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Physical processes and evolution of asteroids: the case of dynamical families

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Abstract The formation of dynamical families is usually considered as the most spectacular outcome of catastrophic impact processes. However, several open problems involve the physical modeling and the interpretation of the observations. Most of the current ideas have been drastically revised on the basis of the first reliable hydrodynamical simulations, and the relevance of the Yarkovsky effect to shape the present distributions of the orbital elements has been put into evidence. However, open problems are still present. Some very recent findings seem to outline a somehow intermediate solution between the former paradigm and the later ideas.

1. The old scenario: the ”standard model”

A few physical processes dominate the evolution of the asteroid Belt: the dynamical evolution due to the complex gravitational interactions among the Solar System bodies, the collisions and the dynamical but non–gravitational Yarkovsky effect.

Even if the current knowledge of these individual effects is rapidly improving, it is not easy to build up a complete, fully convincing evolutionary scenario: several parameters are poorly known and, as recently understood, the outcomes of collisional processes are strongly dependent on the detailed structure of the impacting bodies (previous fractures, porosity, voids (Michel et al. (2003, 2004, 2005))).

The dynamical asteroid families (Zappalá et al. (2002); Bendjoya and Zappalá (2002)) are a natural laboratory for the simultaneous analysis of all these effects. The distributions of orbital elements (mainly the semimajor axis a, the eccentricity e and the inclination i) of family members are probably the most significant observable properties. When the family is formed, the fragments are ejected at different relative velocities, thus into different orbits. During a short period of intense mutual gravitational interaction (tens of days, usually) the bodies change their velocities and are, sometimes, reaccumulated. After this period they move under the gravitational effects of the Sun and the planets. The motion is not exactly keplerian, thus the osculating (i.e. instantaneous) orbital elements change with time. The computation of the so–called proper elements (Knezevic et al. (2002)) allows to obtain a set of –relatively– stable elements (a, e, i), whose distribution is approximately representative of the original one. Thus they may be used to estimate the initial relative velocities among the family members, by means of Gauss formulae (Zappalá et al. (1984, 1996)). The old “standard model” (see Paolicchi et al. (2002)) is

Send offprint requests to: P.Paolicchi based on these computations, which entail very high ejection velocities. Only in some cases the self gravitation among fragments causes a partial reaccumulation of mass into the largest remnant, and the formation of rare binary systems. The observed mass distribution is essentially that of the original fragments, due to the breakup processes, and severely constrained by pure geometrical effects (Tanga et al. (1999)). Apart one –or very few– large partially reaccumulated bodies, the fragments are in principle intended as monoliths, not regularly shaped, often initially tumbling. The increase of rotation rate towards the small size tail of family members is a obvious consequence of the physics, and entails a similar behaviour for all the asteroids (Davis et al. (1989)). Further collisional evolution of fragments can lead to moderate fracturing, thus possibly causing bursting fission processes, with formation of new binaries (Paolicchi et al. (1999)) and with a decrease of the observed spin rates. The collisions between asteroids are qualitatively very similar to those, analyzed within laboratory experiments, between cm–sized colliders. The only difference, due to the different size scales, concerns the value of the empirical parameters S (impact strength, defined as the minimum energy per unit target volume able to disrupt more than 50% of the target; whenever the gravity is important a new parameter Q, including both disruption and dispersion of the fragments, is defined) and f_{KE} (the fraction of the impact energy converted into kinetic energy of the fragments).

2. Crisis of the standard model: the hydrocode and Yarkovsky era

Two main difficulties have caused a substantial dismission of the standard model. The former one is theoretical: with the physical parameters obtained from laboratory experiments, the large impact energy required to overcome the gravitational binding and eject the fragments at the estimated velocities causes the formation of very small –and thus unobservable– fragments. The problem can be solved assuming a very large value of S (Davis et al. (1989)) for asteroid–sized bodies. However, considerations based on the strain–rate lead to the opposite conclusion: large bodies should be weaker than small ones, apart the possible enhancing effect due to the pressure, limited, however, to the central part of the target. This difficulty has been strengthened by the outcomes of the first hydrocode simulations. They have shown that the shattering of the target takes place before the ejection stage, thus drastically affecting the reaction of the body. In general the collisions –even with a moderate impact energy– cause a strong shattering of the target, but the fragments are ejected at small velocities, and the reaccumulation is prevented only by very energetic collisions: in other terms, S is small, $f_{KE} << 1$ (Holsapple et al. (2002); Asphaug et al. (2002); Richardson et al. (2002)).

This scenario has been strongly supported by the latter difficulty of the standard model: the spin rates of asteroids larger than about hundred meter never exceed a limit value (corresponding to a period of about two hours), consistent with the bursting limit of a body bound by gravitational forces only (a "rubble pile"), and not by solid state ones (Pravec et al. (2002)) . Only smaller bodies are allowed to spin as fast as monoliths can. According to these new ideas, families are formed by several reaccumulated bodies, no big original fragment should exist, the original ejection velocities of family members are close to the minimum values required to avoid a complete reaccumulation.

The problem of explaining the present dispersion of families in the space of orbital elements has been solved with the introduction of Yarkovsky effect (Vokrouhlicky (1998); Vokrouhlicky and Farinella (1998); Vokrouhlicky (1999); Spitale and Greenberg (2001)), affecting the orbital elements of small and medium sized asteroids. In particular, retrograde asteroids are moved to smaller semimajor axes, prograde to larger ones. The mobility in the other main orbital elements (e, i) is more complex, and strongly connected to the effect of minor dynamical resonances, widely scattered within the whole Belt. In general, the Yarkovsky driven diffusion causes a general spreading of the orbital elements, which might even be the dominating cause of the observed properties of present families. However, a purely statistical analysis (Dell'Oro et al. (2004)) suggested that the present spread of orbital elements –at least for what concerns the semimajor axis a (the most reliable and stable element) is due approximately half to the formation properties and half to post–formation perturbations. Since the Yarkovsky driven mobility is faster for small objects, it might also explain the observed (Zappalá et al. (2002)) anticorrelations between the size and –respectively– the values $a-a_{CM}, e-e_{CM}, i-i_{CM}$ (the suffix CM refers to the center of mass of the family). This argument holds directly only for what concerns the semimajor axis. As told above, the diffusion along e and i is due to more complex processes, and it is not obvious that the Yarkovsky effect is really capable to cause the observed mass segregation.

Apart the previous considerations, two additional serious problems are still open. Some of the (rather large) asteroids which have been observed from space (for instance, 433 Eros) seem not to be conglomerates of small pieces (i.e. rubble piles in a strict sense). Thus the suggestion that all asteroids larger than a given limit size must be exactly rubble piles is presumably incorrect. Taking into account also the complex structure of density data (Britt et al. (2002)) a more refined modeling will be needed. From a theoretical point of view, as firstly pointed out by Pisani et al. (1999), on the basis of a simple kinematical model, it is not easy, with a regular ejection velocity field of fragments, to obtain a gravitational reaccumulation into several bodies, resulting into a continuous mass distribution with several bodies of comparable size. Often the reaccumulation is strongly focused into one body (the largest one); the simultaneous reaccumulation of many bodies, required to pass from the fine initial shattering to the present observable family, requires an "ad hoc" ejection velocity field. Moreover, whenever the reaccumulation process is very efficient, the "volume" of the family in the space of orbital elements is very small, by far smaller than the observed one. The Yarkovsky diffusion can solve the problem for old families, but not for very young ones, such as the Karin one.

3. Towards a "mixed model"?

The hydrodynamical simulations have been strongly improved in the last years. In particular it has become possible to analyze the different behaviour of targets with an initial different internal structure (monolithic, strongly shattered, fractured). The paper by Michel et al. (2003) has presented very relevant results. The Authors, trying to fit the observed properties of the Karin family, show that the breakup of a monolithic target is unable to reproduce the observed mass and velocity distributions. The outcomes of these simulations are qualitatively very similar –and with similar problems– to those discussed in Pisani et al. (1999). Different simulations can fit the observations, under the assumption of a previously fragmented target (i.e. a target with several fracture surfaces but with no relevant "macroporosity" –no big voids): the formation of more numerous intermediate mass fragments is possible, presumably due to the original presence of large blocks, and the typical ejection velocities may be larger.

In our opinion, many results from this and similar simulations can be understood in terms of elementary physical considerations. Thus the above quoted similarity between the results of a sophisticated hydrodynamical computation and a purely kinematical model is not by chance. Even the suggestion, based only on elementary considerations, that faster fragments come out from a pre–fractured body, was made in a conference paper more than 20 years ago (Paolicchi et al. (1982)). The use of simple arguments may be useful, even at the present time, for details not yet easily described by hydrocodes, such as the rotational properties.

Finally we suggest that this kind of recent results, joined together with some of the previously discussed open questions and observational evidences, might lead to recover a few ideas from the standard model, resulting into a somehow "mixed model":

1) The collisional shattering down to $100m$ is not complete; due to the previous collisional history larger blocks may sometimes survive catastrophic events as part of larger conglomerated bodies or even as individual bodies.

2)The previous collisional history of the target shapes the outcome properties from a catastrophic impact leading to the formation of a dynamical family.
3)The original ejection velocities are smaller than those suggested by the standard model, but probably larger than according to the standard hydrocodes. As a consequence, the present structure of a family in the space of orbital elements is partially reminiscent of its original properties, partially caused by the Yarkovsky diffusion. The fifty–fifty suggestion by Dell'Oro et al. (2004) may be realistic.

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