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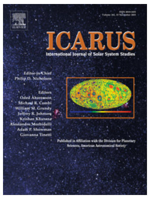

Impact simulation in the gravity regime: Exploring the effects of parent body size and internal structure

P.G. Benavidez[a,b,*], D.D. Durda[c], B. Enke[c], A. Campo Bagatin[a,b], D.C. Richardson[d], E. Asphaug[e], W.F. Bottke[c]

[a] *Departamento de Física, Ingeniería de Sistemas y Teoría de la Señal. P.O. Box 99, 03080 Alicante, Spain*
[b] *Instituto Universitario de Física Aplicad a la Ciencias y la Tecnología*
[c] *Southwest Research Institute, 1050 Walnut Street, Suite 300 Boulder, Colorado 80302 USA*
[d] *Department of Astronomy, University of Maryland, College Park MD, 20742 USA*
[e] *Arizona State University, Tempe, AZ*

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ABSTRACT

In this work we extend the systematic investigation of impact outcomes of 100-km-diameter targets started by Durda et al. (2007) and Benavidez et al. (2012) to targets of D = 400 km using the same range of impact conditions and two internal structures: monolithic and rubble-pile. We performed a new set of simulations in the gravity regime for targets of 400 km in diameter using these same internal structures. This provides a large set of 600 simulations performed in a systematic way that permits a thorough analysis of the impact outcomes and evaluation of the main features of the size frequency distribution due mostly to self-gravity. In addition, we use the impact outcomes to attempt to constrain the impact conditions of the asteroid belt where known asteroid families with a large expected parent body were formed. We have found fairly good matches for the Eunomia and Hygiea families. In addition, we identified a potential acceptable match to the Vesta family from a monolithic parent body of 468 km. The impact conditions of the best matches suggest that these families were formed in a dynamically excited belt. The results also suggest that the parent body of the Eunomia family could be a monolithic body of 382 km diameter, while the one for Hygiea could have a rubble-pile internal structure of 416 km diameter.

1. Introduction

Our understanding of the collisional evolution of populations of small bodies in the Solar System is based on knowledge of details of collisional physics, from the formation of impact craters to the destruction of the entire bodies. The key parameter traditionally used to study these impact outcomes is the specific impact energy, Q (kinetic energy of the projectile divided by the target mass). Studies of such fragmentation processes have given rise to what is commonly referred to as scaling laws. These consist of determining the critical specific energy (denoted by Q^*_D) required to disperse a target into a spectrum of individual and possibly reaccumulated objects, the largest one having half the mass of the original target. Consequently, Q^*_D is a function of target size, where two main regimes are identified: smaller bodies in the strength regime, where self-gravity is not important for holding the object together; and larger bodies in the gravity regime, where fragments can reaccumulate via the self-gravity of the components. The strength-scaling regime for small objects is mostly examined through laboratory impact experiments (e.g., Fujiwara et al., 1977, Arakawa 1999; also see Leliwa-Kopystyski and Arakawa 2014 for a review) while the impact outcomes of larger bodies are studied using numerical simulations.

In this latter case, Benz and Asphaug (1999) used a smoothed-particle hydrodynamics (SPH) method to simulate impacts into rocky and icy bodies in a large range of sizes. They found that gravity plays a dominant role in determining the outcome of collisions even involving relatively small targets. For example, in the size range considered in their work, from 3 cm to 100 km in radii, the enhanced role of gravity is not so much to prevent fracture prevention by gravitational compression, but rather to impede the escape of fragments due to their mutual gravitational attraction. Jutzi et al. (2010) performed simulations in the same size range as Benz and Asphaug (1999). Their results confirm that Q^*_D first decreases with target size in the strength regime (i.e., up to a few hundred meters in diameter) and then increases with target size

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[*] Corresponding author: Departamento de Física, Ingeniería de Sistemas y Teoría de la Señal, Universidad de Alicante, P.O. Box 99, 03080 Alicante, Spain.
E-mail address: paula.benavidez@ua.es (P.G. Benavidez).

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in the gravity regime (see Asphaug et al., 2002; 2015; Jutzi et al., 2015 for reviews). In addition, they found that in the strength regime a porous body requires more energy to be disrupted than its non-porous counterpart while in the gravity regime the situation is reversed but the difference remains small.

The size spectrum of individual fragments produced in a catastrophic disruption is the so-called the size frequency distribution (SFD), usually expressed by a power law of the form $N(>D) \propto D^q$ (the cumulative representation). When this function is represented in a log-log plot we obtain a line with a slope of q, $q<0$ such that there are more small bodies than big ones. The particular morphologies of SFDs have been used to characterize the impact outcomes of a range of targets. For example, in the case of a monolithic non-porous parent body, higher impact energies lead to a more continuous[1] fragment size distribution (Michel et al., 2003; Michel et al., 2004; Durda et al., 2007). Furthermore, Michel et al. (2003), considering pre-shattered non-porous targets with diameters of about 25 km, found that the SFD tends to be more continuous than those of monolithic non-porous targets (2). Durda et al. (2004) also investigated the efficiency of satellite formation during catastrophic disruptions. Subsequently, Durda et al. (2007) and Benavidez et al. (2012) analyzed, in a systematic way, the mean features resulting from impacts on both rubble-pile and monolithic parent bodies with diameters of 100 km. They showed that low-energy impacts into rubble-pile and monolithic targets produce different features in the resulting SFDs and that these are potentially diagnostic of the initial conditions for the impact and the internal structure of the parent bodies of asteroid families. In contrast, super-catastrophic events (i.e., high-energy impacts with large specific impact energy) result in SFDs that are similar to each other.

Many authors have used the fragment SFDs produced by various kinds of impact simulations to glean insights into parent body sizes and disruption conditions for asteroids families (e.g., Tanga et al., 1999, Durda et al., 2007; Benavidez et al., 2012). In particular, several authors have used the results of SPH codes to explore the disruption of $D>$ 100-km-diameter parent bodies. Basically, what these studies do is to plot to the same scale the modeled SFD and the observed family SFD in a single chart. Modeled impacts assume a particular target size; therefore, the resulting largest remnant and SFD of associated fragments may need to be offset in size to the left or right to match the observed SFD. This offset suggests a larger or smaller parent body for the observed family. However, in some cases, especially when the parent body is actually quite different in size from the particular modeled target (usually 100-km-diameter), the methodology used to date could provide results that are not entirely accurate. Specifically, the SFDs of $D>>$ 100-km-diameter targets could have significantly different features compared to those for a $D=100$ km target, i.e., relative mass of the largest fragment and/or the SFD slope of smaller fragments. This is because the effects of gravity in the reaccumulation process of such larger bodies do not simply scale linearly. It is worth mentioning that such an approach to match the SFD is the lowest-order approximation; it is merely a first approximation for estimating the parent body size for an observed family. Ideally, one would use this technique to then run another matrix of simulations using a suite of parent-body targets with diameters around that predicted from the SFD 'shift' approximation, like the Karin family simulations of Nesvorný et al. (2006).

The asteroid belt in general, and asteroid families in particular, provides an outstanding natural laboratory for exploring the outcomes of collisional events in a wide range of sizes. These populations allow us to study both the collisional formation process of the Solar System and its subsequent evolution over time. However some numerical models of the collisional evolution of main-belt asteroids, which use as input the impact outcomes mentioned in the previous paragraph, can have difficulty reproducing the observed SFDs of asteroid families. For example, Cibulkova et al. (2014) propose a new six-part collisional model of the asteroid belt. Relying on the collisional origin of asteroids families, this study assessed whether the number of synthetic asteroid families created during the simulation agrees with the number of observed families. Then, they considered to two models: monolithic and rubble-pile asteroids, concluding that monolithic asteroids are in best agreement with the observations compared to the rubble-pile counterpart. However they do not discard the possibility that some part of the asteroid population could be consistent with rubble-pile structures. There are many possible reasons for this – family members lost to resonances, collisional evolution, interlopers in the family, and so on. Here we focus on one particular issue, namely whether the fragment SFDs made by the disruption of $D=100$-km-diameter parent bodies are a good match to the fragment SFDs made when larger worlds break up ($D=400$ km). On the other hand, another issue where SPH/N-body impact outcome became useful is constraining the amount of mass hidden below our current detection limits (Bottke et al., 2005). In order to do this it is necessary to compare the observed families to the scaled impact outcomes, following the procedure explained in the previous paragraph. These examples highlight the need to extend SPH simulations to larger targets, in order to test the known scaling laws for larger targets and characterize the resulting SFDs for different impact conditions.

While the existence of monolithic large bodies (about $D=400$ km) is broadly accepted, the existence of rubble-pile bodies of such size is controversial. However, we allow the possibility in the present study. On the other hand, Durham et al. (2005) considered ice bodies and found that ~1000 km ice bodies (if cold) can have some residual porosity at pressures of 100 MPa, typical of asteroid cores. Theory and observation indicate that everything bigger than a few 100 km in diameter would have melted if formed in the inner solar system in the first few Ma, so a 400-km-diameter rubble-pile would have to be a second-generation object, or else something that accreted after a few Ma (e.g., far from the Sun). The study by Campo Bagatin et al. (2001) on the abundance of rubble-piles in the main belt found that -under specific conditions- the presence of rubble-piles up to 500 km diameter cannot be ruled out.

Based on the evidence mentioned in the preceding paragraphs, we have decided to extend the systematic investigation of impact outcomes started by Durda et al. (2007) and Benavidez et al. (2012) to 400-km-diameter targets using the same range of impact conditions and two internal structures: monolithic and rubble-pile. In Section 2 we briefly recall the numerical method used to perform the simulations. In Section 3 the results of the comparison between our systematic numerical investigations of rubble-pile versus monolithic targets are presented. In Section 4 a comparison between results from our numerical models and observed asteroid families is discussed. Finally, in Section 5, we present our conclusions.

2. Method

In this work we performed a series of simulations with the same numerical technique used in our previous impact simulation studies (Durda et al., 2004; Benavidez et al., 2012), which is essentially the same numerical scheme introduced by Michel et al. (2001, 2002) to study the formation of asteroid families. As this technique is widely accepted and fully described in the mentioned

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[1] This term is used by Michel et al. (2003) to mean that the SFD contains intermediate-sized bodies.

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