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Collisional evolution of asteroids and Trans–Neptunian objects

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Abstract. Since Pietrowsky's first analytical study of collisional systems of asteroids (1953), through Dohnanyi's comprehensive theory (1969), to the analytical and numerical studies of the last two decades, the collisional evolution of populations of asteroids —and to a less extent, of Trojans and TNOs— has been investigated by many researchers.

The study of such systems is an intrinsically delicate mathematical problem, as their evolution in time is properly described in terms of systems of first–order, non–linear differential equations. Physically, the limited knowledge of some of the collisional properties, rotations and internal structure of bodies, and the complex interplay with dust, non–gravitational effects and dynamical interactions with planets, make the study of the collisional evolution a hard multi–parametric problem. Nevertheless, the task is worth the effort, in fact the understanding of evolutionary processes in the solar system's small body belts provides the main tools to discriminate between the many different theoretical scenarios proposed to explain the formation of the solar system itself.

This review tries to give an updated overall view of the research done in this field, and to show the connections between apparently independent phenomena that may affect the evolution of collisional systems of asteroids and TNOs.

Keywords. Minor planets, Asteroids, Kuiper Belt

1. Introduction

In 1918, when Hirayama firstly pointed out that groups of asteroids —that he was observing to have almost identical orbital elements— may have a common origin, the idea that catastrophic collisions among them could sometimes occur began to raise among astronomers. The pioneering work of Pietrowsky (1953) on the frecuency of collisions, in which he estimated relative velocities to be around 5 km/s, and concluded about an expected stationary distribution for asteroids, was the next step into considering the asteroid belt as a collisional system. Dohnanyi (1969), Dohnanyi (1971) and Hellyer (1970), Hellyer (1971) finally studied analytically the evolution of the cascades of fragments coming from asteroid breakups.

The increasing number of discoveries in the two following decades confirmed the sensation that mutual collisions have been shaping the size distribution of the main belt asteroids during and after the 'heavy bombardment' phase occured some 4500 millions of years ago.

In the meantime, the development of computer science made possible that the sets of differential equations describing the evolution in time of the populations of a whole range of sizes could be discretised and numerically handled. This allowed the first numerical models (Davis *et al.* 1985) of the collisional evolution of the asteorid belt to appear and make us understand new features of the main asteroid belt. By that time, another population of small bodies had been confirmed: more than hundred Trojan asteroids had

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been already found at the stable Lagrangian points of the restricted three–body problem that considers the Sun and planet Jupiter as primary bodies. Soon it was recognised to be a collisional system as well.

The last decade of the XX century put an end to the two–century era of speculations about how asteroids actually look like, and was spotted by the first ever images of *true* asteroids. They offered new opportunities for calculating collision rates and to shed some light into collisional evolution and internal structures.

The origin of short period comets with periods smaller than some puzzled astronomers of the first half of the past century. Edgeworth (1943) and 1949 published his conjecture on the existence of a disk of planetesimals beyond the orbit of planet Neptune, a potential source for comets. During the same period, Kuiper was developing (1951) his own ideas about the same topic. Fernandez (1980) finally showed dynamically the necessity for the existence of such a region. The Kuiper Belt —as the predicted region was finally called at that time— began to be unveiled in 1992, when Luu & Jewitt discovered the first of a long list of objects with semimajor axis beyond Neptune, nowadays known as Trans–Neptunian Objects (TNOs). As more and more TNOs were discovered, it was an evidence that they formed just another population of bodies in a collisional system. Today we see that the structure is complicated by the existende of at least three dynamically different populations: the 'Plutinos', around the 3:2 mean motion resonance with Neptune at 39.4 AU, the Classical Disk, from 40 to some 50 AU, and the Scattered Disk, with large eccentricities and inclinations (Gladman *et al.* 2001, Gladman *et al.* 2002). Beyond that region, a population of large objects ($D > 500km$) in a wide variety of eccentricities and inclinations is being discovered at present.

The present review tries to update and complement the comprehensive review by Davis *et al.* (2002), concentrating on the two major collisional systems in the solar system, the Main Asteroid Belt and the Trans-Neptunian region.

Section 2 is dedicated to summarize the available observational evidences, Section 3 will review the theoretical work developed up to the present, while the main numerical models and their conclusions will be revisited in Section 4. Section 5 will finally try and draw some conclusions, and especially formulate questions yet to be answered in the future.

Amidst all the devoted researchers who have intensely contributed to the knowledge and the understanding of small bodies in the solar system, Paolo Farinella (1953–2000) owns a special place in the recent past of this field. His peculiar skill for interconnecting different areas to explain actual phenomena was only equal to his special hability for seeding and keeping fruitful connections between researchers across the world. To the memory of him this review is dedicated.

2. Observational constraints

Any model of the collisional evolution of asteroids and TNOs has to be checked by trying to match the observed characteristics, those features of the belt that are the product of 4.5 billion years of collisional history. Various authors have attempted to infer the primordial population of asteroids by integrating backwards in time from the present belt distribution, but the inherent instability of the collisional problem prevents such results from converging, as expected from earliest Dohnanyi's result, which showed that under specific circumstances the asteroid population was collisionally relaxed and independent of the starting population.

Direct observables are the size distributions, the existence of Asteroids Vesta and Psyche, and the characteristics of asteroid families. Other observables may help constraining

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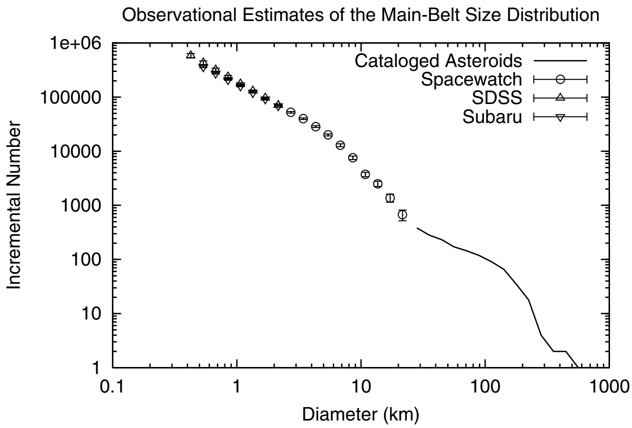

Figure 1. Estimates of the main-belt size distribution, as extrapolated from different observational surveys.

the collisional evolution of asteroids and TNOs, but they may be affected by modelling and non parameter–free assumptions: the distribution of craters on asteroids and on the satellites of planets satellites, the cosmic–ray exposure ages, the NEO populations, and the dust production rates, among others.

2.1. *Size distributions*

The first constraint on models of collional evolution of small bodies populations is the size-frequency distribution.

2.1.1. *Size distribution of the Main Asteroid Belt*

It is widely believed that at least asteroids larger than some 300 km are primordial objects, while the rest of the population is collisionally evolved. The bump in the mainbelt asteroid size distribution centered around 100 km has been explained in a variety of different ways: i) Davis *et al.* (1979), Davis *et al.* (1984) found that this feature marked the transition from the gravity strength regime to the strength–dominated regime and hence was a product of collisional physics. ii) Durda *et al.* (1998) found that this feature was a secondary bump produced by the wave from the strength-gravity regime which occurs at much smaller sizes. iii) Campo Bagatin *et al.* (2002) argued that this shows the effect of non–self–similarity in the physics of fragmentation, that produce a multi–fractal structure in the mass distribution of km–size objects.

Several lines of evidence point to the existence of a variable index in the size distribution of the small asteroid population. Cellino *et al.* (1991) analyzed IRAS data for different zones of the asteroid belt and different size ranges and found incremental size distribution indexes ranging from -2 to -4 for asteroids larger than a few tens of km. Present estimates assume a -4 exponent for the power–law of the distribution in the 5 km to 20 km size range. The Sloan Digital Sky Survey (SDSS) (Ivezic *et al.* 2001) and the Subaru Sub-km Main Belt Asteroid Survey (SMBAS) (Yoshida *et al.* 2003) find similar power–laws for the distributions of objects below 5 km in the size range from ~ 400 m to ~ 5 km. The SDSS finds an exponent of -2.30 ± 0.05 in the ~ 400 m to ~ 5 km size range, and the SMBAS finds -2.19 ± 0.02 for the ~ 500 m to ~ 1 km size range. For smaller sizes, Cheng (2004) assumes a -3.5 exponent based on the analysis of the size distribution of boulders on the surface of asteroid 433 Eros, visited by the NEAR probe.

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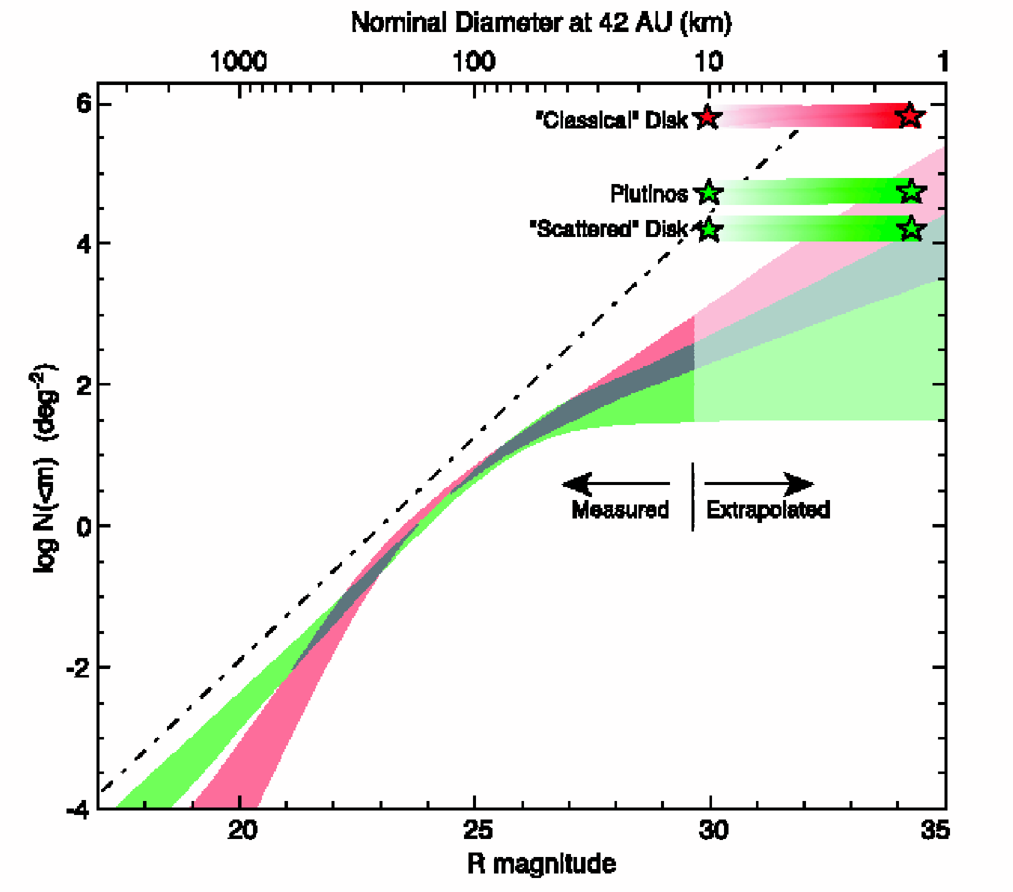

Figure 2. Bernstein *et al* (2004)'s estimates for the distribution of objects – both in R–magnitude and in related size—in the Trans–Neptunian region.

2.1.2. *Size distribution of TNOs*

Since the discovery of the first TNOs in 1992, many other objects have been discovered beyond the orbit of Neptune in a more or less serendipitous way. Sistematic surveys of the Trans-Neptunian populations have been started in the last decade (Gladman *et al.* 1998; Gladman *et al.* 2001, Chiang & Brown, 1999; Luu & Jewitt, 1998; Petit & Gladman, 2003) that have allowed to state the existence of three dynamically different populations for the approximately 1000 objects observed to date. Un-biased samples are needed in order to get reliable orbital elements for TNOs and be able to correctly characterise them dynamically. Nevertheless, it is not straightforward to determine size distributions for those populations, as strong uncertainties remain – among others – about the albedos of TNOs.

Bernstein *et al.* (2004) provided size-bands distributions for TNOs, extrapolating the result of a 0.02 deg^2 survey using the Advanced Camera for Surveys aboard the Hubble Space Telescope (HST), discovering objects down to $m = 28.3$. They show a clear pattern consisting in a steep power-law distibution for the large size end of TNOs, followed by a shallower (including values below the Dohnanyi's exponent) size distributions below a transition size around 70–100 km.

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It can easily seen that the situation is much more fuzzy that in the case of asteroids, and it is hard to say that unambiguous observables are available for TNOs at all.

2.2. *Vesta and Psyche*

A powerful constraint on the asteroid collisional history is the existence of the basaltic crust of Vesta, which dates back to the earliest era of the solar system. Any collisional model must preserve this thin crust during the collisional bombardment (Davis *et al.* 1984). HST observations of Vesta revealed the existence of a ~ 450 km diameter basin caused by the impact of a ~ 40 km diameter projectile (Marzari *et al.* 1996; Asphaug 1997). This impact, presumably the largest since Vesta's crust formed, provides a very specific constraint on Vesta's collisional history.

On the other hand, asteroid 16 Psyche appears to be the collisionally exposed core of a parent body which was virtually identical to Vesta. The possibility to disrupt the Psyche parent body without the formation of a family associated with it, while preserving the crust of Vesta, was investigated by Davis *et al.* (1999). They concluded that it was very difficult, but not impossible —based on collisional modelling— to create Psyche and preserve Vesta's crust, but other explanations for Psyche should be sought. Furthermore, recent work suggests a mean density for Psyche of $1.8 \pm 0.6 g/cm^3$ (Viateau 2000), which is inconceivably low for the iron core of a differentiated body.

2.3. *Asteroid families*

Asteroid families are an observable which is a direct product of collisions. There are over 60 statistically significant clusters identified in asteroid proper elements (Benjoya & Zappalà 2002). Marzari *et al.* (1999) used this number of recognized families in the present belt as a constraint on the overall asteroid collisional history, and found that a small mass initial belt best reproduced the observed number and type of families originated by disruption of parent bodies larger than 100 km diameter. Non–gravitational forces like Yarkovsky effect together with chaotic resonances can push family members to slowly disperse over time (Nesvorný *et al.* 2002).

3. Theoretical studies

3.1. *Asinthotic collisional evolution*

The task of analytic studies on the collisional evolution of the mass distribution of asteroids has been tackled in the past by various researchers: Pietrowski (1953), Hellyer (1970, 1971) and Dohnanyi (1969, 1971).

Dohnanyi's theory is especially important as it also includes and develops the studies made by the other quoted authors. The most important result of this theory is that, as the collisional process in the main asteroid belt gives raise to a cascade of fragments shifting mass toward smaller and smaller sizes, a simple power–law equilibrium mass distribution is approached under well defined assumptions on the collisional response parameters and on the size range. This equilibrium distribution extends over all the size range of the population, except near its high–mass end. It corresponds to a number of bodies dN in the mass interval $(m, m + dm)$, or in the diameter interval $(D, D + dD)$, proportional to $m^{-11/6} dm$ or to $D^{-3.5} dD$, respectively, with the proportionality coefficients decreasing with time as the disruptive process goes on. Relaxation to this equilibrium mass distribution may be sometimes fast: i.e., in the asteroid belt it occurs over a time span much shorter than the age of the solar system.

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Two critical assumptions of the Dohnanyi model are: (i) all the collisional response parameters are size–independent, implying that the transition from cratering to fragmentation outcomes occurs for a fixed projectile-to-target mass ratio, and no gravitational reaccumulation of fragments is taken into account. (ii) The population has an upper cutoff in mass, but no lower cutoff.

The $-11/6$ value of the mass distribution index has been recovered by Paolicchi (1994), and in a general way by Tanaka *et al.* (1996) who showed that the equilibrium exponent is independent on the details of collisional outcomes as long as the fragmentation model is self-similar. Williams & Wetherill (1994) have shown that the $-11/6$ exponent changes less than 10^{-4} when Dohnanyi's collisional physical assumptions — e.g., the relative importance of cratering and catastrophic breakup events, the mass distribution of fragments from a single impact, etc. — are varied in a substantial way. Martins (1999) found that for a non-stationaty state, the size distribution can be expressed by a power series of $m^{-5/3}$.

3.2. *Releasing Dohnanyi's assumptions*

The basic assumptions of Dohnanyi's theory are not fulfilled in real planetary collisional systems. In contraddiction with assumption (i), collisional response parameters are not size–independent, and they are often expressed as scaling laws describing how the collisional outcomes vary with target and impactor size. In its most general form, a scaling law extrapolates the outcomes of collisions —for which we have direct, physical experimental experience— to the outcomes of collisional events at size scales much larger (or smaller) than the ones that can be handled under laboratory conditions. One important component of scaling laws is determining the shattering impact specific energy, that is given in terms of the energy per unit target mass required for the catastrophic shattering of the target, Q^*_S, such that the largest fragment produced has a mass of one-half that of the original target. Dimensional analyses (Farinella *et al.* 1982; Housen & Holsapple 1990; Housen *et al.* 1991), impact experiments (Ryan 1992; Martelli 1994; Holsapple 1993; Housen & Holsapple 1999; Holsapple *et al.* 2002), and hydrocode studies (Benz & Asphaug 1999) show that Q^*_S scales as roughly $D^{-0.24}$ to $D^{-0.61}$ for strength-dominated targets. Recent results (Housen 2004) show that rotation may have an effect on the results of catastrophic fragmentation making it easier to shatter objects in rotation state.

The size dependence of Q^*_S in the gravity-dominated regime shows a dependence on D^{α}, with $\alpha \sim 2$, and it is due to the effect of the self–compression exerted by gravity on the body's interior at increasing sizes.

Another way to see the scaling problem is considering the critical impact specific energy, Q^*_D, the energy per unit target mass required for catastrophic disruption of the target, i.e., such that the largest resulting object, formed by partial reaccumulation of fragmente, has a mass one-half that of the original body (e.g., Davis *et al.* 1985; Love & Ahrens 1996; Melosh & Ryan 1997; Benz & Asphaug 1999). Estimates of Q^*_D scale as $D^{1.13}$ to D^2.00. Hydrocode studies (Benz & Asphaug 1999), numerical collisional models (Durda *et al.* 1998), and observations of asteroid spin rates (Pravec & Harris 2001; Pravec *et al.* 2002) suggest that the transition from the strength-dominated to the gravity-dominated regime occurs at target diameters about 100–500 meters, while the other quoted authors generally place the transition in the 1–10 kilometer size range.

Both self–gravity and strain–rate effects on the scaling of Q^*_S influence the resulting mass distribution in every single collision and they are expected to affect the collisional cascade in a noticeable way, as will be illustrated in sec. 4 (Fujiwara 1989; Davis *et al.* 1989; Davis *et al.* 1994; Campo Bagatin *et al.* 1994a). The self–gravity of celestial

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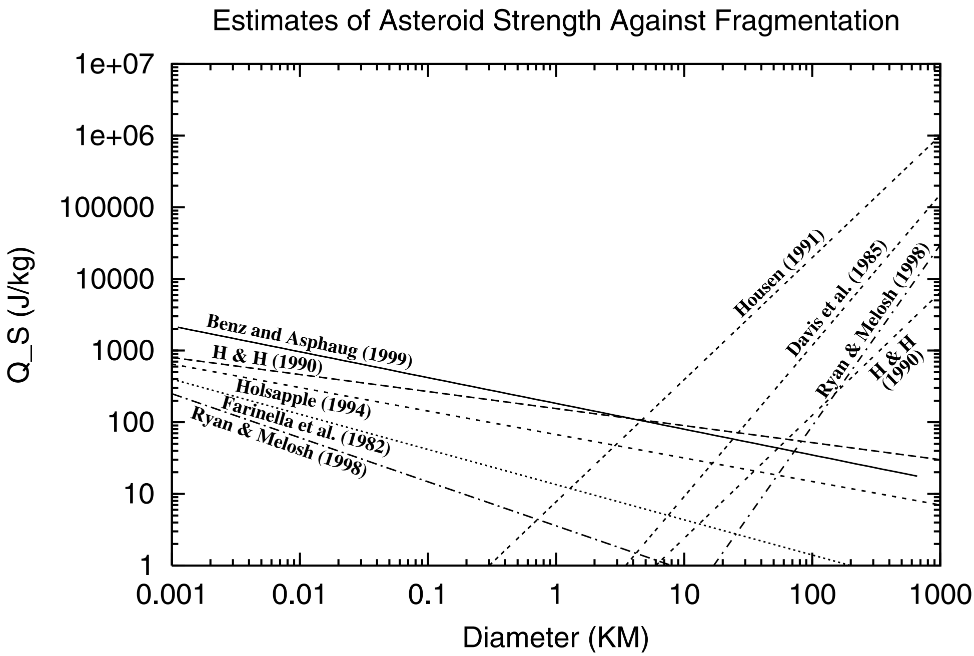

Figure 3. Different published estimates of the scaling laws for the specific energy for fragmentation, Q_S^*.

bodies grows at increasing sizes, its effect being —apart from the self–compression quoted above— to directly affect the escape velocity of the produced fragments remarkably, especially in targets greater than a few–km size. This effect combines with the experimental results found by many authors (Davis & Ryan, 1990; Nakamura & Fujiwara 1991; Giblin *et al.* 1994; Giblin 1998), indicating a shallow mass–velocity dependence in the velocity distribution of the ejected fragments of a fragmentation event as a function of mass, and they are yet another source for non–self–similarity.

The large amount of data available today for asteroids (about 200,000 catalogued) seem to confirm that the real distribution departs from a single exponent power–law, at least for objects larger that a few km. The fact that the size distribution of multi–km objects is not represented by a single exponent power–law is not surprising from a theoretical point of view. As a matter of fact, the Dohnanyi's result may be interpreted in terms of fractal distributions, that are the natural outcomes of self–similar multiplicative cascades. When the cascade is non self–similar the whole process is rather described by multifractal distributions, and they may be conveniently fitted in this way, as shown by Campo Bagatin *et al.* (2001). Deviations from Dohnanyi's exponent may occur when size–dependent specific energy for fragmentation (or disruption) holds either in the strenght or in the gravity regimes: O'Brien & Greenberg (2003) showed that if $Q{*}_S \propto D^s$, then $d^N(D, D + dD) \propto D^{-p}$, with $p = (7/2 + s)/(3/2 + s)$, and that wavy behaviour may be triggered due to transition between the two scaling regimes.

Assumption (ii) in Dohnanyi's theory is not fulfilled either: in fact, it is not clear what the size range of the asteroidal and TNO populations are. In some case the greatest body is well known (e.g.: Ceres, for the asteroid belt), but this is not the case for the smallest end of the distribution, and we do not know if there is a more or less sharp size

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cutoff due to physical constraints or to the effect of non–gravitational forces. The consequences of the existence of such a cutoff at small sizes were explained and discussed by Campo Bagatin *et al.* (1994a), resulting in deviations from a single power–law, as wavy patterns appear in the numerically simulated distributions of equilibrium. Cheng (2004) reexamined analytically the colisional evolution in the asteroid belt and calculated the relative importance of various collisional processes versus asteroid size, confirming that self–similar size distributions do not apply to asteroids due to size–dependent collisional processes, and underlines that as destruction and creation rates do not balance, a collisional model cannot explain why the asteroid size distribution is close to the Dohnanyi's slope.

Notwithstanding the enumerated 'emendaments' to the Dohnanyi's theory, his analytical finding is still a very useful result, as it is valid for the average distribution of collisional systems in stationary conditions.

3.3. *Relative velocities and collision probabilities*

In order to understand the actual amount of impacts that may occur within a collisional system, a useful magnitude is the intrinsic collisional probability, P_i, that gives the collision rate per unit cross-section area. The actual average number of collisions onto a target of radius R_T by projectiles of radius R_P within a time ΔT is then given by:

$$N_{col} = P_i(R_T + R_P)^2 N_T N_P \Delta T$$

where P_i depends on the average relative encounter velocity and on the available volume. N_T and N_P are the number of targets and projectiles, respectively. The basic theory for calculating collision rates and speeds was developed by Öpik (1951) and Wetherill (1967) and applied by various researchers in subsequent years, but there has been recent work to refine such calculations and to extend them to both Trojans, Hildas and TNOs in recent years. The main corrections are related to specific features of the orbital distribution of the population under study or to statistical mechanics (Greenberg 1982; Farinella & Davis 1992; Bottke & Greenberg 1993; Bottke *et al.* 1994; Vedder 1998; Dell'Oro & Paolicchi 1998; Dell'Oro *et al.* 1998, Dell'Oro *et al.* 2001). Alternatively, different authors have preferred a direct numerical approach based on the integration of the orbits of asteroids over a sufficiently long timespan. The derived distribution of close encounters and mutual speeds recorded during the integration can be extrapolated to infer the collision probability and characteristic impact speed (Yoshikawa & Nakamura 1994; Marzari *et al.* 1996; Dahlgren 1998).

4. Collisional evolution models

4.1. *The asteroid belt*

To trace the detailed time history of collisional evolution and to include realistic collisional physics requires numerical models. As the asteroid belt is the best known between the solar system collisional systems, most of the numerical research concentrated on its study.

Even if not all models use the same physical characterisations, they may depend on a number of poorly known critical parameters that govern the mass distribution and the re-accumulation of fragments after their formation:

1) The scaling laws for Q^*_S or Q^*_D may vary widely, as outlined in section 2.

2) The inelasticity parameter, f_{KE}, that determines what fraction of the relative kinetic energy of the collision goes into kinetic energy of the fragments. Its value may well

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depend on the composition, internal structure, and size of the bodies, and it is often taken between1% and 10%. f_{KE} is also implicitely embedded into the specific energy for disruption (Q_D^*) (Campo Bagatin *et al.* 2001).

3) A relationship of the form $V(m) = Cm^{-r}$ may aplly for the mass and velocity of ejected fragments, like argued experimentally (Nakamura *et al.* 1992; Giblin 1998), with mass–velocity dependence ranging from none to $r = 1/6$, as found by Giblin (1998) and Giblin *et al.* (2004). This relationship is important because even a shallow dependence does make a significant difference in the amount of mass that can be re–accumulated by objects. The effects of this dependence have been studied by Petit & Farinella (1993) and Campo Bagatin *et al.* (1994b).

Davis *et al.* (1985) pioneered the era of collisional evolution models based on realistic collisional physics, including the effect of self–compression, and provided the first attempt to fit current observed distributions with a self–consistent numerical model.

Davis *et al.* (1994) and Campo Bagatin *et al.* (1994a) introduced new algorithms for the collisional outcomes of single asteroidal collisions, taking into account experimental results as well as scaling–laws based on dimensional analysis. Campo Bagatin *et al.* (1994a) also studied the effect of releasing (ii) assumption in Dohnanyi's theory, including a sudden break in the size distribution of the studied population which introduced a wavy pattern in the final distribution.

Durda (1993) and Durda & Dermott (1997) examined the influence of Q_D^* on the shape of an evolving size distribution by showing that the power–law exponent of a population in collisional equilibrium is a function of the size dependence of Q_D^*. When Q_D^* decreases with target size, as is the case in the strength-scaling regime, the slope index of the equilibrium size distribution is steeper than Dohnanyi's; instead, when Q_D^* increases with size, as in the gravity-scaling regime, the resulting slope index is shallower than, -3.5. Durda *et al.* (1998) presented results from numerical experiments illustrating in a more systematic fashion the sensitivity of an evolved size distribution on the shape of the strength scaling law. They found that if there is non-linearity in the relationship between $logQ_S^*$ and $logD$ then a structure is introduced into the evolved size distribution due to non-linearity in collisional lifetimes of the colliding objects, a result also shown in Campo Bagatin (1998).

Gil–Hutton & Brunini (1999) included the effect of early collisions by scattered comets from the Uranus–Neptune zone.

One of the most interesting issues about small bodies in the solar system is their internal structure (Asphaug *et al.* 2002; Britt *et al.* 2002). Campo Bagatin *et al.* (2001) modelled asteroid collisional evolution considering two different kinds of objects: monoliths (simulated by high f_{KE}), and gravitational aggregates (low f_{KE}) (often called rubble–piles) (Richardson *et al.* 2002). The relative number of gravitational aggregates can be estimated to be be between 50%to 100% in the $10 - 200$ km range, depending on the adopted scaling law and on the choice of other collisional parameters, especially the inelasticity parameter, f_{KE}. The size scale at which a significant ratio of gravitational aggregates is expected seems to depend strongly on the reaccumulation model. For instance: assuming a mass-velocity relationship with r = 1/6 provides some 10% aggregate asteroids for 2 km-size bodies, while ignoring that dependence avoids reaccumulated objects up to some 10 km. Even if reaccumulation is treated in a simple way in the model, it shows that it is necessary to make further efforts in understanding the dependence of ejection speeds of fragments on their masses.

Vokhroulický & Farinella (1998) revived the effect predicted by the russian engineer Ivan O. Yarkovsky, who noted (1900) that the diurnal and seasonal heating of a rotating object in space would cause it to experience a radial force that —even if small— could lead

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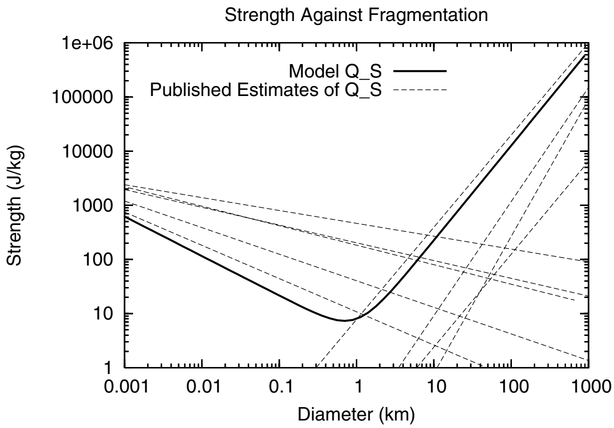

Figure 4. O'Brien & Greenberg (2005) recent best fit scaling law for Q^*_S.

to large secular effects in the orbit of small bodies. The Yarkovsky effect is a potential mechanism for removal of asteroids from the main belt, and further calculations have demonstrated that it may help to explain the mechanisms of refilling the Near Earth Asteroids populations (Bottke *et al.* 2000, and Bottke *et al.* 2002)). Penco *et al.* (2004) have included this effect in their model by updating the Campo Bagatin *et al.* (1994a,b, and 2001) algorithms, and found that the Yarkovsky non–gravitational force may affect significantly the absolute number of objects at given size ranges, but that it is not efficient enough to produce unambiguous overall effects in the final size distribution, that is. A wave pattern driven by this effect alone may arise, but it can be completely overruled by other effects (i.e., a low–mass cutoff, non–self–similarity in Q^*_S, etc.). In any case the effect on the size distribution cannot probably be ignored if one wants to compute a reliable Q^*_S scaling law from the observed size distributions.

Bottke *et al.* (2005) collisional evolution model includes an approximate method to estimate the effect of early dynamical depletion evolution governed by Jupiter's accretion. They find that the best fit to the observed asteroid belt distribution and to other observables correspond to an evolution which rapidly reached the wavy pattern recently observed, including the bump at the 100–km size. They conclude that this should be a fossile signature of the initial evolution of the belt, settled at the end of the Late Heavy Bombardement period, and that the distribution of objects larger than this size is probably unchanged since that time. The scaling law for Q^*_D that allows to achieve such results is very similar to results produced by numerical hydrocode simulations of asteroid impacts (Benz & Asphaug 1999).

O'Brien & Greenberg (2005) tackled the issue of collisional evolution including an evaluation of the Yarkovsky non–gravitational force and considering the removal of objects from the asteroid belt by dynamical effects. The authors explored the parameter space as to fulfill the available observables, making the model reproduce fairly well the observed main asteroid belt distribution and the estimated size distribution of NEAs by means of a best fit scaling–law for Q^*_S and Q^*_D (Figure 4).

4.2. *The trans–Neptunian region*

The physical properties of TNOs are likely to be different from those of asteroids. TNOs seem to be made of different kinds of ices with none to some extent of mixture with silicates, and the recent Deep Impact experiment on comet Temple I shall hopefully

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throw some light on this issue. A few set of experiments have been run impacting pure and porous water ice at some hundred meters per second (Ryan *et al.* 1999; Giblin *et al.* 2004), or silicate–ice porous mixtures (Arakawa *et al.* 2002). Authors agree in estimating the energy density for shattering (Q^*_S) in the $10^5 - 10^6$ erg/g^3 range, while f_{KE} varies around 5%.

The first numerical model of the TNO populations was performed by Davis & Farinella (1997), based on Davis *et al.* (1994)'s former model for the collisional evolution of asteroids. They concluded that the population of TNOs larger than 'break' size 100 km are not significantly altered by collisions, while objects with size below that seem to be distributed close to the steady–state. They also argue that the population of Centaurs can hardly be considered to be originated by collisions in the TNO region, while short–period comets might well be collisional fragments that experienced some type of alteration in the inteior of the parent bodies.

Kenyon & Bromley (2004) modelled the TNO region by means of a multi–annulus coagulation code; their results show a 'break' size in the 1–30 km range, a shallow power–law index (-3.5) in the size distribution of TNO populations at large sizes and an even shallower one ($b \simeq -3.0$, that is below the steady state distribution) for bodies below the break size. These results are not in agreement with estimations from observations and with the results of models by other authors. However, their simulations seem to be affected by the presence of a sharp cutoff at the low–size end, resulting in the standard pattern for the final distribution shown by Campo Bagatin *et al.* (1994a)

Krivov *et al.* (2005) developed a detailed model for the collisional evolution of a disk of particles evolving through collisions by considering mass and orbital elements as independent variables of a phase space, instead of the classical mass–semimajor axis binning. They derive a kinetic equation for a distribution function that contains information on the combined mass, spatial and velocity distributions of particles. When applied to the TNO population, the model provides qualitatively similar results to Davis & Farinella (1997) and to Bernstein *et al.* (2004), as far as the two–slope power–law for the size distribution is concerned. They also investigated the dependence of collisional lifetime on size, and the mass density as a function of size at given heliocentric distances, as well as the collisional mass loss with varying initial masses.

Pan & Sari (2005) semi–analytical model calculates the size dependence distribution for TNOs considering them as gravity–dominated objects with negligible material strength. In this way they evaluate the size distribution and find that the largest objects are distributed according to an exponent -5 down to a transition size located around 40 km, somewhat below numerical and present observational estimates. Smaller object are found to follow a much shallower power–law distribution, with an exponent close to -3.

Campo Bagatin & Benavidez (2005) modelled the TNO region within a classical particle–in–a–box scheme, by dividing it into three different –but potentially interacting–populations, according to the dynamical characterisation presently accepted. They follow the evolution for each of the three populations and find the common pattern shown by other authors: two power–law distributions linked at a transition size. The three populations have different transition sizes, with an average around 100 km in agreement with Davis & Farinella (1997), Krivov *et al.* (2005) and Bernstein (2004). The model also shows that the final power–law ditribution for objects larger than the transition size is basically the same that at the beginning of the simulations, whatever the initial conditions were, implying that this population suffered little collisional evolution and that it should be mostly primordial. On the other hand, the power–law size distribution of objects below the transition size does not seem to be affected by different initial conditions, and it seems to be in a relaxed state: different initial conditions give raise to different

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absolute numbers of objects in the size intervals, but they produce the same exponent for the power–law size distribution.

5. Open questions and conclusions

Remarkable improvements to the knowledge of the collisional evolution of populations of asteroids and TNOs have been achieved in the last two decades, especially due to the increased volume of data on the asteroid size distribution and the TNO populations; the close encounters with asteroids and comets have provided important clues about the internal structure and collisional rates. As a matter of fact, the modelling of the collisional evolution of asteroid populations is a very complex problem, due to the fact that a number of poorly known free parameters are embedded in the modelling of the involved physical phenomena. More observational data —on one hand— and more refined modelling techniques —on the other hand— are needed in order to get a comprehensive and self-consistent picture of fragmentation and collisional evolution of small bodies populations. Even if advances in the correct description of fragmentation physics has been possible, a better understanding of what is the outcome of energetic collisions certainly remains a challenge for the future.

The development of smooth particle hydrocode (SPH) calculations of the fragmentation process coupled with N-body integrators to follow the trajectories of fragments once the material interactions have ceased (Michel *et al.* 2002; Michel *et al.* 2004) have introduced a new paradigm for collisional outcomes. The new models argue that gravitational reaccumulation is the fundamental mechanism for forming individual bodies during disruptive collisions. Hence, the velocity field established by the collision would determine the number and size of fragments, not the propagation of cracks that fracture material bonds. Further work is certainly needed in this area, but this approach suggests a very different physical basis for understanding the outcomes of disruptive collisions. A better understanding of the response of gravitational aggregates to collisions is indeed necessary as well. Once these techniques will be reliable enough to be sistematically run, it will be desirable that in the future they may provide an alternative way of feeding the algorithms for the solution of the kinetic equations typical of the collisonal evolution problem.

Between the very many interesting issues regarding the collisional evolution of asteroids, a number of open questions are especially waiting to be answered:

• Collisions have modified asteroid rotation rates over solar system history, so information about the collisional history of the belt is embedded in the spin rates of asteroids of all sizes. How do rotations evolve as part of the collisional evolution? As discussed by Davis *et al.* (1989), the uncertainties in modelling how collisions alter rotation rates are so large that any definitive work on this topic is yet to be done and there have been no publications in the past decade on the collisional alteration of asteroid rotation rates. Do rotations have some effect on fragmentation, like suggested by Housen (2004)? Does this signicantly affect the final size distribution of asteroids?

• The somehow wavy distribution observed in the actual asteroid size distribution may be the result of the interplay between the existence of scaling–laws —with the effect of propagating wavy patterns induced by non uniform Q^*_S— and the potential existence of a cutoff in the small–size end, abrupt enough to trigger its own wavy pattern. Then, how is the small-particle end of the actual asteroid population, and how does it affect the overall evolution? The answer to this question is not obvious, but many non-gravitational forces do indeed act on interplanetary matter and are efficient at different sizes (Burns, 1979): the solar wind, Poynting-Robertson drag, and the Yarkovsky effect. Clearly, more

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work is needed in this area to explicitly treat within collisional models the various non-gravitational forces that act to remove especially dust–size partticles from the asteroid population, and especially to determine how strong and abrupt a small–mass cut-off must be in order for wave–like features to appear in the evolved size distribution. One of the key matters in this issue is the way sub-cm particles do fragment when they undergo shattering events. Do scaling–laws still make sense for collisions among dust particles? Can the collisional physics at this size range rather be explored with more detail?

• The lack of self–similarity implies a multifractal structure for multi–km objects — rather than the single exponent fractal behaviour characteristic of self–similarity— that may be used to match their distribution. Starting from observed collisional populations, and establishing the driving parameters of the corresponding multifractal distributions, is it possible to relate them with critical parameters governing the collisional cascade, such as Q^*_D? In other words, could we recover potatoes back from mushed potatoes?

As for the populations of Trans–Neptunian Objects, the state of knowledge is indeed, at present, at a lower level respect to the asteroid belt; therefore there are many issues pending in order to allow reliable comparisons of collisional evolution studies with the observed populations.

The first, and more urgent issue is to achieve a large reliable list of orbital parameters which are not affected by any bias. Establishing the dynamical characterisation of these objects is the cornerstone on which to build further understanding. Related to this is the recent discovery of popolations of massive objects well beyond $50AU$ that may, once again, change our view and understanding of the outer solar system, as well as of the mechanisms of its formation.

A second issue is certainly to acquire more data on the physical characteristics of TNOs, in particular on their albedos and surface compositions, that are still not univocally determined.

Some of the main questions that the study of collisional evolution of TNOs may help to answer are:

• How did the Scattered Disk, the Centaurs populations and the outer part of the Trans–Neptunian region form and evolve in time?

• What was the initial mass of this region?

• Are TNOs larger than some size mostly pristine bodies? And what fraction of km–size populations are gravitational aggregates?

More and more questions will soon add, hopefully, as answers will be found to the above ones: this is the main rule of the game of knowledge.

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