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Catastrophic disruption of asteroids and family formation: a review of numerical simulations including both fragmentation and gravitational reaccumulations

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Abstract

In the last few years, thanks to the development of sophisticated numerical codes, a major breakthrough has been achieved in our understanding of the processes involved in small body collisions. In this review, we summarize the most recent results provided by numerical simulations, accounting for both the fragmentation of an asteroid and the gravitational interactions of the generated fragments. These studies have greatly improved our knowledge of the mechanisms that are at the origin of some observed features in the asteroid belt. In particular, the simulations have demonstrated that, for bodies larger than several kilometers, the collisional process not only involves the fragmentation of the asteroid but also the gravitational interactions between the ejected fragments. This latter mechanism can lead to the formation of large aggregates by gravitational reaccumulation of smaller fragments, and helps explain the presence of large members within asteroid families. Numerical simulations of the complete process have thus reproduced successfully for the first time the main properties of asteroid families, each formed by the disruption of a large parent body, and provided information on the possible internal structure of the parent bodies. A large amount of work remains necessary, however, to understand in deeper detail the physical process as a function of material properties and internal structures that are relevant to asteroids, and to determine in a more quantitative way the outcome properties such as fragment shapes and rotational states.

Keywords: Asteroids composition; Asteroids dynamics; Collisional physics; Impact processes

1. Introduction

Collisional events are of great importance in the formation and evolution of planetary systems, including our own Solar System. In the first stages of planetary formation, low-speed collisions between planetesimals drive planetary growth by collisional accretion. In the particular case of our Solar System, some energetic events also started to take place quite early on, as indicated by the iron-rich composition of the planet Mercury, which can be explained by the ejection of its original mantle due to a giant impact (Benz et al., 1988). The Moon of our Earth is also understood as the product of ejected debris reaccumulation resulting from the impact of a planetesimal with our proto-Earth (e.g. Ward and Canup, 2000). When planetary embryos interacted and in further stages, once the planets were formed, relative speeds between small bodies increased as a result of planetary perturbations. Consequently, our Solar System entered a new regime of high-impact energy, in which it continues to evolve. In this regime, collisions no longer lead to accretion phenomena, but rather to disruptive events. Meteorites collected on Earth are another indication of this collisional activity as they are the remnants of collisions that took place in the asteroid Main Belt between the orbits of Mars and

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Jupiter. Collisions represent an important threat against human efforts in space, and can even lead to the destruction of our biosphere. The collisional process is therefore not a second-order problem in the understanding of the past, present, and future history of our Solar System; it is actually at the heart of its formation and evolution.

The scales of the phenomena that are involved in planetary and small-body impacts are far larger than those reached in laboratory experiments. Extrapolations by 15 orders of magnitude in mass are necessary to achieve ranges that are relevant to asteroids and planetesimals. Analytical models of catastrophic collisions try to fill this gap by establishing dimensionless relationships between the projectile size, the impact speed, the target strength, the target density, etc. that are supposed to be valid at all scales, and which are collected in the so-called *Scaling Laws* (see e.g. Housen and Holsapple, 1990). Nevertheless, such relationships are necessarily idealized, as they assume a uniformity of the process as well as a structural continuity. Consequently, they cannot predict with a high degree of reliability large-scale impact outcomes.

It is now possible to numerically simulate an impact with useful accuracy using numerical codes developed in recent years and accompanied with the improvement of computer performance. Important problems can now be addressed concerning the physical nature of individual objects with a collisional history, the origin of asteroid families, the formation of planets through collisional accretion, etc. Impact experiments in the laboratory are vital to validate those numerical models at small scales before they are applied to large-scale events. In the 1990s, a hydrodynamical code (hydrocode) based on the *Smooth Particle Hydrodynamics* method (SPH) was developed by Benz and Asphaug (1994, 1995). The code also included a model of brittle failure. It has successfully reproduced the results of centimeter-scale laboratory experiments. However, in the size range adapted to Solar System small bodies (>100 m), its use alone is insufficient as it is limited to the computation of the fragmentation of a solid body, whereas at those scales the role of gravity can strongly influence the collisional outcome. Indeed, it has been realized that in a collision involving large bodies, ejected fragments produced by the fragmentation process alone can actually interact gravitationally. Therefore, some reaccumulation can occur when relative speeds between fragments are below their mutual escape speeds, and can eventually lead to a distribution of large aggregates (Michel et al., 2001, 2002, 2003; Richardson, 1994). Accounting only for the fragmentation phase and neglecting the gravitational one would prevent the formation of such bodies and would then lead to different outcome properties that may not correspond to real ones.

To determine whether both our understanding of the collisional process and our methods to simulate it are correct, we have at our disposal a unique laboratory at the appropriate scales: asteroid families. More than 20 asteroid families have been identified in the asteroid belt, each corresponding to a group of small bodies sharing the same spectral and dynamical properties (see e.g., Knezěvic̀ et al., 2002; Zappalà et al., 2002). This similarity of properties has suggested that all members within a group belonged to a larger asteroid, called the parent body, that was catastrophically disrupted by an impact with a smaller projectile at high speed (Hirayama, 1918). Therefore, each asteroid family constitutes the outcome properties of a collisional event at large scales, and any numerical model must be able to reproduce the main charateristics of this outcome to assess its validity.

This paper reviews the recent results of numerical simulations that successfully reproduced for the first time the main properties of asteroid families formed in different impact energy regimes, from barely disruptive to highly catastrophic. The method used to obtain these results is briefly recalled in Section 1. Section 2 presents the outcome properties obtained by simulating the disruption of monolithic parent bodies, while the outcome properties obtained by disrupting pre-shattered parent bodies are given in Section 3. Section 4 presents some conclusions and perspectives.

2. Numerical method

The most recent simulations of a large asteroid (kilometer-size at least) breakup as a result of the impact of a projectile have divided this process in two phases. First, the fragmentation phase is computed using a three-dimensional SPH code. Once fracture ceases to propagate, the hydrodynamic simulations are stopped and intact fragments are identified. Typically, for the collisions considered here, the bodies are totally shattered into fragments of mass equal to our mass resolution. This corresponds to boulder sizes of ≈ 1–4 km. These fragments and their corresponding velocity distributions are then fed into an N-body code which computes the dynamical part of the evolution of the system over several days. In the following sections, a brief description of these codes is presented.

2.1. Numerically simulating the fragmentation phase

The 3D Lagrangian hydrocode developed by Benz and Asphaug (1994, 1995) represents the state-of-the-art in numerical computations of dynamical fracture of brittle solids. This code solves in a Lagrangian framework the usual conservation equations (mass, momentum, and energy) in which the stress tensor has a non-diagonal part, the so-called deviatoric stress tensor for which the rate of change is assumed to be proportional to the strain rate (Hooke's law). The so-called Tillotson equation of state for basalt is generally used for problems related to asteroid disruption (Tillotson, 1962; Michel et al., 2004). It has the advantage of being computationally expedient while sophisticated enough to allow its application over a wide range of physical conditions. Plasticity is introduced by suitably modifying the stresses beyond the elastic limit using a von Mises yielding relation. For the lower tensile stresses associated with brittle failure, a fracture model based on the nucleation of incipient flaws whose number density is given by a Weibull distribution (Weibull, 1939; Jaeger and Cook, 1969) is then used.

Computationally, the code uses the method called smooth particle hydrodynamics (SPH). Complete details about this method can be found in a review by Benz (1990). Basically, the value of the different hydrodynamics quantities are known at a finite number of points which move with the flow. Starting from a spatial distribution of these points (called particles), the SPH technique allows computation of the spatial derivatives without the necessity of an underlying grid. Once these derivatives have been computed and forces determined, the system is integrated over time in usual ways. Thus, this technique avoids the use of a grid and differs widely from grid-based methods not only conceptually but also because of the numerical requirements and algorithms that allow good efficiency. Using this technique, the 3D SPH hydrocode is then able to simulate consistently from statistical and hydrodynamical points of view the fragments that are smaller or larger than the chosen resolution (number of SPH particles). Statistical flaws (microscopic) are propagated at the particle scale according to the Grady–Kipp fracture model (Grady and Kipp, 1980), while actual flaws (macroscopic) are solved in a manner that does not depend on the resolution. The method thus guarantees that any increase in resolution does not alter the physics of fracture, but only modifies the accuracy. The reader interested in all the details of this code can refer to Benz and Asphaug (1994, 1995).

The resulting system has been used to predict the sizes, positions, and velocities of the largest fragments of laboratory experiments with a very good accuracy.

2.2. *Gravitational phase: large-scale simulations*

The fragmentation of an asteroid larger than tens of kilometers can generate several 10^5 kilometer-size fragments. The early stages of the gravitational evolution of these fragments is still part of the collisional process. Current readily available computer resources are insufficient to simulate this phase in reasonable time using traditional N-body codes based on direct force calculations. Indeed, the CPU time required to compute the evolution of N particles with such codes scales with N^2.

The most recent results obtained on the collisional process at asteroid scales have taken advantage of the creation of new and fast methods to compute N-body interactions. More precisely, a modified version of a cosmological N-body code, called `pkdgrav`, which is based on the so-called hierarchical tree method, has been used to compute the gravitational interactions (see e.g. Richardson et al., 2000). This code can be run on both shared-memory and distributed-memory parallel architectures. The tree component of the code provides a convenient means of consolidating forces exerted by distant particles, reducing the computational cost (Barnes and Hut, 1986). The parallel component divides the work evenly among available processors, adjusting the load each timestep according to the amount of work done in the previous force calculation. The code uses a straightforward second-order leapfrog scheme for the integration and computes gravity moments from tree cells to hexadecapole order.

An important aspect of the gravitational phase is that some fragments may reaccumulate with each other, depending on their relative velocities, to form larger bodies. Therefore, it is necessary to account for this aspect in the computation. A big advantage of `pkdgrav` is that it treats collisions and mergers between particles. Indeed, particles are considered to be finite-sized hard spheres and collisions are identified each step using a fast neighbor-search algorithm. Whenever two fragments collide they can merge, creating a new fragment located at and moving with the center of mass of the system, and with a mass equal to the sum of the individual masses. The radius of the new fragment is computed from knowing the mass and the density and assuming a spherical shape. A merging criterion based on relative speed and angular momentum is defined such that fragments are allowed to merge only if their relative speed is smaller than their mutual escape speed and when the resulting spin of the merged fragment is smaller than the threshold value for rotational fission. Non-merging collisions are modeled as bounces between hard spheres whose post-collision velocities are determined by the amount of dissipation taking place during the collisions. The latter is determined by the coefficients of restitution in the tangential and normal directions (see Richardson, 1994, for details on this computation). Since the values of these coefficients are poorly constrained, they are arbitrarily set equal to 0.5 in the results presented below.

Despite the sophistication of the code, the computation of the gravitational phase still contains some simplifications and a great amount of work remains necessary (and is under way) to increase the degree of realism. In particular, fragment shapes are currently not accounted for, as all particles remain spherical and aggregates formed by reaccumulation are represented by a single spherical particle of equivalent mass and momentum.

3. Current understanding and latest results

In the following, the most recent results obtained by simulating numerically the catastrophic disruptions of large asteroids are reviewed.

Asteroid families represent a unique laboratory that Nature provides to study large-scale collisional events. Indeed, observed asteroid families in the Main Asteroid Belt are each composed of bodies which originally resulted from the break-up of a large parent body (e.g. Hirayama, 1918; Marzari et al., 1995).

Interestingly, until recently, the theory of the collisional origin of each asteroid family rested entirely on the similarities in dynamical and spectral properties of its members and not on the detailed understanding of the collisional physics itself. Indeed, laboratory experiments on centimeter-scale targets, analytical scaling rules, or even complete numerical simulations of asteroid collisions were not able to reproduce the physical and dynamical properties of asteroid families (e.g. Ryan and Melosh, 1998). The extrapolation of laboratory experiments to asteroidal scales yields bodies much too weak to account for both the mass spectrum and the dynamical properties of family members. More precisely, in a collision resulting in a mass distribution of fragments resembling a real family, which can contain many big members, the ejection speeds of individual fragments are much too small for them to overcome their own gravitational attraction. The parent body is merely shattered but not dispersed and therefore no family is created. Conversely, matching individual ejection speeds and deriving the necessary fragment distribution results in a mass spectrum in which no big fragment is present, contrary to what is indicated by most real families (e.g. Davis et al., 1985; Chapman et al., 1989).

The collisional origin of asteroid families thus implies that not only has the parent body (up to several hundreds of kilometers in size) been shattered by the propagation of cracks but also that the fragments generated this way typically escape from the parent and reaccumulate elsewhere in groups in order to build up the most massive family members. Such a process had already been suggested (e.g. Chapman et al., 1982), and the possibility that at least the largest fragment from a collision consists in a rubble pile had also been indicated later by means of numerical simulations (Benz and Asphaug, 1999). The effect of gravitational reaccumulation was then estimated by a procedure which consists of searching for the largest group of gravitationally bound debris immediately following the collision, and not in computing explicitly the gravitational interactions between the fragments. More recently, the formation of many large family members by reaccumulation of smaller fragments was demonstrated explicitly by Michel et al. (2001, 2002, 2003, 2004).

Such aggregates of gravitationally bound fragments, as the ones formed in the most recent simulations, are usually defined as *rubble piles* or more rigorously *gravitational aggregates* in the asteroid community, which means that they are loose aggregates of fragments held together by gravity. A detailed definition and a review of this topic are presented in Richardson et al. (2002). Roughly, such bodies have little to no tensile strength, i.e. they can be torn apart easily by planetary tides. Only indirect evidence for such structures exist. Indeed, the structural properties of asteroids are difficult to establish since directly measurable quantities do not distinguish between solid bodies and rubble piles. Rubble piles have been invoked to explain, for instance, the low density of some observed bodies like 253 Mathilde whose measured density by the *NEAR* probe is $1.35\,\mathrm{g/cm^3}$ (Yeomans et al., 1997), or the lack of fast rotators among asteroids with sizes larger than a few hundreds meters (Pravec and Harris, 2000).

For the first time, we have simulated entirely and successfully the formation of asteroid families in two extreme regimes of impact energy leading to either a small or a large mass ratio of the largest remnant to the parent body $M_{\mathrm{lr}}/M_{\mathrm{pb}}$ (Michel et al., 2001). Two well-identified families were used for comparison with simulations: the Eunomia family, with a 284-km parent body and $M_{\mathrm{lr}}/M_{\mathrm{pb}} = 0.67$, was used to represent the barely disruptive regime, whereas the Koronis family, with a 119-km parent body and $M_{\mathrm{lr}}/M_{\mathrm{pb}} = 0.04$, represented the highly catastrophic one. In these simulations, the collisional process was carried out to late times (typically several days), during which the gravitational interactions between the fragments could eventually lead to the formation of aggregates or rubble piles far from the largest remnant. It was first assumed somewhat unrealistically that fragments colliding with each other during the gravitational phase always stuck perfectly and merged regardless of relative speed and mass. Michel et al. (2002) then improved on this treatment by allowing for the dissipation of kinetic energy in such collisions and applying an energy-based merging criterion (see Section 2.2). This improved treatment did not change the conclusion obtained with the more simplistic method because typical relative speeds between ejected fragments are below their mutual escape speed. Therefore, the reaccumulation process being at the origin of large family members was confirmed.

3.1. Disruption of monolithic family parent bodies

The two studies mentioned above used as a starting condition a monolithic parent body represented by a basalt sphere. The projectile's parameters (diameter, speed, and impact angle) were defined such that the expected value of $M_{\rm lr}/M_{\rm pb}$ was successfully obtained by the simulation (see Michel et al., 2001, 2002, for details). However, we found that this value was not obtained directly from the fragmentation phase. Indeed, we found that in all the explored impact energy regimes, the fragmentation phase always leads to the complete pulverization of the parent body down to a fragment size corresponding to the resolution limit (of the order of 1 km). Then, the gravitational phase during which these fragments interact leads to many reaccumulations (see Fig. 1). Eventually, the fragment size distribution is dominated by aggregates formed by reaccumulation of smaller fragments and only the smallest-size end of the distribution consists of individual (or *intact*) fragments. Moreover, for each family, the simulated distribution is qualitatively compatible with that of real family members, even though typically some large fragments were missing between the largest and smaller ones, compared to the observed distribution (this discrepancy will not be found using pre-shattered parent bodies; Section 3.2). Another important result was that many binary systems were formed during the gravitational phase, so that the formation of asteroid satellites can be seen as a natural outcome of catastrophic collisions. However, the timescale of the simulations is too short and external perturbations (solar tides, etc.) should be included to determine their long-term stability and lifetime. Nevertheless, their occurrence provides a possible explanation of the origin of some of the observed asteroid binaries (see Durda et al., 2004, for a detailed study of satellite formation during collisions).

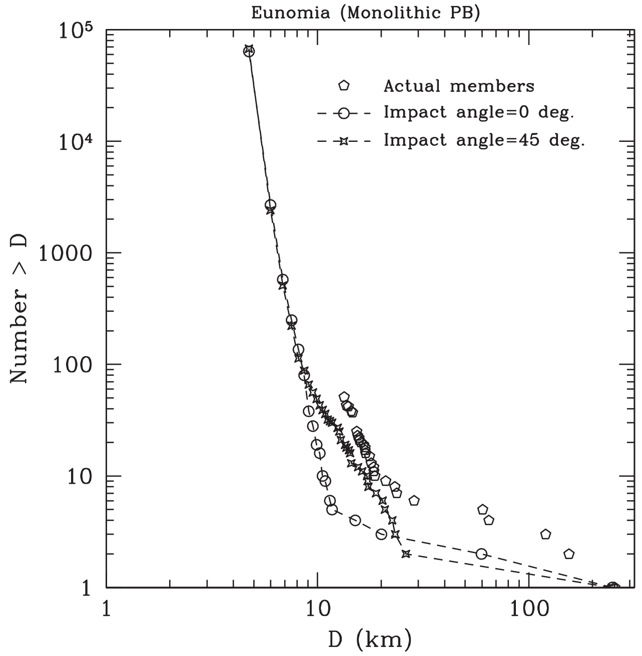

Fig. 1. Cumulative diameter distributions (in km) of the fragments resulting from the simulations of the Eunomia family formation in a log–log plot; the simulations were performed using a monolithic parent body (PB) with diameter and bulk density corresponding to the parent body of the family. The number of particles used to define the target was set to 2×10^5. Two impact angles were considered and are shown on the plot. The impact speed of the projectile was $5\,{\rm km\,s^{-1}}$. Actual members are also represented (Tanga et al., 1999). Note that the second- and third-largest members are certainly interlopers, since they display featureless spectra similar to C-type asteroids, in contrast with the other members, which have been characterized as S type (Lazzaro et al., 2001). These results are described in Michel at al. (2002, 2004).

As for the orbital dispersion of fragments obtained from these simulations, it is always smaller than the dispersion of real family members computed from their proper orbital elements (Zappalà et al., 2002; Knežěvič et al., 2002). However, the computation of the dispersion of simulated fragments is confronted with many unknowns, such as the values of the true anomaly and perihelion argument of the parent body at the instant of impact, which are required by Gauss' formulae to convert ejection velocities into orbital elements (see e.g. Michel et al., 2002). Nevertheless, the compact orbital dispersions found in simulations are still consistent with the larger ones of real families. Indeed, it has been realized that the current orbital dispersion of family members may not represent the original one following the break-up of the parent body. The post-collisional evolution of family members is affected by dynamical mechanisms such as high order resonances and/or the thermal Yarkovsky effect which can both cause a diffusion of the orbital elements over long-enough timescales (see e.g. Bottke et al., 2001, 2002; Nesvorný et al., 2002a, 2002b). When the estimated age of the considered family and the diffusion timescale of the orbital elements of family members due to these mechanisms are taken into account, the comparison between the compact dispersions obtained by the simulations and the larger one of real members leads to a good agreement (see e.g. Fig. 3).

3.2. Disruption of pre-shattered parent bodies

The simulations of monolithic family parent body break-ups already reproduce qualitatively the main properties of real family members. However, the cumulative size distribution of simulated fragments is systematically characterized by a lack of intermediate-sized bodies and a very steep slope for the smaller ones (see Fig. 1). Such characteristics are not observed in the size distributions of real family members, which generally look rather continuous. It is then important to determine whether this systematic effect is a general failure of the simulations, or whether it depends on the initial parameters and assumptions used to start the simulations. In particular, instead of being monolithic, the parent bodies may be modelled with an internal structure composed of different zones of voids and fractures, as if they had first been shattered during their collisional history before undergoing a major event leading to their disruption. If a better agreement could be obtained by adjusting the original internal structure of the parent body, this would be an important result with many implications. For instance, simulations could then be used to determine the internal structures of parent bodies that lead to collisional outcome properties in good agreement with the properties of known asteroid families.

The assumption that large parent bodies are pre-shattered before being disrupted is appropriate not just because it may potentially lead to a closer match with observed properties. The assumed pre-shattered state is thought to be a natural consequence of the collisional evolution of main belt asteroids. Indeed, several studies have indicated that for any asteroid, collisions at high impact energies leading to a disruption occur with a smaller frequency than collisions at lower impact energies leading to shattering effects only (see, e.g. Asphaug et al., 2002; Davis et al., 2002; Richardson et al., 2002). Thus, in general, a typical asteroid gets battered over time until a major collision eventually disrupts it into smaller dispersed pieces (Melosh and Ryan, 1997). Consequently, since the formation of an asteroid family corresponds to the ultimate disruptive event of a large object, it is reasonable to think that the internal structure of this body has been modified from its primordial state by all the smaller collisional events that it has suffered over its lifetime in the belt. In particular, macroscopic damaged zones and/or voids may be present within large asteroid bodies.

The size and velocity distributions of family members are the major constraints that can be compared with results of simulations starting from different models of parent bodies. However, as already stated, these distributions can be modified over time by collisional erosion and dynamical diffusion, depending on the proximity of diffusion mechanisms to family members and on the family's age. Recently, a very young family, called Karin, has been identified thanks to the increasing database of asteroid proper elements. Its young age of 5 Myr was estimated by integrating numerically the orbits of its members backward in time from their current state to the state where the heliocentric orbit shapes and orientations of all cluster members were nearly the same (Nesvorný et al., 2002a, 2002b). The authors concluded that this convergence could not happen by chance. The Karin family is thus so young that it provides a unique opportunity to study a collisional outcome almost unaffected by erosion and dynamical diffusion.

We have recently reported on numerical simulations aimed at determining which classes of collisions reproduce the main Karin family characteristics (Michel et al., 2003). In order to study how the collisional outcome depends on the internal structure of the parent body, we considered different models of such a body and searched for the one which, once disrupted, best matched the observed properties of the Karin family. More precisely, two kinds of parent bodies, both spherical in shape, were considered: (1) purely monolithic, and (2) pre-fragmented (pre-shattered with damage zones but no internal voids—see Fig. 2—or rubble pile with internal voids). The simulations then showed that the heterogeneities introduced in this way result in significant changes in the size spectrum of the final fragments left after the collision, even though in both cases the targets are completely shattered by the impact. In particular, we concluded that the Karin family must have originated from the breakup of a pre-fragmented parent body. Indeed, whereas the fragment size distribution obtained from a monolithic parent body still lacks some fragments at intermediate sizes, disruptions involving a pre-fragmented (pre-shattered or rubble pile) parent body on the other hand result in a much more continuous cumulative size distribution of fragments. Hence, the presence of intermediate-sized bodies, as observed in the real family, is most likely a

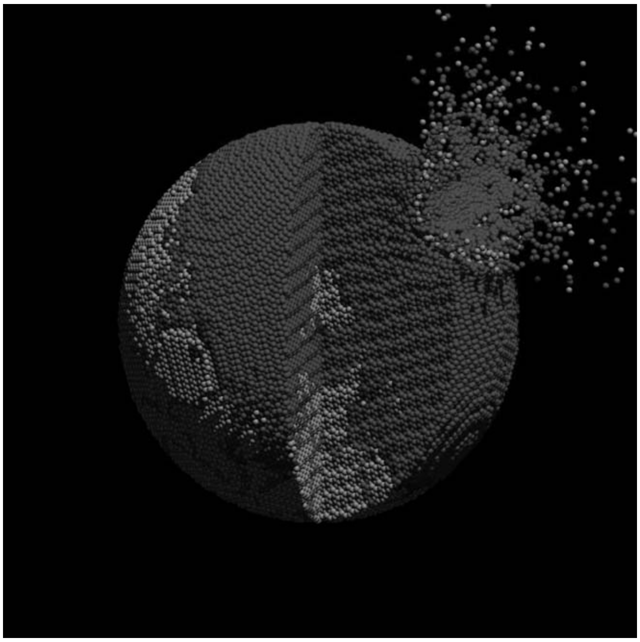

Fig. 2. Image taken from the simulation of the fragmentation of a pre-shattered Karin parent body with diameter equal to 25 km. Particles close to the impact point are rapidly ejected while the large dark zone is already fully damaged. Light-grey regions have not been affected yet and the small dark lines correspond to fractures (damaged zones) pre-existing within the pre-shattered body. Their initial presence will have a great influence on the ejection velocity field and consequently on the reaccumulation process. Results are described in Michel et al. (2003).

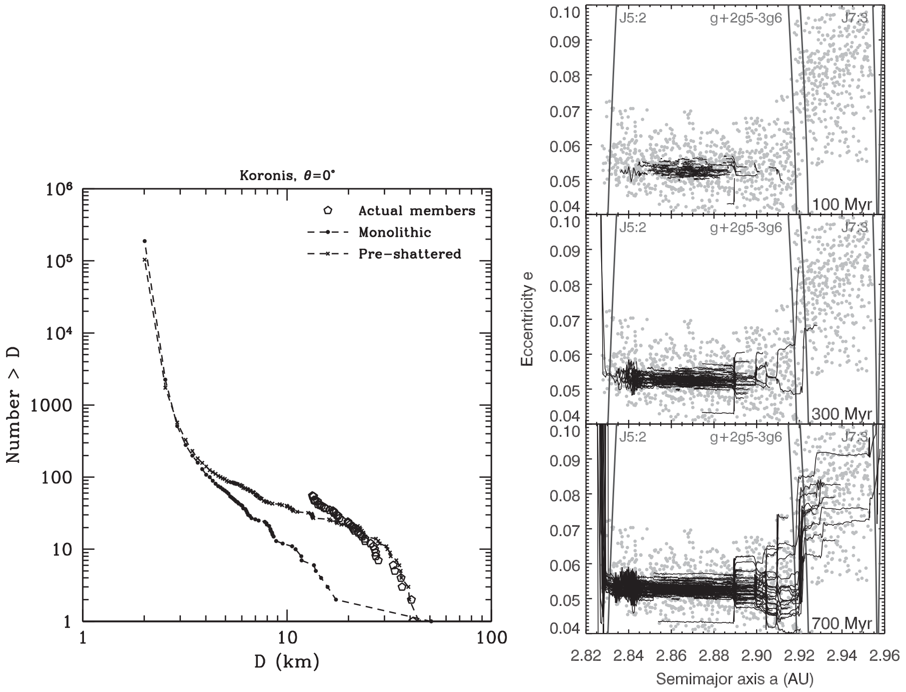

Fig. 3. Left: Cumulative diameter distributions (in km) in a log–log plot for the fragments of the simulated Koronis family (Michel et al., 2004). An impact at 5 km/s^{-1} with an angle of incidence of 0° gave rise to these distributions. Different symbols are used depending on the different parent body models used in the simulations as indicated on the plots. The estimated sizes of the actual members are also shown on the plot (Ryan and Melosh, 1998). Note that simulations of the disruption of a pre-shattered parent body are able to produce the four similar-sized largest members. Right: Evolution in the (semimajor axis a, eccentricity e) plane of 210 simulated Koronis family members under the influence of the Yarkovsky thermal effect and dynamical diffusion due to several resonances indicated on the plot (J5:2 and J7:3 correspond to the 5:2 and 7:3 mean motion resonances with Jupiter, respectively; $g + 2g_5 - 3g_6$ is a secular resonance that involves the precession rate of the small body's longitude of perihelion g, and the fundamental frequencies of Jupiter g_5 and Saturn g_6). The test family members (in black) were started with a dispersion which is consistent with the ones obtained from our simulations of Koronis family formation. They were integrated over 700 Myr, which is still shorter than the estimated age of the family (>1 Gyr). However, this evolution shows that the current shape of the family cluster (in light gray) in the proper element space does not represent the original one from the collisional event but is well explained by its subsequent evolution (from Bottke et al., 2001).

direct consequence of the presence of large-scale fractures or big blocks within the parent body. Since such large members cannot be obtained starting with a monolithic parent body regardless of the impact geometry and material type in all the investigated cases, we concluded that the parent body of the Karin family must have been pre-fractured or reaccumulated before suffering the disruption that formed the family. This is consistent with the fact that the Karin parent body actually belonged to the older Koronis family, which, as we showed in previous simulations, is composed of large members that are necessarily reaccumulated objects (Michel et al., 2001, 2002).

We then remarked that intermediate-size fragments are also present in most major asteroid families, implying that many parent bodies in the asteroid belt were probably pre-fragmented, and we confirmed this statement by new simulations (Michel et al., 2004). More precisely, we redid our simulations of the Eunomia and Koronis family formations, using pre-shattered parent bodies, and compared the results with the ones obtained with monolithic parent bodies. The best agreement was again found with pre-shattered parent bodies. In particular, in the case of the Koronis family, an interesting result was obtained from these simulations, which may have important implications concerning the real family history. The size distribution obtained from the disruption of a pre-shattered parent body contains four largest fragments of approximately the same size (Fig. 3). This peculiar characteristic is shared by the real family, and has been a source of debate as it was assumed that a single collisional event cannot produce such a property (see Michel et al., 2004, for a discussion). Moreover, the simulation using a monolithic parent body did not result in such a distribution. We then demonstrated numerically for the first time, by using a pre-shattered parent body, that these fragments can actually be produced by the original event, and therefore no subsequent mechanism needs to be invoked to form them, which would otherwise require a revision of the entire family history (Michel et al., 2004). According to these results showing that even old families may well have originated from pre-shattered parent bodies, we concluded that most large objects in the present-day asteroid belt may well be pre-shattered or gravitational aggregates/rubble piles.

In addition to the size distribution, a second important constraint concerns the ejection velocity distribution of simulated fragments, which must be compatible with that of real family members. Karin's young age (≈ 5 Myr) implies that dynamical diffusion has had no time to alter appreciably the initial ejection velocity distribution, which is not the case for the other much older families. Again, we found that a better match is obtained from the pre-shattered parent body (Michel et al., 2003). Conversely, the dispersion of the larger fragments produced by a monolithic parent body is definitely too small with respect to that of real members.

In summary, a good match of both the continuous size distribution and the orbital dispersion of the Karin family requires that the parent body was pre-fragmented or reaccumulated. This result supports the overall picture that all large members of asteroid families are reaccumulated bodies, given that the Karin cluster is at least a second-generation family in the lineage of the older Koronis parent body.

Another major feature of these simulations is that they can be used to determine the impact energy needed to produce a given degree of disruption as a function of the internal structure of the parent body. It is generally found that disrupting a pre-shattered target requires less energy per unit mass than disrupting a monolithic body with the same degree of disruption. This, at first glance a surprising result, is related to the fact that the fractures as modelled by us (no porosity and no material discontinuities except damage) do not affect shock waves but only tensile waves. Hence, fragments can be set in motion immediately upon being hit by the shock wave without having to wait for fracture to occur in a following tensile wave. Thus, transfer of momentum is more efficient and disruption facilitated. Note that the presence of large voids such as those in rubble piles affect the propagation of the shock wave, thus reversing this trend. A more detailed study of these properties is in development, but it is already clear that the internal structure of an asteroid plays an important role in the determination of its response to impacts (see also Asphaug et al., 1998). This is not only relevant for estimating the collisional lifetime of a body in the asteroid belt, but also for developing strategies to deflect a potential Earth impactor.

4. Conclusions

In recent years, thanks to the development of sophisticated numerical codes and the advances in computer technology, a great step has been achieved in our understanding of the collisional process at large asteroid scales. Results from laboratory experiments on centimeter-size targets cannot be extrapolated easily to those scales but they remain useful to validate at small scales the developed numerical tools. The most recent simulations of asteroid collisional disruption have successfully reproduced the main characteristics of big asteroid families in several impact energy regimes. They have shown that the collisional process at large scales does not only involve the fragmentation of the parent body, as is the case in the laboratory, but also the gravitational interactions of the fragments. Those interactions can eventually lead to the formation of large aggregates produced by the reaccumulation of smaller fragments. According to these results, most large family members consist of gravitational aggregates/rubble piles and not monolithic bodies. Moreover, the internal structure of the parent body itself greatly influences both the impact energy required to achieve a given degree of destruction and the collisional outcome. In particular, pre-shattered parent bodies generate in general a much larger number of big fragments—formed by gravitational reaccumulation of smaller ones—than their monolithic counterparts. The resulting size distributions are then in better agreement with those of real families, suggesting that most of these families originated from pre-shattered parent bodies. This agrees with the idea that large asteroids get battered over time by small impacts which modify their surface and internal structure until a large event eventually disrupts them. However, this is a complication for models of collisional evolution of small body populations as it makes it more dubious to use a simple rule in order to define the collisional outcome of each event during the evolution. Indeed, the outcome properties depend highly on the internal structures of the bodies involved, which are specific to each impact.

Finally, let us recall that although a big step has been taken, many uncertainties still remain, even concerning the physical process itself. All numerical codes are limited by (i) the numerical method itself, (ii) the physics put into the code, much of which is still based on models, (iii) the knowledge of physical parameters that are valid for terrestrial materials, and (iv) the huge parameter space that needs to be explored. It is however comforting that, despite these uncertainties, the results are already consistent with the observational constraints provided by asteroid families. But one should keep in mind these uncertainties until physical data directly appropriate to asteroids become available. Future space missions devoted to in-situ measurements and sample returns will certainly help to improve our knowledge.

References

Asphaug, E., Melosh, H.J., 1993. The Stickney impact of PHOBOS—A dynamical model. Icarus 101, 144–164.

Asphaug, E., Ostro, S.J., Hudson, R.S., Scheeres, D.J., Benz, W., 1998. Nature 393, 437.

Asphaug, E., Ryan, E.V., Zuber, M.T., 2002. Asteroid interiors. In: Bottke, W.F., Cellino, A., Paolicchi, P., Binzel, R.P. (Eds.), Asteroids III. University of Arizona Press, Tucson, AZ, pp. 463–484.

Barnes, J., Hut, P., 1986. A hierarchical $O(N \log N)$ force-calculation algorithm. Nature 324, 446–449.

Benz, W., 1990. Smooth Particle Hydrodynamics—A review. In: Buchler, J.R. (Ed.), Proceedings of the NATO Advanced Research Workshop on The Numerical Modelling of Nonlinear Stellar Pulsations Problems and Prospects. Kluwer Academic Publishers, Dordrecht.

Benz, W., Asphaug, E., 1994. Impact simulations with fracture. I—Method and tests. Icarus 107, 98–116.

Benz, W., Asphaug, E., 1995. Simulations of brittle solids using smooth particle hydrodynamics. Comput. Phys. Comm. 87, 253–265.

Benz, W., Asphaug, E., 1999. Catastrophic disruptions revisited. Icarus 142, 5–20.

Benz, W., Slattery, W.L., Cameron, A.G.W., 1988. Collisional stripping of Mercury's mantle. Icarus 74, 516–528.

Bottke, W.F., Vokrouhlický, D., Borz, M., Nesvorný, D., Morbidelli, A., 2001. Dynamical spreading of asteroid families via the Yarkovsky effect. Science 294, 1693–1696.

Bottke, W.F., Vokrouhlický, D., Rubincam, D.P., Broz, M., 2002. The effect of Yarkovsky thermal forces on the dynamical evolution of asteroids and meteoroids. In: Bottke, W.F., Cellino, A., Paolicchi, P., Binzel, R.P. (Eds.), Asteroids III. University of Arizona Press, Tucson, AZ, pp. 501–515.

Chapman, C.R., Davis, D.R., Greenberg, R., 1982. Apollo asteroids: relationships to main belt asteroids and meteorites. Meteoritics 17, 193–194.

Chapman, C.R., Paolicchi, P., Zappalà, V., Binzel, R.P., Bell, J.F., 1989. Asteroid families: physical properties and evolution. In: Binzel, R.P., Gehrels, T., Matthews, M.S. (Eds.), Asteroids II. University of Arizona Press, Tucson, AZ, pp. 386–415.

Davis, D.R., Chapman, C.R., Weidenschilling, S.J., Greenberg, R., 1985. Collisional history of asteroids: evidence from Vesta and the Hirayama families. Icarus 62, 30–53.

Davis, D.R., Durda, D.D., Marzari, F., Campo Bagatin, A., Gil-Hutton, R., 2002. Collisional evolutions of small body populations. In: Bottke, W.F., Cellino, A., Paolicchi, P., Binzel, R.P. (Eds.), Asteroids III. University of Arizona Press, Tucson, AZ, pp. 545–558.

Durda, D.D., Bottke, W.F., Enke, B.L., Merline, W.J., Asphaug, E., Richardson, D.C., Leinhardt, Z.M., 2004. The formation of asteroid satellites in large impacts: results from numerical simulations. Icarus 167, 382–396.

Grady, D.E., Kipp, M.E., 1980. Continuum modeling of explosive fracture in oil shale. Int. J. Rock Mech. Min. Sci. Geomech. Abstr. 17, 147–157.

Hirayama, K., 1918. Groups of asteroids probably of common origin. Astron. J. 31, 185–188.

Housen, K.R., Holsapple, K.A., 1990. On the fragmentation of asteroids and planetary satellites. Icarus 84, 226–253.

Jaeger, J.C., Cook, N.G.W., 1969. Fundamental of Rock Mechanics. Chapman and Hall, London.

Knezěvic, Z., Lemaître, A., Milani, A., 2002. The determination of asteroid proper elements. In: Bottke, W.F., Cellino, A., Paolicchi, P., Binzel, R.P. (Eds.), Asteroids III. University of Arizona Press, Tucson, AZ, pp. 603–612.

Lazzaro, D., Mothé-Diniz, T., Carvano, J.M., Angeli, C.A., Betzler, A.S., 2001. The Eunomia family: a visible spectroscopic survey. Icarus 142, 445–453.

Marzari, F., Davis, D.R., Vanzani, V., 1995. Collisional evolution of asteroid families. Icarus 113, 168–187.

Melosh, H.J., Ryan, E.V., 1997. Asteroids: shattered but not dispersed. Icarus 129, 562–564.

Michel, P., Benz, W., Tanga, P., Richardson, D.C., 2001. Collisions and gravitational reaccumulation: forming asteroid families and satellites. Science 294, 1696–1700.

Michel, P., Benz, W., Tanga, P., Richardson, D.C., 2002. Formation of asteroid families by catastrophic disruption: simulations with fragmentation and gravitational reaccumulation. Icarus 160, 10–23.

Michel, P., Benz, W., Richardson, D.C., 2003. Disruption of fragmented parent bodies as the origin of asteroid families. Nature 421, 608–611.

Michel, P., Benz, W., Richardson, D.C., 2004. Catastrophic disruption of pre-shattered parent bodies. Icarus 168, 420–432.

Nesvorný, D., Bottke, W.F., Dones, L., Levison, H.F., 2002a. The recent breakup of an asteroid in the main belt region. Nature 417, 720–722.

Nesvorný, D., Ferraz-Mello, S., Holman, M., Morbidelli, A., 2002b. Regular and chaotic dynamics in the mean-motion resonances: implications for the structure and evolution of the Asteroid Belt. In: Bottke, W.F., Cellino, A., Paolicchi, P., Binzel, R.P. (Eds.), Asteroids III. University of Arizona Press, Tucson, AZ, pp. 379–394.

Pravec, P., Harris, A.W., 2000. Fast and slow rotation of asteroids. Icarus 148, 12–20.

Richardson, D.C., 1994. Tree code simulations of planetary rings. Mon. Not. R. Astron. Soc. 269, 493–511.

Richardson, D.C., Quinn, T., Stadel, J., Lake, G., 2000. Direct large-scale N-body simulations of planetesimal dynamics. Icarus 143, 45–59.

Richardson, D.C., Leinhardt, Z.M., Bottke, W.F., Melosh, H.J., Asphaug, E., 2002. Gravitational aggregates: evidence and evolution. In: Bottke, W.F., Cellino, A., Paolicchi, P., Binzel, R.P. (Eds.), Asteroids III. University of Arizona Press, Tucson, AZ, pp. 501–515.

Ryan, E.V., Melosh, H.J., 1998. Impact fragmentation: from the laboratory to asteroids. Icarus 133, 1–24.

Tanga, P., Cellino, A., Michel, P., Zappalà, V., Paolicchi, P., dell'Oro, A., 1999. On the size distribution of asteroid families: the role of geometry. Icarus 141, 65–78.

Tillotson, J.H., 1962. Metallic equations of state for hypervelocity impact. Gen. Atom. Rep. GA-3216.

Ward, W.R., Canup, R.M., 2000. Origin of the Moon's orbital inclination from resonant disk interactions. Nature 403, 741–743.

Weibull, W.A., 1939. A statistical theory of the strength of material (transl.). Ingvetensk. Akad. Handl. 151, 5–45.

Yeomans, D.K., and 12 colleagues, 1997. Estimating the mass of asteroid 253 Mathilde from tracking data during the NEAR Flyby. Science 278, 2106–2109.

Zappalà, V., Cellino, A., Dell'Oro, A., Paolicchi, P., 2002. Physical and dynamical properties of asteroid families. In: Bottke, W.F., Cellino, A., Paolicchi, P., Binzel, R.P. (Eds.), Asteroids III. University of Arizona Press, Tucson, AZ, pp. 619–631.