Completing the Inventory of the Solar System
ASP Conference Series, Vol. 107, 1996
T. W. Rettig and J. M. Hahn, eds.

Asteroid Families, Old and Young

P. Farinella

Gruppo di Meccanica Spaziale, Dipartimento di Matematica, Università di Pisa, Via Buonarroti 2, I–56127 Pisa, Italy

D.R. Davis

Planetary Science Institute, 620 North 6th Avenue, Tucson, Arizona 85705–8331, U.S.A.

F. Marzari

Dipartimento di Fisica, Università di Padova, Via Marzolo 8, I–35131 Padova, Italy

Abstract. Some recent progress is reported on the long–standing problem of estimating asteroid family ages, namely of dating in a reliable way the impact break–up or cratering events which formed the observed families. Recent results on this issue come from improved estimates of asteroid collisional lifetimes, from numerical modelling of the post–formation "erosion" of families, from a "chaotic chronology" method based on dynamical diffusion–like effects in proper element space, and from recent *Galileo* observations of (243) Ida, one of the largest Koronis family members, and its satellite Dactyl.

1. Introduction

In his 1924 paper on the families of asteroids, K. Hirayama stated: *"The existence of the asteroid families will no longer be questioned. It is too manifest to require confirmation by the calculation of probabilities, or by future discoveries of asteroids. A certain number of the suspected families, however, will probably be established by future discoveries"*. He went on stressing that: *"The matter of real importance which must be left for future enquiry is the determination of the ages in which the original bodies were broken up into fragments. This is not easy in any way..."*.

Today we have discovered many more families, and also realize that the mechanism by which asteroid families have been formed over solar system lifetime is the fragmentation of precursor asteroids due to rare, large–scale interasteroidal collisions. However, dating in a reliable way these events in specific cases has proven to be a very difficult challenge indeed. Here, we will shortly report on some recent findings on this problem. In particular, in Sec. 6 we will discuss some implications of the recent spacecraft observations of the Koronis family asteroid (243) Ida and its moon Dactyl, encountered in 1993 by the *Galileo* probe *en route* to Jupiter.

2. Asteroid families: the state of the art

According to the most recent searches (Bendjoya, 1993; Zappalà et al., 1994, 1995), about 1/3 of the main-belt asteroids with well-determined orbits belong to some 30 statistically robust dynamical families. Many other "clumps" of bodies, generally with less than 10 members, might be either statistical flukes or real families, and must await further studies for a final assessment. Some families are better described as "clans", that is broad groupings whose statistical significance is strong, but whose memberships and internal structure cannot be defined unequivocally from the orbital data alone. These searches were based on the work of Milani & Knežević (1990, 1992, 1994) to derive asteroid proper elements from a huge catalogue of accurate osculating elements, through the application of a very refined secular perturbation theory. Subsequently, two different automated statistical procedures were applied to discriminate real families from random groupings and to define the memberships of the families. The latest family search, reported by Zappalà et al. (1995), was performed in a sample of about 12,500 proper elements triplets (including some 7,900 unnumbered asteroids with relatively well-determined orbits) using both the *wavelet analysis* technique of Bendjoya (1993) and the *hierachical clustering* method of Zappalà et al. (1994), and comparing in some detail the two sets of results. The different methodologies involved in this work have been reviewed and discussed by Milani et al. (1992), and the reader is referred to that paper for a self-consistent presentation of the various steps required for identifying families.

As pointed out by Zappalà & Cellino (1994) and Zappalà et al. (1995), the comparison between the family lists obtained by the two independent clustering procedures shows a remarkable overlap, and as mentioned above about 30 families have a large fraction of their members in common. The agreement is also good with the family list obtained by Lindblad (1992, 1994) from a smaller proper element set, and in most cases the families identified by the automated procedures have plausible counterparts among the most populous families identified, with a visual procedure and an *a posteriori* "Poisson test", by Williams (1989, 1992). We refer to Zappalà et al. (1994) and Farinella (1994) for a discussion of why the agreement with Williams is poorer for the small families, with less than about 10 members.

In the current context, it is remarkable that in the list of the most reliable families we have a wide variety of collisional outcomes, ranging from fragments ejected after giant cratering events on 500–km sized asteroids (Vesta, Pallas, Hygiea), to the partial disruption — probably limited by self–gravitational reaccumulation — of fairly large bodies (Themis, Eunomia, Eos, Adeona), to the complete break–up of parent asteroids smaller than 50 km in diameter. As we shall see, families of different types have probably also different typical ages.

3. Family ages and asteroid collisional lifetimes

Collisional lifetimes (τ) of possible family parent bodies of different diameters (D) vs. the impact of a projectile of diameter $> d$ can be estimated through the simple formula

$$\tau^{-1} = \frac{P_i D^2}{4} N(> d)\,, \tag{1}$$

where $N(> d)$ is the number of existing asteroids of diameter larger than d, and $P_i = 2.85 \times 10^{-18}$ km^{-2} yr^{-1} is the average intrinsic collision probability for main–belt asteroids as defined by Wetherill (1967) and calculated numerically by Farinella & Davis (1992) and Bottke et al. (1994). In Farinella (1994), this formula was used to derive both the lifetimes of single asteroids and the typical intervals separating in the main belt two disruption events involving targets in a given size range. Of course, in most cases the relevant factor $N(> d)$ is poorly known, as it depends on both the diameter d of the smallest projectile which can cause a given collisional outcome (e.g., catastrophic target disruption), and on the size distribution of small asteroids. We have used the results of Housen et al. (1991) and Petit & Farinella (1993) on the former problem and those of Davis et al. (1994) on the latter one. Alternative choices — e.g. taking into account hydrocode simulations of impact disruption events to find out how the critical projectile–to–target mass ratio scales with size (Davis et al. 1995; Melosh et al. 1994, p. 1117) — can change the results, but only within about plus or minus a factor two. Thus the following conclusions are reliable at a semi–quantitative level.

¿From the collisional lifetimes of their parent bodies, family ages may be expected to span at least a couple of orders of magnitude. As for families generated by catastrophic break–up, their ages probably range from $1 - 4 \times 10^9$ yr for those resulting from the disruption of targets 200–400 km across (Themis, Eunomia, Eos, Adeona), to 10^8–10^9 yr for disrupted parents in the 100–150 km diameter range (e.g., Maria, Erygone, Padua, Veritas), down to less than 10^8 yr for even smaller parent bodies. A particular case could be that of the Koronis family, for which several lines of evidence suggest a complex collisional history rather than a single break–up event (see Secs. 5 and 6 later). In general, the above statistics supports the conclusion that for parents larger than about 200 km in diameter we are probably seeing all the major families ever created in the asteroid belt, whereas families from smaller parent bodies have been continuously "erased" by subsequent disruptive collisions, and therefore are detectable only if they are relatively young. This process will be discussed in some more detail in Sec. 4.

As for families generated by giant cratering events, we remark that in the 500 km diameter range collisional disruption appears unlikely. However, smaller impacts (say, by projectiles 20 to 50 km across) may generate large impact basins and eject swarms of fragments up to ≈ 10 km in size at velocities sufficient to escape the parent's gravity (i.e., exceeding ≈ 300 m/s). Using Eq. (1) with $D = 500$ km and $N(> 30$ km$) = 1500$, we can calculate that for every existing target one or two such events are expected over the solar system history. This has been confirmed by numerical simulations of the asteroid collisional evolution (Davis et al. 1994, Marzari et al. 1996), and indeed matches well the observed families: all the three existing asteroids in this size range — (2) Pallas, (4) Vesta, and (10) Hygiea — are the major members of three crater–type families, consisting of one large asteroid surrounded by a swarm of much smaller bodies. Binzel & Xu (1993) have obtained strong evidence from spectroscopic observations of the minor members of the Vesta family that they do come from Vesta's basaltic crustal layer. These bodies have now been assigned to the V taxonomic type, which formerly included only Vesta and some small near–Earth asteroids. Similar results for the Hygiea and Pallas families cannot be easily obtained, as the spectra of these two bodies are less distinctive than Vesta's with respect to the background asteroids.

4. Collisional erosion of families

In this Section we summarize the recent work of Marzari et al. (1995) on the post–formation evolution of families and the corresponding implications concerning family ages. These authors interpreted the observed properties of asteroid families as recognizable outcomes of specific catastrophic disruption events. The initial size distribution of a family is expected to resemble a power law, according to most laboratory experiments on high–velocity impacts, and its dispersion in the orbital element space is related to the energy of the collision. However, subsequent collisions modify both the sizes and the orbits of family members, so the distributions that we see today can be quite different from those following the break–up of the parent body. Thus, the relationship between the original and the present size and orbital distributions can be used to estimate an evolutionary age of a family.

Marzari et al. (1995) developed a computer model which starts with the break–up of a parent body to form a family and then follows the subsequent collisional evolution of the family members. With this model it is possible to keep track of both the sizes and the orbits of the members and visualize how a family appears at different evolutionary stages. It was found that the size distribution becomes less steep with time while the dispersion in proper element space slowly increases. By matching the distribution of sizes and orbits predicted by the model at different evolutionary ages with those observed at present for the real families, it is possible to estimate the ages of the families. The uncertainties affecting these estimates are mainly due to the present limited understanding of collisional break–up processes for bodies hundreds of km in size, and to the poor knowledge of the size distribution of small asteroids. This last uncertainty affects in the same way the estimates of the cratering ages of (243) Ida and (951) Gaspra, the two asteroids encountered by the *Galileo* probe (see Sec. 6).

The Marzari et al. (1995) model has been used to describe the possible evolutionary histories of the three most populous and well known Hirayama families: Themis, Koronis and Eos. The Themis family appears to be the outcome of the catastrophic disruption of a 380 km size parent body that occurred between 2 and 3 Byr ago. This very large–scale disruption event probably has been unique in the history of the asteroid belt. As we remarked in Sec. 3, this is confirmed by the fact that the three existing asteroids somewhat larger than the inferred Themis parent body (Vesta, Pallas and Hygiea) are the largest members of very different families, apparently formed by cratering impacts. The Koronis and Eos families appear to have been formed from smaller parent bodies, but peculiar features characterizing both these families seem to require specific processes or events. Koronis' size distribution has several bodies of comparable size at the large diameter end, which could be explained if the largest fragment of the initial break–up underwent subsequent fragmentation (see Sec. 6). This interpretation of Koronis' size distribution allows one to assume for the parent asteroid a larger body (diameter of about 200 km) with respect to some previous estimates (Gradie et al. 1979, Zappalà et al. 1984) and to set an upper bound to the age of the family of about 2 Byr.

Compared to Koronis, the impact event that generated the Eos family was very probably more energetic and involved a larger parent body (with a higher escape velocity), as indicated by the observed mass distribution. Nevertheless, the Eos family looks more clustered in semimajor axis (though wider in eccentricity) than the Koronis family. This "anisotropic" orbital distribution requires either a peculiar fragment velocity field, or the action of poorly understood dynamical processes on the orbits of its members. The model of Marzari et al. (1995) generates an isotropic distribution of ejecta velocities and, as a consequence, cannot reproduce the peculiar orbital distribution of this family. Due to the weak constraints from comparing the model with the real family, the age estimate for the Eos family (a few hundred Myr) is only indicative.

In a subsequent paper (Marzari et al. 1996), a similar model has been applied to study the Vesta family. In this case the size and ejection velocity distribution of the fragments have been predicted from current impact cratering physics, in agreement with the idea that this family was generated by one or more large–scale cratering events. The observed morphology of the family in proper element space suggests two possible scenarios: (i) The family is the outcome of a major cratering event, resulting from the impact of an asteroid $\approx$ 40 km in diameter on the surface of Vesta about 1 Byr ago, and followed by a more recent lower–energy impact (by a projectile $\approx$ 20 km in diameter), producing the family's subgrouping close to the 3:1 mean motion Jovian resonance. (ii) A single impact occurred $\approx$ 1 Byr ago and formed the entire family at the same time. In the latter case the additional assumption must be made that the fragments were ejected isotropically over a hemispheric region of Vesta, instead of being concentrated near the surface of a 90° aperture cone, as suggested by laboratory impact experiments with planar targets. This different ejection geometry yields a more scattered distribution of the orbital elements, resulting into a better agreement with the observed family. In both scenarios the cratering event(s) which formed the family is/are likely to have injected a significant number of km–sized and smaller fragments into the 3:1 resonance, thus generating V–type near–Earth asteroids and the HED (basaltic achondrite) meteorites. However, it appears likely that the current influx of HED meteorites cannot be directly traced back to the family–forming event(s), but results from more recent, smaller impacts on Vesta (or other family members).

5. Family ages from "chaotic chronology"

Another method to estimate family ages is based on dynamical arguments. Within some tens of thousands of years planetary perturbations affect in a differential way the initially close osculating elements of the family members, so that the family tends to spread out in the osculating element space. This is the main reason for using proper elements in searching for families, as it was first realized by Hirayama himself. However, proper elements are not exactly constant, but undergo a similar (although much slower) "diffusion" process as time passes. Measuring the rate of this diffusion and comparing it with the size of the region occupied by the family in proper element space can set an upper limit on the age of the family itself. Already in 1973, Yuasa tried to exploit the quasi–constancy of the sum of the proper apsidal (ϖ_p) and nodal (Ω_p) longitudes, to derive family ages from correlations between ($\varpi_p + \Omega_p$) and $d(\varpi_p + \Omega_p)/dt$, estimated from analytical theories. However, Farinella et al. (1989) compared the predictions of such theories with the results of numerical integrations of asteroid orbits, and concluded that this method can yield just lower bounds to the family ages of the order of 10^6 yr, unless of course the family is younger. But this time span is so short compared to the collisional lifetimes discussed in Sec. 3 that it appears unlikely that the most prominent observed families are so young — although the situation may be different for some families formed from relatively small parent bodies.

The same basic concept nowadays can be used in a somewhat different, but potentially more fruitful way. As shown by Milani & Nobili (1992) and Milani & Knežević (1994), the proper elements of many asteroids undergo a slow chaotic diffusion, caused by high–order secular or mean motion resonances. In most cases, this chaotic diffusion is so slow that families can still be recognized billions of years after their formation. But sometimes a few family members wander in proper element space at a higher pace, so that they exit from the region occupied by most other members of their family after a characteristic time much shorter than the age of the solar system. In this case, this characteristic time provides an approximate upper limit to the age of the family.

Milani & Farinella (1994) have identified a concrete example of this phenomenon in the Veritas family, a very compact cluster of asteroids located in the outer part of the main belt, which appears to be the outcome of the catastrophic disruption of a parent body about 150 km across. Integrating backward in time the orbits of 7 Veritas family members (and also of 4 nearby nonfamily asteroids), they found that the proper elements of two members, including (490) Veritas itself, evolve chaotically at such a rate that they would have been unlikely to be found in the family before about 50 Myr ago. Due to the stochasticity of chaotic orbits, the argument is only a probabilistic one: taking this into account, one can conclude that the age of the family is unlikely to be longer than 50 Myr. Therefore, the origin of this family probably represents one of the most recent catastrophic disruption events involving a sizeable target asteroid. Actually, for $D = 150$ km, Eq. (1) yields $\tau \approx 3 \times 10^{10}$ yr, and with ≈ 100 potential targets of this size one such event should take place approximately every 300 Myr. Therefore an age of the order of 50 Myr is not unreasonable for the Veritas family.

Another interesting case from the dynamical point of view has been discussed by Milani & Farinella (1995). Asteroid (2953) Vysheslavia, a Koronis family member about 15 km in diameter, very close to the outer edge of the 5:2 Kirkwood gap, has been shown by numerical integrations to fall into the resonance; then it approaches Jupiter and ends up into a hyperbolic orbit. The typical dynamical lifetime is of the order of 10 Myr. This "marginally unstable" region of the orbital element space bordering the 5:2 resonance is only $\approx 10^{-3}$ AU wide in semimajor axis. Thus Vysheslavia has stayed in its current "dangerous" location in orbital element space for a time much shorter than the age of the solar system, almost certainly less than 100 Myr. Several hypotheses are possible on the origin of this object, including a comparatively young age of the whole Koronis family or of a subset of it, generated by a "secondary" break–up event, or alternatively the implantation into a quasi–stable main–belt orbit of a stray body coming from a comet–type orbit. But unless other objects "on the brink" are discovered in the family, only physical observations have the potential to discriminate among these possibilities.

6. Family ages: Constraints from (243) Ida and its satellite

The heavily cratered surface of (243) Ida (one of the largest Koronis family members) was revealed by the first close–up image returned in 1993 from the *Galileo* probe. For craters larger than 1 km across, Ida's crater area density is 5–10 times the density earlier observed on (951) Gaspra (Chapman 1994, Belton et al. 1994, Chapman et al. 1996). This leads to a cratering age for Ida of 1–2 Byr, surprisingly old when compared to some pre–encounter estimates (Binzel 1988) and to the collisional lifetimes inferred in Sec. 3. Eq. (1) implies that families formed from 100 km sized parent bodies (as the Koronis family had been estimated to be from the current sizes of its members; see e.g. Gradie et al. 1979, Zappalà et al. 1984) would be generated in the current belt every 50–100 Myr. Since only 10 to 20 such families are actually visible, they would be expected to be the ones young enough to have survived "erosion" (see Sec. 4), i.e. formed in the last 500–1000 Myr. Koronis' family is a very prominent one, and thus could be expected to be at most a few hundred Myr old.

On the other hand, the comparatively old age of Ida's surface inferred from the cratering record is consistent with the idea that the collisional lifetime of Ida is longer than Gaspra's. Actually, Housen's et al. (1991) impact strength scaling law predicts that both Ida and Gaspra are in the gravitational compression strength regime, so that the 2.5 diameter ratio between the two bodies would result in a $2.5^{1.65} \approx 4.5$ strength ratio in favour of Ida. For the same projectile population with a size distribution $N(> d) \propto d^{-2.5}$, it is easy to see that Ida's collisional lifetime would be longer by a factor $4.5^{5/6} \approx 3.5$. According to Belton et al. (1992), Gaspra's lifetime is 500 Myr, so Ida's would be 1.75 Byr — roughly in agreement with Bottke's et al. (1994) estimate of 2.64 Byr. Since Belton et al. estimate that Gaspra's real age is only about 40% of its lifetime, namely $\approx$ 200 Myr, a factor 5–10 between the two ages could be explained simply by Ida's age being within a factor two of the mean collisional lifetime for bodies of that size.

We stress that the above argument is affected by several sources of uncertainty: Gaspra's and Ida's compositions and material properties are probably not the same; the projectile populations hitting the two asteroids and the corresponding average impact speeds are somewhat different; if the two asteroids are "rubble piles" (and perhaps even if they are not, see Greenberg et al. 1994, 1996), their response to impacts is dominated by gravity rather than strength. However, if Ida's age is really > 1 Br, we have a problem with the Koronis family lifetime, as discussed above. A possible solution has been suggested by Marzari et al. (1995), who have explained the peculiar size distribution of the family by assuming that it has been generated from a parent body some 200 km in diameter, with the largest fragment from the original break–up (about 100 km in size) subsequently removed by a further impact. In this case, the family age could well be in the few Byr range, as asteroids about 200 km in size are much less abundant and more resistant to impacts than those of 100 km. In the current belt there are only some 5 families from such parent bodies, which is close to the total number expected to be generated over the solar system's lifetime. Thus, this scenario could explain both Ida's old age, and the peculiar size distribution of the Koronis family.

One *caveat* to the above hypothesis is that occasionally laboratory experiments show a size distribution where there are several large fragments clustered at the large size end. For example, the work of Ryan et al. (1991) on the fragmentation of "rubble pile" structures shows some experiments where there are 4 to 7 fragments having masses within a factor two of each other, comparable to the mass range covered by the largest members of the Koronis family. Thus an alternative interpretation is that the Koronis parent body had a "rubble pile" structure, and the unusual resulting size distribution reflects the poorly understood break–up of such structures.

We shall now consider some factors that could affect the projectile flux on Ida relative to Gaspra, and thus could provide an alternative explanation of Ida's higher crater density, allowing it (and the whole Koronis family) to be relatively young.

First, since Ida is a member of the Koronis family, its orbit is located in a part of the main asteroid belt where it will be impacted by projectiles from all the three major families, namely Themis, Eos and Koronis itself. All of these families have size distributions which are steeper than the average for all asteroids in the size range larger than about 20 km (Cellino et al. 1991). If this steep size distribution continues to smaller sizes (as indicated by the fact that debris associated with the three families apparently dominates the infrared radiation flux from 10–μm particles detected by IRAS), then the flux from these families would substantially enhance the projectile flux on outer–belt asteroids, leading to a lower age and lifetime for Ida. However, this enhanced flux would have only a small effect on inner–belt asteroids such as Gaspra, since the maximum eccentricities reached by members of the Eos and Koronis families do not allow them to hit Gaspra, and for Themis family members collisions with Gaspra are possible but only for a small fraction of the time, when both their and Gaspra's eccentricities are at the peaks of their secular cycles. So, this is one possible way that Ida's age is reduced relative to that of Gaspra. It should be noted, however, that in the inner belt there are also families with steep size distributions, such as Vesta, Nysa and Flora, which could contribute in a preferential way to the cratering flux in Gaspra's part of the belt.

Second, Ida being a member of the Koronis family means that it was produced by the break–up of a larger parent asteroid, a process which in itself could have affected the cratering flux on the current surface. According to Davis et al. (1996), there are basically three timescales on which Ida's surface could have been affected before the present dynamical environment was established. The first is the initial hour or so following the break–up. If there was a velocity gradient among the ejected fragments, then perhaps Ida was bombarded by proto–Koronis fragments as part of the break–up process, thus giving Ida an "instantly old" surface. This process would produce very low velocity impacts, though. Also, the best current explanation for the origin of Ida's small satellite discovered by *Galileo* (and named Dactyl) is that it was captured during the break–up event of proto–Koronis, and capture requires low relative velocities (Martelli et al. 1993). So appealing to the same process to produce a heavily cratered surface at high speeds and at the same time to capture a satellite seems inconsistent.

The second timescale, of the order of a few years, is that over which a subset of the fragments with nearly identical orbits would collide after having traveled exactly one orbit. According to the estimates of Davis et al. (1996), though, this subset is so small that the corresponding craters are unlikely to have contributed a significant fraction of the observed crater population on Ida. The longest timescale, on the order of 10^5 yr, is that on which the orbital nodes and periapses of the fragments had not yet fully randomized. This could have produced some enhancement in the cratering rate, but again, the impact velocities would be reduced due to the correlation among the orbital geometries, and quantitatively it does not seem likely that this mechanism would greatly increase the cratering rate for a long enough time.

The biggest "paradox" posed by the heavily cratered surface of Ida is the existence of its km–sized satellite, Dactyl. The same flux that cratered the surface also bombarded the satellite and should have shattered it well before the observed heavily cratered surface was formed. The estimated collisional lifetime of Dactyl should be shorter than Gaspra's and of the order of 100 Myr, implying a factor $\approx$ 10 between Ida's and Dactyl's lifetimes — a significant difference, though perhaps not enough for ruling out that Dactyl was preserved for an unusually long time just by chance. A possibility discussed in some detail by Davis et al. (1996) is that Dactyl is a second– or multi–generation satellite, formed by the reaccumulation of the debris left in orbit by the fragmentation of a larger parent satellite. This might also explain why Dactyl, though being much smaller than Ida, has a much more regular, nearly–spherical shape (Chapman et al. 1995). Some of the proto–Dactyl fragments could also have impacted Ida, thus adding to the cratering flux. Again, though, the impact speeds would have been low, tens to hundreds of m/s. A useful investigation to test the scenarios involving low–velocity impacts would be to study the outcomes of these impacts and to find out at what speed does the impact produce characteristics that distinguish it from the high–velocity regime. Obviously having the projectile surviving unshattered (such as it appears to be the case for the blocks observed on Ida's surface; see Chapman 1994, Geissler et al. 1996) is one measure, but maybe there are others, such as crater elongation reflecting oblique impacts, peculiar ejecta, and so on.

We stress that the above discussion is just a preliminary one, and that much more detailed studies on the origin and history of the Ida/Dactyl system are required (and are actually in progress). Together with future observations from both space and the Earth of other family asteroids, such investigations should provide soon more constraints to discriminate between the alternative scenarios, and to better estimate the ages of families.

Acknowledgments. Helpful comments by W.F. Bottke are acknowledged. Support through ESA's "G. Colombo" fellowship has allowed P.F. to stay at the Observatoire de la Côte d'Azur (Nice, France) while contributing to the work described here, and also to attend the Flagstaff meeting.

References

Belton, M.J.S., J. Veverka, P. Thomas, P. helfenstein, D. Simonelli, C. Chapman, M.E. Davies, R. Greeley, R. Greenberg, J. Head, S. Murchie, K. Klaasen, T.V. Johnson, A. McEwen, D. Morrison, G. Neukum, F. Fanale, C. Anger, M. Carr, C. Pilcher 1992, Science, 257, 1647

Belton, M.J.S., C.R. Chapman, J. Veverka, P. Klaasen, A. Harch, R. Greeley, R. Greenberg, J.W. Head III, A. McEwen, D. Morrison, P.C. Thomas, M.E. Davies, M.H. Carr, G. Neukum, F.P. Fanale, D.R. Davis, C. Anger, P.J. Gierasch. A.P. Ingersoll, C.B. Pilcher 1994, Science, 265, 1543

Bendjoya, Ph. 1993, A&AS, 102, 25

Binzel, R.P. 1988, Icarus, 73, 303

Binzel, R.P., S. Xu 1993, Science, 260, 186

Bottke, W.F., M.C. Nolan, R. Greenberg, R.A. Kolvoord 1994. Icarus, 107, 255

Cellino, A., V. Zappalà, P. Farinella 1991, MNRAS, 253, 561

Chapman, C.R. 1994, in Asteroids Comets Meteors 1993, A. Milani, M. Di Martino & A. Cellino, Dordrecht: Kluwer, 357

Chapman, C.R., J. Veverka, P.C. Thomas, K. Klaasen, M.J.S. Belton, A. Harch, A. McEwen, T.V. Johnson, P. Helfenstein, M.E. Davies, W.J. Merline, and T. Denk 1995, Nature, 374, 783

Chapman, C.R., E.V. Ryan, W.J. Merline, G. Neukum, R. Wagner, P.C. Thomas, J. Veverka, R.A. Sullivan 1996, Icarus, in press

Davis, D.R., E.V. Ryan, P. Farinella 1994, Planet. Space Sci., 42, 599

Davis, D.R., E.V. Ryan, P. Farinella 1995. Lunar Planet. Sci. Conf., XXVI, 319

Davis, D.R., C.R. Chapman, D.D. Durda, P. Farinella, F. Marzari 1996, Icarus, in press

Farinella, P., 1994, in Seventy–five years of Hirayama asteroid families: The role of collisions in solar system history, Y. Kozai, R.P. Binzel & T. Hirayama, Astron. Soc. Pac. Conf. Ser. Vol. 63, 76

Farinella, P., M. Carpino, Ch. Froeschlé, C. Froeschlé, R. Gonczi, Z. Knežević, V. Zappalà 1989, A&A, 217, 298

Farinella P., D.R. Davis 1992, Icarus, 97, 111

Geissler, P., J.–M. Petit, D. Durda, R. Greenberg, W. Bottke, M. Nolan, 1996, Icarus, in press

Gradie, J.C., C.R. Chapman, J.G. Williams 1979, in Asteroids, T. Gehrels, Tucson: University of Arizona Press, 359

Greenberg, R., W.F. Bottke, M. Nolan, P. Geissler, J.–M. Petit, D.D. Durda 1996, Icarus, in press

Hirayama, K. 1924, Jap. J. Astr. Geophys., vol. I, 55

Housen, K.R., R.M. Schmidt, K.A. Holsappple 1991, Icarus, 94, 180

Lindblad, B.A. 1992, in Asteroids Comets Meteors 91, A.W. Harris & E. Bowell, Houston: Lunar and Planetary Institute, 363

Lindblad, B.A., 1994, in Seventy–five years of Hirayama asteroid families: The role of collisions in solar system history, Y. Kozai, R.P. Binzel & T. Hirayama, Astron. Soc. Pac. Conf. Ser. Vol. 63, 62

Martelli, G., P. Rothwell, I. Giblin, M. Di Martino, P. Farinella, 1993, A&A, 271, 315

Marzari, F., D.R. Davis, V. Vanzani 1995, Icarus, 113, 168

Marzari, F., A. Cellino, D.R. Davis, P. Farinella, V. Zappalà, V. Vanzani 1996, A&A, in press

Melosh, H.J., I.V. Nemchinov, Yu.I. Zetzer 1994, in Hazards due to Comets and Asteroids, T. Gehrels, Tucson: University of Arizona Press, 1111

Milani, A., Z. Knežević 1990, Celest. Mech., 49, 347

Milani, A., Z. Knežević 1992, Icarus, 98, 211

Milani, A., Z. Knežević 1994, Icarus, 107, 219

Milani, A., P. Farinella 1994. Nature, 370, 40

Milani, A., P. Farinella 1995. Icarus, 115, 209

Milani, A., A.M. Nobili 1992, Nature, 357, 569

Milani, A., P. Farinella, Z. Knežević 1992, in Interrelations between Physics and Dynamics for Minor Bodies in the Solar System, D. Benest & C. Froeschlé, Gif–sur–Yvette: Editions Frontières, 85

Petit, J.–M., P. Farinella 1993, Celest. Mech., 57, 1

Ryan, E.V., W.K. Hartmann, D.R. Davis 1994, Icarus, 94, 283

Wetherill, G.W. 1967, J. Geophys. Res., 72, 2429

Williams, J.G. 1989, in Asteroids II, R.P. Binzel, T. Gehrels & M.S. Matthews, Tucson: University of Arizona Press, 1034

Williams, J.G. 1992, Icarus, 96, 251

Yuasa, M. 1983, in Dynamical Trapping and Evolution in the Solar System, V.V. Markellos & Y. Kozai, Dordrecht: Reidel, 203.

Zappalà, V., P. Farinella, Z. Knežević, P. Paolicchi 1984, Icarus, 59, 261

Zappalà, V., A. Cellino 1994, in Asteroids Comets Meteors 1993, A. Milani, A. Cellino & M. Di Martino, Amsterdam: Kluwer, 395

Zappalà, V., A. Cellino, P. Farinella, A. Milani 1994, AJ, 107, 772

Zappalà, V., Ph. Bendjoya, A. Cellino, P. Farinella, C. Froeschlé 1995, Icarus, 116, 291