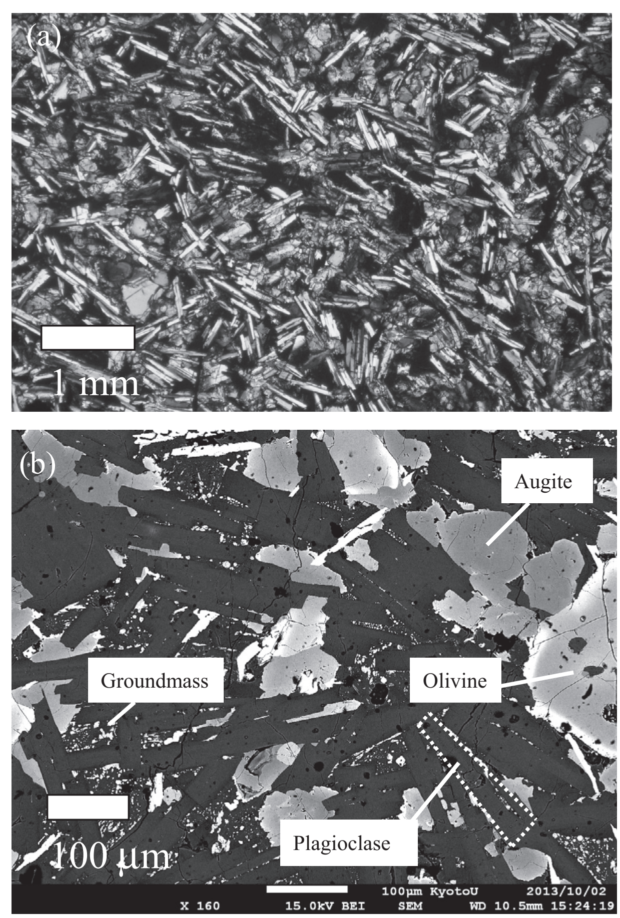

Fig. 1. Microscopic images of the basalt samples used as targets. (a) Optical microscope image of a thin section in crossed polarized light. (b) SEM back scattered electron image of the thin section.