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Interpretations of family size distributions: The Datura example

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A R T I C L E I N F O

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A B S T R A C T

Young asteroid families are unique sources of information about fragmentation physics and the structure of their parent bodies, since their physical properties have not changed much since their birth. Families have different properties such as age, size, taxonomy, collision severity and others, and understanding the effect of those properties on our observations of the size-frequency distribution (SFD) of family fragments can give us important insights into the hypervelocity collision processes at scales we cannot achieve in our laboratories.

Here we take as an example the very young Datura family, with a small 8-km parent body, and compare its size distribution to other families, with both large and small parent bodies, and created by both catastrophic and cratering formation events. We conclude that most likely explanation for the shallower size distribution compared to larger families is a more pronounced observational bias because of its small size. Its size distribution is perfectly normal when its parent body size is taken into account. We also discuss some other possibilities. In addition, we study another common feature: an offset or "bump" in the distribution occurring for a few of the larger elements. We hypothesize that it can be explained by a newly described regime of cratering, "spall cratering", which controls the majority of impact craters on the surface of small asteroids like Datura.

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1. Introduction

Asteroid families are groups of asteroids of a common origin, first recognized by Hirayama (1918). They originate from material cast off from one minor body during an impact from another. That impact can be a cratering event, with a small part of the parent body being removed; or a catastrophic event, with a complete breakup into smaller pieces. Although the most prominent reported families were created from asteroids larger than 100 km, the discovery of families with smaller parent bodies has become possible using larger telescopes dedicated to discovering asteroids, by using more sophisticated numerical methods of searching for families in large datasets, and generally from a more concentrated effort of asteroid family research. That is very important because asteroid families are unique natural laboratories of breakup physics on scales we cannot study in our experimental facilities. The fragment properties contain information on the interior of the parent asteroid and provide us with important constraints of the asteroid physical properties. However, interpretations are required to extract that information. Those interpretations must be based on an understanding of how the family-forming event depends on the parameters of the bodies and the impact.

Our observations give us the size-frequency distribution (SFD) of family fragments. That distribution commonly has a number of recognizable characteristics—the separation of the second largest and the largest fragment in size, the slope of a first power-law part, a bend-over of the steep part to a shallower slope, an offset in sizes observed at larger fragments in some families and so on. All of these are probably an imprint of the break-up process and the properties of the parent asteroid. This information can be seriously confused by the presence of interlopers in the SFD. Those are asteroids with similar proper elements but no relation to a family whatsoever (Migliorini et al., 1995). There are several methods to remove interlopers from the family list which use various physical properties (albedos, colors, spectra) together with the proper elements to identify asteroid families without interlopers (Parker et al., 2008; Masiero et al., 2013; Carruba et al., 2013). Moreover, size dependence of the fragment ejection velocity and the Yarkovsky drift (Vokrouhlický et al., 2015) can put additional constraints on the family membership (Nesvorný et al., 2003).

Understanding those data will enable us to understand collisional physics at large scale, for various impact conditions, and for various asteroid types. This can help us create better fragmentation models for Solar System evolution models and, in turn, leads to a better description of the Solar System history. Here we consider and interpret the SFD of one young and interesting family with small members, the Datura family (Vokrouhlický et al., 2017).

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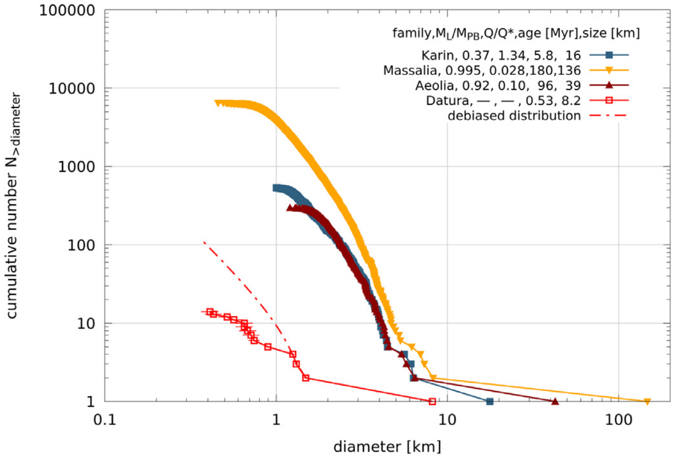

Fig. 1. Observed (red open squares) and an example debiased (red dot-dashed line, Vokrouhlický et al., 2017) size distribution of the Datura family compared to larger-member families created by cratering, and to the Karin family produced by a catastrophic disruption. Note that Datura family members are much smaller than the majority of members of other families in the plot. In the plot legend we give estimates of the family's fraction of largest to parent body mass, severity of the impact as measured by the Q/Q^* ratio, age and size of the largest member. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

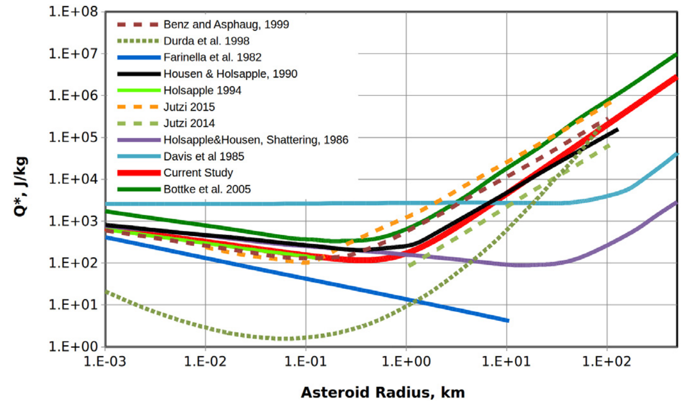

Fig. 2. The Q^* curve we use in the present study (thick red solid line), we used $\mu = 0.55$ for non-porous rock-like materials in this plot. Shown in the plot are also estimates of the Q^* from selected previous studies [Davis et al. (1985), Durda et al. (1998), Farinella et al. (1982), Holsapple and Housen (1986), Jutzi (2015), Jutzi and Michel, 2014]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. The Datura family

The Datura family in the Main Belt (MB) was discovered and recognized as a very young family by Nesvorný et al. (2006). At that time, seven members of that family were known, 1270 Datura being the largest of them. Its age was calculated by numerically tracking family members' present trajectories backward in time resulting in a 450 ± 50 kyr estimate. That value was revisited by Vokrouhlický et al. (2009), and the current estimate is 530 ± 20 kyr. This relatively young age makes this family a very interesting group that can provide important insights into large-scale fragmentation and other physical processes that affect asteroids after their formation.

Rosaev and Plávalová (2015) found three new members of the Datura family, and later Vokrouhlický et al. (2017) presented a wealth of new data on that family: they extended its population to 17 members and two candidate members. They were able to derive spins for the six largest members and shapes of the four largest known members. The shape of the largest, 1270 Datura, was derived by Vokrouhlický et al. (2009). It is spinning rather fast (3.36-h period) and its shape is moderately elongated. On the other hand, the next three smaller members are all very elongated and slow rotators. Because the total mass of the known fragments compared to 1270 Datura is small, Vokrouhlický et al. (2017) concluded that the Datura family was formed by a cratering event in which the impact energy was much less than that for a catastrophic collision. They also derived a debiased fragment size distribution using a well-studied detection efficiency function of the Catalina Sky Survey. They noted that the size distribution of the Datura family is shallower than size distributions of other cratering families which originate from larger parent bodies.

2.1. The Datura family size distribution

Datura's size distribution is compared to other asteroid families in Fig. 1, along with the families in Vokrouhlický et al. (2017). We added one more cratering family, Aeolia, to present a wider range of family characteristics. We also show the debiased distribution as derived by Vokrouhlický et al. (2017). Note that we have chosen the distribution shown in the upper panel of their Fig. 16 to illustrate what the real distribution might look like. From the second largest and smaller, it is a two-part power-law distribution. The first part (larger fragment sizes) is steeper (the slope of −5.36 in this case) and the second part (smaller fragments) is shallower (the slope of −2.11). The transition (or break-point) size where the slope of the distribution changes is 1.08 km.

It is the flattening of the second part that we first consider. We recognize that some flattening of slope must be present in any size distributions at some small member size, because of the necessity of mass (volume) conservation. That is, the slopes of the family size cumulative distributions are usually quite steep, but a slope more negative than −3 cannot apply for increasingly smaller sizes, because the total volume of the fragments would then integrate to infinity. Thus there must be eventually some transition size at which the slope changes to some smaller value.

However, in this plot using the members' absolute sizes, it is apparent that other families also have a significant slope change beginning at about the same body size of about 2 km, not where the total family fragments mass approaches that of the putative parent body. That suggests that the feature is not real, but is simply due to an observational completeness limit due to natural biases of astronomical observations. Those biases are caused by the finite limiting magnitude of objects observable with our telescopes, resulting in a rapid decrease of the detection efficiency below that size. The fact that there remains some range of sizes at which the kick-over occurs for various families can easily be attributed to different albedos and distances at which those asteroids orbit the Sun in the Main Belt, both of which affect their brightness. So we propose that the shallower slope of the second part of the Datura family size distribution is not so surprising, because that shallow slope is the same as we observe in other families. It is due to the observational biases.

2.2. Further comparisons

A major factor affecting the SFD's is the severity of the impact. In terms of the impactor mass m_p, its velocity U and the target mass M, the energy per unit mass of an impact is given by $Q = ½ m_p U^2 / M$. That value can be compared to the specific energy Q^* required to catastrophically disrupt and disperse the target body using the $qratio = Q/Q^*$. The values of Q^* are given in other studies, including in Holsapple et al. (2002). In Fig. 2 we give our current estimate of the Q^* curve, an updated version of that in Holsapple et al. (2002) and compare it to some previous studies.

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