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Correlation between fragment shape and mass distributions in impact disruption

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ABSTRACT

We propose that the shape of impact fragments reflects their fragmentation mechanisms; the fragmentation process that generates smaller fragments (fractal crack bifurcation) produces the shapes frequently observed in the previous studies, and those that generate larger fragments (spallation, random tessellation, and geometrical effects) produce flatter fragments. Fragment shape analyses derived from hypervelocity impact experiments in a variety of mass distribution ranges qualitatively support this view.

The shapes of the rock fragments created by impacts, which are often characterized by the tri-axial spatial dimensions, a, b, and c (ordered such that $a \geq b \geq c$), has been investigated since the first work by Fujiwara et al. (1978), and some remarkable features have been found. In particular, for a wide range of experimental conditions, the b/a and c/a ratios have mean values of ~0.7 and ~0.5, respectively (e.g., Fujiwara et al., 1989). Several studies on mechanism that could reproduce such fragment shape characteristics were carried out in the 1990s (e.g., Paolicchi et al., 1989; Verlicchi et al., 1994; Paolicchi et al., 1996; LaSpina and Paolicchi, 1996), but the question has since seen little attention.

For the past two decades, much of the information about small objects in the solar system such as asteroids and comets has been obtained from space exploration with onboard cameras, and this has made direct and detailed comparisons between natural objects and the results of impact disruption experiments possible (e.g., Nakamura et al., 2008; Michikami et al., 2010; Tsuchiyama et al., 2011, 2014). For example, Nakamura et al. (2008) found that the boulders on the Itokawa asteroid had similar shape distributions to those of laboratory rock impact fragments despite being several orders of magnitude different in size. These similarities suggest that the physics controlling the fragmentation processes does not change over a wide range of spatial scales. Such situation leads us to revisit the fragment shapes produced by catastrophic impact disruptions (e.g., Michikami et al., 2016, 2018; Durda et al., 2015).

In this note, we consider correlations between fragment shape and mass distribution. There are some at least two components to the fragment mass distributions (e.g., Fujiwara et al., 1977; Matsui et al., 1982; Takagi et al., 1984; Capaccioni et al., 1986; Fujiwara et al., 1989; Mizutani et al., 1990): one for smaller fragments that exhibits a power-law form that is largely independent of the experimental conditions, and another for larger ones that is strongly dependent on the impact conditions. The second component can be expressed in various ways, such as with two subcomponents (Takagi et al., 1984; Mizutani et al., 1990) or in an exponential form (e.g., Kadono, 1997a). Hereafter, we will call these components the "power-law" and "non-power-law" regions, respectively.

The differences between these size distributions suggest that they involve different fragmentation mechanisms, resulting in different fragment shapes. We suppose that small fragments in the power-law region are generated through fractal crack bifurcation, leading to the frequently observed average values of c/a and b/a, and large fragments in the non-power-law region are generated through spallation, random tessellation, and geometrical effects, leading lower average of c/a.

First, we consider the power-law region in the mass distributions. Hypervelocity impacts generate very rapidly forming and unstable cracks that bifurcate and create fractal networks. Since the fragments are surrounded by these crack networks, their mass dis-

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tributions should be related to the characteristics of the networks. This implies that power-law mass distributions are caused by the fractal nature of the cracks (e.g., Kadono and Arakawa, 2002; Aström, 2006). In fact, the mass distributions are only exponential in form when the cracks cannot bifurcate, such as for the fragmentation of metal rings (e.g., Grady and Benson, 1983; Grady and Kipp, 1985), rods (into fragments larger than the rod's diameter, e.g., Ishii and Matsushita, 1992; Kadono, 1997b), and liquids (e.g., Kadono and Arakawa, 2005; Villermaux, 2007; Kadono et al., 2008).

The fractal nature of the mechanism for generating small fragments is consistent with the fact that their mass distributions are largely independent of the impact and boundary conditions (e.g., Takagi et al., 1984), which would imply that their shapes should also be independent of the impact conditions. This has been actually seen in most previous experiments, which have shown features that are robust over a wide range of different experimental conditions. The shape distributions of fragments in power-law regions should thus reflect the self-similar fractal crack networks and the average values of b/a and c/a are expected to be provided as ~0.7 and ~0.5, respectively. However, describing crack behaviors such as bifurcation and coalescence theoretically is a rather complex problem (e.g., Lawn, 1993), so it is currently difficult to evaluate the fragment shape distributions precisely. Numerical simulations will be probably required to investigate the relationships between fractal crack networks and fragment shape distributions quantitatively, but these are beyond the scope of this paper.

Next, we consider the mechanisms for generating larger fragments. Giblin et al. (1994) found, during explosive tests on a spherical target, that a large thin cap-like fragment detached from the antipodal point (Fig. 9 of Giblin et al. (1994)). In addition, Durda et al. (2015) found that plate-like fragments were created near the core. At certain points in targets (e.g., core, surfaces, and antipodal point), the shock and the subsequent expansion waves play central roles in the fragmentation process, generating large flat (lower c/a) fragments through "peeling off", that is, spallation (e.g., Melosh, 1984).

Mass distributions in non-power-law region are sometimes exponential in form (e.g., Kadono, 1997a), which may be due to random tessellations. For example, randomly cutting a target with a volume of V into N fragments gives a distribution of the form $\sim\exp[-v/v_0]$, where v is the fragment volume and v_0 is the characteristic (average) fragment volume V/N (e.g., Gilvarry, 1961; Grady, 1990). The form of the size distribution directly reflects the impact and target conditions (here, N and V), so random tessellation may also contribute to the production of larger fragments. La Spina and Paolicchi (1996) investigated the fragment shapes generated by random tessellation and showed that the average of c/a was low, ~0.2–0.3, as shown in their Table 1 (the corresponding b/a ratio was ~0.6–0.7). Stochastic processes (e.g., random tessellation) are therefore another mechanism for generating large flat fragments with lower c/a ratios.

The target shape should also affect the mass distributions of larger fragments and also perhaps, their shapes (e.g., Paolicchi et al., 1996). Durda et al. (2015) found that the fragment shapes were not significantly dependent on the shape of irregular targets ($C/A \sim 0.5$, where C and A are the target's shortest and longest dimensions, respectively), and Michikami et al. (2016) showed that "slab" targets (with $C/A \sim 0.1$) resulted in smaller c/a ratios. Hence, in the cases that original targets have rather irregular shape ($C/A <\sim 0.1$), geometry effect may appear and decrease c/a, although systematic additional studies will be needed to investigate the dependence of the fragment shape on target geometry in detail.

Thus, though there are several mechanisms that generate the fragments in the non-power-law region, any of these mechanisms seem to generate flatter fragments.

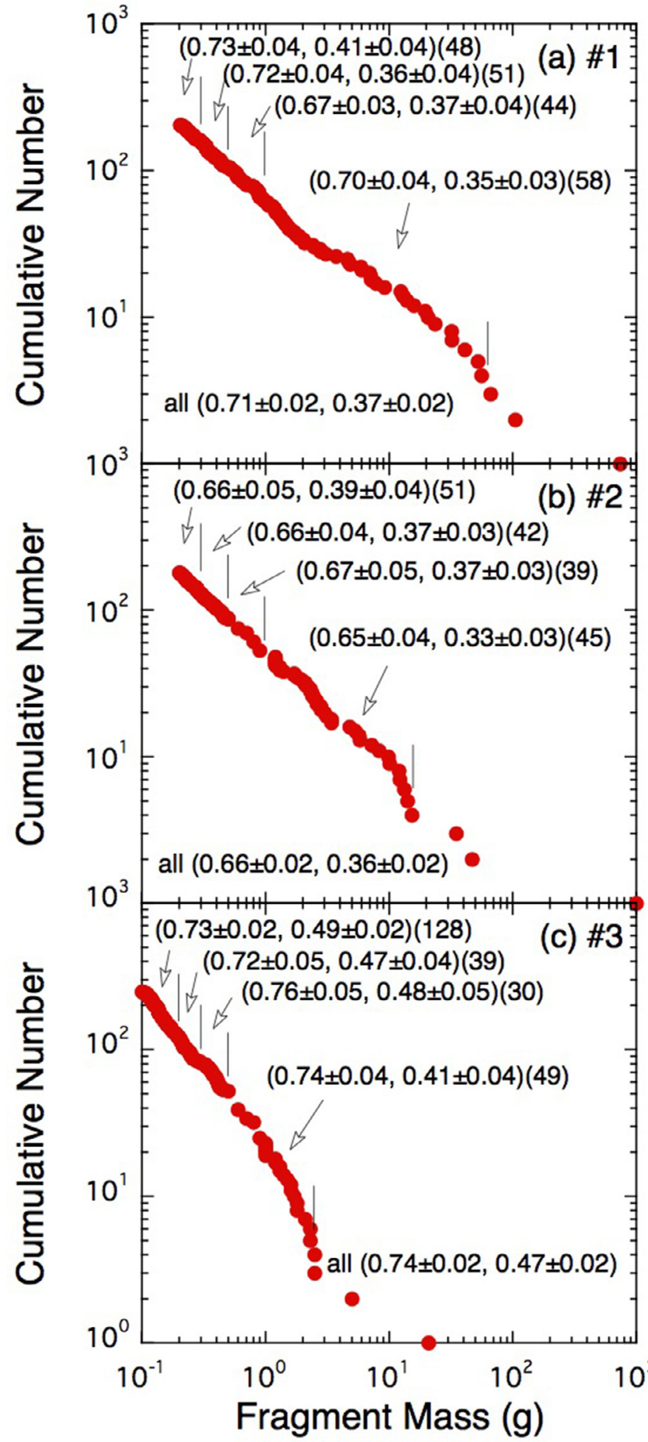

Fig. 1. The cumulative number distributions as a function of fragment mass for (a) shot #1, (b) shot #2, and (c) shot #3. The average values of fragment shape parameters b/a and c/a are shown for different fragment mass ranges with > 1.0 g, 1.0–0.5 g, 0.5–0.3 g, and 0.3–0.2 g for shots #1 and #2, and > 0.5 g, 0.5–0.3 g, 0.3–0.2 g, and 0.2–0.1 g for shot #3. The number in the parenthesis following the average values of b/a and c/a in each range indicates the number of the fragments in this range. The largest three fragments are excluded for each shot from the shape measurement process because these fragments appeared to be outliers with respect to the mass distributions. The averages and its errors are evaluated by the bootstrap method.