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Analysis of the kinematics of ejecta created after a catastrophic collision

A. Dell'Oro [a,*], A. Cellino [b], P. Paolicchi [c], P. Tanga [d]

[a] INAF - Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125 Firenze, Italy
[b] INAF - Osservatorio Astrofisico di Torino, Strada Osservatorio 20, 10025 Pino Torinese, Italy
[c] Università di Pisa, Dipartimento di Fisica, Largo Pontecorvo 3, 56127 Pisa, Italy
[d] Observatoire de la Côte d'Azur, Bv de l'Observatoire - CS 34229, 06304 Nice Cedex 4, France

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ABSTRACT

According to the results of hydrodynamical simulations, the creation of an asteroid dynamical family as the outcome of a high-energy collision consists of the partial or complete shattering of the parent body followed by re-accumulation of many fragments into larger bodies due to the mutual gravity. This scenario seems to reproduce satisfactorily the observed properties of the asteroid families, and in particular the size distribution of the members. In this paper we show a preliminary analysis of the ejection velocity fields predicted by hydrodynamical models, in comparison with the ejection velocity fields simulated by semi-empirical models, in order to identify the features of the velocity distribution that trigger or prevent the fragments' gravitational re-accumulation.

1. Introduction

According to current understanding (see, for instance, Michel et al., 2015, and references therein) the creation of a dynamical family of asteroids as the outcome of a high-energy collision event can be schematically described as a three-step process: (1) a hydrodynamical phase, in which the colliding system (projectile+target) is partially or completely shattered and fragments are created and ejected from their original locations; (2) a ballistic phase, in which the ejecta may experience mutual collisions and/or may be re-accumulated under the effect of gravitational interactions; (3) a dynamical phase in which each fragment is an independent body orbiting along a separate trajectory around the Sun, subject to gravitational and non-gravitational perturbations present in the Solar System. At the end of the phase (2) the final physical structure of the asteroid family is established, and its observable properties, also after a long dynamical evolution, can keep significant footprints of the original event from which it was originated (D'Abramo et al., 1999; Michel et al., 2004). The size distribution of the members of the family is closely connected to the physics of fragmentation of the parent body and ejection of the fragments (the latter process possibly including collisions and re-accumulation). The overall structure of a dynamical family observed after its formation is a consequence of the initial distribution of fragment ejection velocities (and their possible correlations with the fragment sizes), and the subsequent evolution due to gravitational perturbations by the planets and non-gravitational forces (Bottke et al., 2001; Carruba et al., 2003; Cellino et al., 2004; Vokrouhlický et al., 2006). More recently, the additional role of non-destructive collisions among asteroids producing a weak, but stable transfer of linear momentum has also been outlined by Dell'Oro and Cellino (2007) and Wiegert (2015).

In this paper we focus on the phases (1) and (2) described above. A lot of work has been done in the past to investigate the physics of inter-asteroid impacts and the predicted outcomes in terms of size distribution, ejection velocities, spin rates and shapes of the fragments. The final goal of such studies is to correctly understand and interpret the observable properties of asteroid families, considered to be the outcomes of catastrophic collisions. The problem has been addressed in laboratory experiments (impacts involving centimeter-scale targets) as well as by means of theoretical models. In turn, different theoretical approaches have been followed. Numerical models based on fundamental laws of the hydrodynamics (known as Smoothed-particle hydrodynamics (SPH) models, or briefly hydrocodes) have been developed and proved to work to reproduce the outcomes of laboratory experiments (Melosh et al., 1992). Attempts to extend the models to the case of impacts among asteroids have been done (Love and Ahrens, 1996; Ryan and Melosh, 1998). Using hydrocode models,

* Corresponding author.
E-mail addresses: delloro@arcetri.inaf.it (A. Dell'Oro), cellino@oato.inaf.it (A. Cellino), paolicchi@df.unipi.it (P. Paolicchi), Paolo.Tanga@oca.eu (P. Tanga).

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Benz and Asphaug (1999) computed the impact energy threshold for fragmentation characterizing typical impacts between Main Belt asteroids, a result that has been independently confirmed by models of collisional evolution of the whole asteroid population (Bottke et al., 2005).

Hydrocode models usually succeed in reproducing well the size distributions of fragments produced in impact experiments in laboratory. When applied to simulate collisions among kilometer-size bodies in the asteroid Main Belt, however, hydrocodes predict a complete fragmentation of the parent body down to sizes corresponding to the numerical resolution of the model (Benz and Asphaug, 1999). Such complete "pulverization" of the parent body is in contrast with the observational evidence about the size distributions of asteroid families members, which tend to follow a power law size distribution. In most cases the sizes of fragments predicted by hydrocode models would be much smaller, to the point that family members would be too faint to be detected, ruling out even the mere possibility to identify families.

The discrepancy between hydrocode outcomes and the observed size distributions of asteroid families has been solved by suggesting that family members have sizes that are eventually produced by a process of massive gravitational re-accumulation occurring at the end of the ballistic phase (2).

This scenario has been demonstrated by Michel et al. (2001), who made a numerical simulation of the formation of the Eunomia and Koronis asteroid families. In practical terms, Michel et al. (2001) used the output of hydrocode models as the input of a N-body integrator in order to follow the dynamical evolution of the system of particles and detect their mutual collisions for several days after fragmentation. The results of Benz and Asphaug (1999) already suggested that at least the family largest remnant could be the result of a gravitational re-accumulation of fragments, forming a so-called *rubble-pile*, but Michel et al. (2001) showed that many smaller family members can also be the product of a re-accumulation, too. A perfect match between the observed size distributions of the major families and those predicted by this model has never been obtained, because the observed size distributions tend to be shallower than the predictions; however, this can be explained as the result of subsequent collisional evolution of the families (Michel et al., 2002). The key result is the following: it is possible to obtain an "ordered" re-accumulation characterized by a power law distribution of the final family members, starting from the ejection velocity field provided by hydrocodes.

An approach similar to that of Michel et al. (2001) had been tried before by Pisani et al. (1999). These authors did not use the outcomes of hydrocode models, but assumed as initial condition of the ballistic phase (2) the ejection velocity fields predicted by some Semi-Empirical Models (SEM) developed in the 90s (Paolicchi et al., 1989, 1996). The SEM was originally developed to closely mimic the observed kinematic properties of fragments produced in laboratory experiments of catastrophic breakup events. In the most recent versions of SEM, a more accurate treatment of the evolution of fragments during the ballistic phase has been included, incorporating an N-body integration to follow the dynamical evolution of the fragments (Paolicchi et al., 1996; Doressoundiram et al., 1997). In Pisani et al. (1999) the model parameters of the SEM were tuned in order to obtain a good match between some distributions of initial ejection velocities predicted by the hydrocode model of Love and Ahrens (1996) and those predicted by the SEM. At that time hydrocodes were able to compute only the size and velocity distributions of the fragments, but not yet a detailed list of initial positions and velocities for individual fragments. Pisani et al. (1999) did not assign to the fragments the sizes predicted by the SEM on the basis of some considerations based on the properties of the ejection velocity field (Paolicchi et al., 1989, 1996), but they divided the parent body into a number of small and equal spherical particles, to match more closely the hydrocode outcomes. This analysis, however, failed to reproduce the observed size distributions of asteroid families. The results suggested that the re-accumulation involves only one or very few fragments (the largest remnant and a few other bodies), and the observed size distributions of asteroid families could not be reproduced.

This lack of re-accumulation processes during the ballistic phase of family formation as modelled by the SEM is somehow puzzling, taking into account that this model closely reproduces the kinematic properties of the fragments produced in laboratory experiments. One could object that the gravitation is negligible in the experiments, whereas it can be much more important when much larger bodies are involved in catastrophic collisions. On the other hand, it is not easy in any case to obtain a significant re-accumulation into many, larger bodies, from a set of small fragments moving outwards as the effect of an ejection velocity field (for example in simple kinematic models as a purely spherical expansion). It is therefore natural to wonder whether some special properties of an ejection velocity field are necessary to trigger a general process of re-accumulation in agreement with both the results of hydrodynamical codes by Michel et al. (2001), and with the existence of observable asteroid families.

To try and find an answer to this question, we have analyzed in depth two velocity fields produced by the SPH model used by Michel et al. (2001) and used them as the input of an N-body integrator in order to simulate the ballistic phase of the two simulated events. Having at disposal for the moment only two examples of SPH ejection fields, in this paper we can show only some partial results, and we plan a more extensive analysis in the future.

We name the two fields "50k" and "koronis". The field "50k", obtained by the fragmentation of a parent body about 200 km in size, produced a fast re-accumulation into a largest remnant and many smaller bodies. The field "koronis" has been produced by Michel et al. (2001) to fit the observed properties of the Koronis family, characterized by a relatively small largest remnant. This field was produced by assuming a much larger impact energy than in the case of the "50k" and a parent body having a diameter of 119 km, corresponding to the estimated size of the parent body of the Koronis family.

The aim of the present work is to compare the final outcomes of these two SPH ejection velocity fields and those predicted by the SEM starting from the same sets of initial conditions, in order to shed light on the qualitative differences that make the final outcomes of those models so different. We note that this investigation is not only interesting *per se*, but it can have implications also for what concerns investigations aimed at assessing the possible formation of binary systems in family-forming events (Doressoundiram et al., 1997).

2. Direct collisions among fragments

The approach we follow in this work is not simply to carry out again an N-body numerical integration starting from the initial conditions of the particles after the hydrodynamical phase, to analyze the final outcome of the ballistic phase. What we do is rather to investigate directly the geometrical and kinematic properties of the system of particles at the beginning of the ballistic phase, namely the properties of the initial ejection velocity field before any evolution.

Our first finding was that collisions among the fragments of "50k" and "koronis" may occur even if no mutual gravitational attraction is taken into account. In other words, if we assume that each fragment is moving along a straight line with a constant