Physical and Dynamical Properties of Asteroid Families

V. Zappalà, A. Cellino, A. Dell’Oro
Istituto Nazionale di Astrofisica,
Osservatorio Astronomico di Torino

P. Paolicchi
University of Pisa

The availability of a number of statistically reliable asteroid families and the independent confirmation of their likely collisional origin from dedicated spectroscopic campaigns has been a major breakthrough, making it possible to develop detailed studies of the physical properties of these groupings. Having been produced in energetic collisional events, families are an invaluable source of information on the physics governing these phenomena. In particular, they provide information about the size distribution of the fragments, and on the overall properties of the original ejection velocity fields. Important results have been obtained during the last 10 years on these subjects, with important implications for the general understanding of the collisional history of the asteroid main belt, and the origin of near-Earth asteroids. Some important problems have been raised from these studies and are currently debated. In particular, it has been difficult so far to reconcile the inferred properties of family-forming events with current understanding of the physics of catastrophic collisional breakup. Moreover, the contribution of families to the overall asteroid inventory, mainly at small sizes, is currently controversial. Recent investigations are also aimed at understanding which kind of dynamical evolution might have affected family members since the time of their formation. In addition to potential consequences on the interpretation of current data, there is some speculative possibility of obtaining some estimate of the ages of these groupings. Physical characterization of families will likely represent a prerequisite for further advancement in understanding the properties and history of the asteroid population.

1. INTRODUCTION

The improvements of the techniques of family identification, leading to the establishment of a database of about 20 statistically reliable families recognized during the last decade (see Bendjoya and Zappalà, 2002), and the subsequent confirmation of the cosmochemical self-consistency of these groupings from dedicated spectroscopic campaigns (see Cellino et al., 2002) has introduced new exciting perspectives for the physical studies of asteroids.

Since the early times of the first family discoveries by Hirayama at the beginning of the past century, these groupings have been interpreted as the observable outcomes of energetic collisional events, leading to complete disruption of a number of original parent bodies, and to dispersion of the collisional fragments. In this respect, asteroid families are nothing but nice examples of the collisional phenomena that have marked the history of the solar system, although generally at much smaller energy regimes with respect to major events involving large planetary bodies (origin of the Earth’s Moon, tilt of the spin axis of Uranus, etc.).

In the framework of asteroid studies, families are crucially important in many respects. In general terms, they represent a constraint for any attempt at modeling the overall collisional history of the asteroid belt. In other words, the models should be able to justify the number of currently observed families, and to estimate the typical times needed to progressively erode freshly formed families in such a way to make them no longer identifiable at later epochs. The most recent investigations of this particular aspect have been published by Marzari et al. (1999).

Another essential aspect concerns the information that can be obtained about the physics of the breakup events from which families originated. Understanding how asteroids react to mutual collisions typically characterized by relative velocities around 5–6 km/s (Farinella and Davis, 1992; Bottke et al., 1994) is an essential piece of information for any attempt at modeling their overall history, as well as their internal properties. Apart from the purely theoretical issues, understanding the internal structure of asteroids is a necessary prerequisite to developing any reasonable strategy of mitigation of the near-Earth asteroid (NEA) impact hazard.

In the past, most of our understanding of the way asteroids behave when they are collisionally disrupted came from laboratory experiments, based both on hypervelocity impacts and explosive charge techniques [for reviews of this subject, see Fujitara et al. (1989) or Martelli et al. (1994)]. The major source of uncertainty, in this respect, was the scaling problem. In other words, it was not clear how to extrapolate the results of laboratory tests involving centimeter-sized targets, to the astronomical situation of kilometer-sized bodies, including relevant gravitational effects.
Moreover, 951 Gaspra, also observed by Galileo, might be a member of the Flora family, although it has not been listed as such in the most recent family classification by Zappalà et al. (1995). It is known that for the Flora family the nominal membership has been likely underestimated due to the severe statistical criteria used for identification (Migliorini et al., 1995). The important results of the Galileo observations of these two objects, including analyses of the size distributions of impact craters on their surfaces (consequences of their collisional histories), are extensively discussed in Chapman (2002) and Sullivan et al. (2002).

The family spectroscopic data (item 3 in the above list) deserve a separate analysis, and are the subject of Cellino et al. (2002). In what follows, we then focus our attention on the properties mentioned in items 1 and 2 of the above list.

2.1. Ejection Velocity Fields

The structure of the families in the space of proper elements are used to derive information on the ejection velocities of the fragments in family-forming events. This is possible because we can interpret the differences in orbital elements in terms of differences in ejection velocity from the original parent body. The conversion from velocities to orbital elements or vice versa is given by the well-known Gaussian formulas, which can be written as follows, under the assumption (verified for families) that the ejection velocities are much smaller than the orbital velocity of the parent body.

\[
\begin{align*}
\delta a/a &= \frac{2}{na(1 - e^2)^{1/2}} [(1 + e \cos f)V_T + (e \sin f)V_R] \\
\delta e &= \frac{(1 - e^2)^{1/2}}{na} \left[ \frac{e + 2 \cos f + e \cos^2 f}{1 + e \cos f} V_T + (\sin f)V_R \right] \\
\delta I &= \frac{(1 - e^2)^{1/2}}{na} \frac{\cos(\omega + f)}{1 + e \cos f} V_W
\end{align*}
\]

where \(na\) is the mean orbital velocity, and \(V_T, V_R,\) and \(V_W\) are the components of the ejection velocity vector along the direction of the motion, radial, and normal to the orbital plane respectively. The parameters \(f\) and \(\omega\) are the true anomaly and the argument of perihelion of the parent body at the epoch of its disruption. These angles are \textit{a priori} unknown, and this fact has long prevented any attempt at reconstructing the original ejection velocity fields from the presently observed locations of the members in the proper elements space.

By means of extensive numerical simulations, however, Zappalà et al. (1996) showed that very reasonable reconstructions of the velocity fields in family-forming events are possible when the real velocity fields were not completely random, but were characterized by a wide variety of possible field structures, including spherical, ellipsoidal, conical (cratering), and more complicated combinations of the above fields, in which some symmetry property is (even

(see Holsapple et al., 2002). In this context, the availability of a number of reliable families placed at the disposal of theoreticians a number of breakup experiments that nature performed for us, directly in a range of masses and energies absolutely beyond current and future laboratory capabilities.

As a consequence, a great effort has been made in recent years to derive from the observed properties of family members clues about the physics and the kinematics of the events from which families originated. These studies have been able to obtain relevant results, whose interpretation is still somewhat debated, as we shall see in the following sections.

We should still mention the problem that the presence of random interlopers represents for physical studies of families. The likely numbers of objects sharing purely by chance the same orbital proper elements of “true” family members have been predicted on the basis of pure statistics by Migliorini et al. (1995) as a function of size. At the same time, spectroscopic observing campaigns have been able to identify in several cases a number of likely interlopers, as described in Cellino et al. (2002). Interlopers are more “harmful” when they are relatively big, since they can affect the overall behavior of the family size distributions, and the reconstruction of the original ejection velocity fields of the fragments (see below). However, we can now be confident that nearly all the biggest interlopers have been identified in most cases. Thus, the results described in the following section are not expected to be appreciably affected by the presence of these undesired guests.

2. AVAILABLE DATA AND COMMON INTERPRETATIONS

Physical studies of dynamical families are based on analyses of essentially three pieces of information: (1) the coordinates of the family members in the space of the proper elements \(a', e',\) and \(i'\) (proper semimajor axis, eccentricity, and inclination respectively); (2) the size distributions of family members; and (3) spectroscopic and spectrophotometric properties of the members.

In addition to the items listed above, we should mention that some photometric data are also available. The major problem for this kind of investigation is certainly the faintness of most family members, apart from the generally few largest members of the different groupings. A few light-curves are not sufficient for any relevant statistical inference. For this reason, no definitive indications have yet come from photometry. The only exception is a tentative clue of a likely young age of the Koronis family, based on the observed distribution of lightcurve periods and amplitudes (Binzel, 1988). This investigation found also evidence that in the case of the Eos family the distribution of spin periods seems to suggest collisional relaxation and a likely old age.

Another important source of information has come from direct \textit{in situ} explorations by means of space probes. In particular, the Ida-Dactyl binary system observed by the Galileo probe is a nominal member of the Koronis family.
weakly) satisfied. The basic idea was to use some adimensional parameters, given by some combinations of the distributions of the velocity components of the family members, to estimate the most likely values of the unknown $f$ and $\omega$ angles. Of course, in practical cases the reconstruction can be attempted only when a sufficiently large number of members is available, because of statistical reliability. In many situations a reconstruction of the fields was found to be possible, as in the cases of Vesta, Dora, Merxia (Zappalà et al., 1996), and Maria (Zappalà et al., 1997). The reconstructed fields turn out to be generally symmetric and similar, in terms of general structure, to what is observed in laboratory experiments involving much smaller targets. These results could be obtained in spite of the difficulty related to the fact that families are identified in the space of the orbital proper elements, whereas the Gaussian formulas describe the expected behavior in the osculating elements space. According to Bendjoya et al. (1993) the overall structure of the ejection velocity field is conserved in the transformation from osculating to proper elements. The major effect of the transformation was found to be a parallel displacement of the whole set of family members, leading to conservation of the overall velocity field structure. Of course, one can expect that over long timescales the stability of the proper elements can change, making a reconstruction of the velocity fields harder to obtain. On the other hand, one can also expect that over long timescales families tend in any case to disappear due to progressive collisional erosion (Marzari et al., 1995, 1999).

An indication that aging of the proper elements is likely present in several cases is given by the fact that the resulting values of the computed $f$ and $\omega$ angles turn out not to be homogeneously distributed within their natural range of variation. This is related to the well-known fact that most families appear to be more elongated in proper eccentricity and inclination with respect to semimajor axis (Zappalà et al., 1984).

Another problem is that the computed ejection velocities of family members resulting from their differences in orbital proper elements turn out to be considerably large (see section 3.3).

2.2. Size Distributions and Size-Velocity Relationship

The study of the fragment size distributions is another major field of investigation. Astroid sizes are generally not directly measured, but they are derived from knowledge of absolute magnitude and albedo. Families have been found to be characterized by very homogeneous albedo distributions according to the available radiometric data, and this fact has also been used to derive an estimate of the limit of completeness of the current asteroid inventory in terms of apparent magnitude (Zappalà and Cellino, 1996).

The size frequencies of all the major families have long been known to exhibit a power-law trend, characterized by steep slopes, much larger than the typical slopes of samples of nonfamily asteroids in different regions of the main belt (Cellino et al., 1991; Klačka, 1992).

For a long time such behavior has been essentially misunderstood. General models based on an assumed power-law trend coupled with simple requirements of conservation of the total mass of the parent body led Petit and Farinella (1993) to make predictions that were able to fit satisfactorily only a minor fraction of the whole set of known family size distributions. In most cases, the slopes of the observed power laws were much steeper than the predictions. A possible explanation was developed by Tanga et al. (1999), based on a very simple concept first proposed by Paolicchi et al. (1996). The idea was that the fragmentation processes must satisfy other constraints in addition to conservation of the parent body’s mass. In particular, the fragments are formed in a finite volume, and cannot mutually overlap. A simple model taking into account these geometric constraints was developed by Tanga et al. (1999), and was found to give excellent fits of the observed size distributions of a large number of families (see Fig. 1). As a byproduct of this technique, some estimates of the original parent body size and of the actual ratio $m_{LR}/m_{PB}$ between the mass of the largest remnant and that of the parent body were also obtained. More recently, the likely role of geometric constraints in fragmentation phenomena has been also recognized by Campo Bagatin and Petit (2001), although the authors did not find any real proof that the modeled geometric effects are in any way related to the actual physics of collisions.

These above-mentioned results have important and debated implications concerning the overall inventory of the asteroid population, since they suggest that family members might dominate the asteroid population at small sizes, at least if we can believe in the reliability of extrapolations of the observed size frequencies to small sizes (around 1 km). This will be discussed more thoroughly in the following section.

Another recent result that must be mentioned concerns the relationship found between size and ejection velocity of the fragments in family-forming events. This problem has been analyzed by Cellino et al. (1999). The result was that a relation exists between the sizes of the fragments and their maximum possible ejection velocities. In particular, families generally fit the predictions of a model that assumes that the maximum amount of kinetic energy achievable by fragments in family-forming events is a constant. As a consequence, the maximum possible ejection velocity as a function of size follows a power-law trend, and is represented by a straight line in a log-log plot of size vs. velocity, as shown in Fig. 2. In particular, the following relationship holds under the assumptions mentioned above, and is found to fit satisfactorily the observational data for most families

$$\log \left( \frac{d}{D} \right) = \frac{-2}{3} \log V - K'$$

where $d$ and $D$ are the diameters of the $i$th fragment and of
the parent body respectively, and $V$ is the maximum possible value for the ejection velocity of the fragment of size $d$. The $K'$ parameter is given by

$$K' = -\frac{1}{3} \log \left(2f_{KE}E/M\right)$$

where $E/M$ is the specific energy of the impact (defined as the ratio between the kinetic energy of the projectile and the mass of the impacted body), $f_{KE}$ is the so-called anelasticity parameter, defined as the fraction of $E$ that is converted into kinetic energy of the fragments, and $A$ is an *a priori* unknown parameter, describing the maximum fraction of the total kinetic energy of the set of fragments that can be delivered to fragments of any size.

Apart from the most technical issues, an important result of the analysis has been to recognize that not only a fixed slope around $(-2/3)$ is found to actually fit the behavior of most families, but also the value of the intercept $K'$ turns out to be a linear function of $\log m_{LR}/M$ ($m_{LR}$ being the mass of the largest family member, and $M$ the mass of the parent body). This prediction is respected by most fami-

---

**Fig. 1.** The size distributions of four prominent families identified in the asteroid main belt are shown, with corresponding error bars due to the uncertainties in the sizes of the single family members. The lines represent fits of the size distributions obtained by Cellino *et al.* (1999) using their model. Three different curves (practically identical) are shown for each family, corresponding to different choices of some random seeds determining the results of different simulations. The simulations show a very good agreement with the data. Also shown are the limits of completeness for each family, due to the fact that the available inventory is not complete at small sizes due to the corresponding faintness of the smallest objects.
lies for which $m_{LR}/M < 0.8$. This fact, if fully confirmed, has some important, although not yet fully explored, implications for our understanding of the physics of catastrophic breakup processes. In particular, it would suggest that the currently observed ejection velocity fields were determined mostly by the impact energies (directly related to the $m_{LR}/m_{PB}$ ratio) and that the original size-velocity trend has been scarcely affected by subsequent dynamical and/or physical evolution, being still visible today. Such a conclusion may be still premature, however, and what can be said at this stage is only that the Cellino et al. (1999) size-velocity model seems to be in good agreement with available data for a large number of known families, and also with some laboratory experiments.

3. IMPLICATIONS AND OPEN PROBLEMS

The observational facts mentioned above are generally self-consistent, and suggest some kind of coherent scenario. In particular, it turns out that families were formed by events that produced ejection velocity fields having “reasonable” structures (when we compare them with the outcomes of laboratory experiments), although the resulting velocities were generally high. The fragmentation of the parent bodies produced huge swarms of fragments, with size frequencies characterized by steep power-law trends, still recognizable today. However, several facts must be taken into account before accepting literally all the above conclusions. Moreover, the exact implications of the above-mentioned

Fig. 2. Size-ejection velocity plots for nine of the most prominent families in the asteroid main belt. The straight lines shown in each plot have a fixed slope equal to $-2/3$, and correspond to a computed best-fit value, plus or minus its uncertainty. The value $K'$ of the intercept corresponding to the best-fit line are also written in each plot. From Cellino et al. (1999).
scenario must be adequately stressed and discussed. We touch here on a number of very delicate points affecting our overall understanding of the properties and history of the asteroid population.

In what follows, we give (in no special order) a list of open problems and general implications of the results coming from analyses of the family data at our disposal.

3.1. Dynamical and Physical Aging of the Families

It is certain that, over time, asteroid families undergo an evolution modifying their originally observable features. This evolution is expected to affect both the physical properties of the members and their location in the proper element space.

In particular, the orbital proper elements \( a', e', \) and \( i' \) cannot be assumed to be really constant over time (see also Knežević et al., 2002). They are expected to vary slowly over timescales on the order of 10–100 m.y. An estimation of the range of fluctuation of the proper elements was given by Milani and Knežević (1992, 1994). As a consequence, the inferred kinematical properties of families (including a reconstruction of their original ejection velocity fields) should slowly vary as a function of the time elapsed since family formation. This does not prevent us from identifying today a number of around 20 “robust” families in the space of proper elements, and to derive information on the original collisional events from which they originated. However, it is reasonable to expect that the apparent kinematical properties of families can be somewhat “aged” with respect to the original configurations at the epoch of their formation.

Not all the proper elements behave in the same way. The semimajor axis seems to be the most stable parameter according to available dynamical theories (see Knežević et al., 2002). Dynamical aging of the proper elements affects mainly eccentricities and inclinations. This may influence the determination of the unknown \( f \) and \( \omega \) angles in the Gaussian equations when the techniques of reconstruction of the ejection velocity fields are applied. As shown by the simulations performed by Zappalà et al. (1996), this effect can produce a spurious clustering of the inferred values of \( f \) around 90°. In turn, this can affect the derived ejection velocities, since an enhancement of the dispersion of the eccentricities and the inclinations produces a spurious increase of the radial and normal ejection velocity components, leaving the transversal component essentially unchanged (as can be easily seen from equation (1)).

Another possible source of variation of the proper elements is the so-called Yarkovsky effect (Vokrouhlický and Farinella, 1998; Farinella and Vokrouhlický, 1999; Vokrouhlický, 1999; Bottke et al., 2000; Bottke et al., 2002). Unlike the dynamical aging processes mentioned above, the Yarkovsky effect produces changes of the orbital semimajor axis, and is size dependent. Several parameters, whose values are currently uncertain, determine the effectiveness of the Yarkovsky effect, and the range of sizes for which it is really important. The effect depends on the thermal properties of the surface, on the orientation of the spin axis, and on the obliquity angle (the angle between the spin axis and the normal to the orbital plane). In its “diurnal” variant, the Yarkovsky effect can cause the orbital semimajor axis to drift either inward or outward, depending on the sense of rotation of the body. In addition, there is a “seasonal” variant, due to the periodic preferential heating of different hemispheres during the orbital motion. The net effect of this variant is a systematic decrease of the orbital semimajor axis.

An estimate of the expected variation of the semimajor axis due to the Yarkovsky effect has been recently computed by Spitale and Greenberg (2001). The effectiveness of this kind of nongravitational force is stronger for smaller objects, and should be negligible for bodies larger than kilometer-sized (the exact value depending on many poorly known parameters). Moreover, another kind of relevant long-term dynamical effect that is expected to affect the orbital semimajor axes of all asteroids, including family members, is that of mutual close encounters with the massive Ceres, Pallas, and Vesta objects (Carruba et al., 2000).

In summary, dynamical aging can increase the dispersion of the eccentricities and inclinations of family members, while the Yarkovsky effect and close encounters can also increase the dispersion of the semimajor axes. Dynamical aging does not depend on the size of the body, whereas the Yarkovsky effect is certainly negligible for objects larger than, e.g., 10–20 km.

The interplay of dynamical aging and the Yarkovsky effect can be important, because during a Yarkovsky-driven drift in semimajor axis the objects can be trapped into some of the many dynamically unstable regions crossing the asteroid main belt (Nesvorný and Morbidelli, 1998; Morbidelli and Nesvorný, 1999), with the effect of being eventually removed from the family. Of course, the timescales of dynamical and Yarkovsky-driven evolutions must be compared with typical collisional lifetimes for bodies of comparable sizes. We touch here on some key problems that will be likely the subject of extensive analyses in the near future.

In fact, collisions independently produce a “physical” aging of the families. Collisional lifetimes of main-belt asteroids are size-dependent, and range between 10^7 and 10^9 yr. The exact estimates are model-dependent, since they are derived from estimates of both the impact strength of the objects and the number of existing projectiles capable of disrupting an object of a given size. For a 100-km asteroid, the average collisional lifetime should be on the order of 10^9 yr. As a consequence, and according to Marzari et al. (1995), the smallest family members tend to be collisionally disrupted over shorter timescales with respect to the bigger members. As a consequence, collisions not only modify the size distribution of families, but also produce an erosion in the space of the orbital proper elements, leading to progressive disappearance of the families as recognizable groupings (Marzari et al., 1999).

Moreover, the possibility of secondary events involving first-generation family members must also be taken into
account, since this may potentially produce very complicated structures in the space of proper elements, as possibly in the cases of the so-called “clans,” such as the Flora family (Farinella et al., 1992).

All the facts mentioned above must be seriously taken into account when interpreting the data at our disposal. Moreover, we observe today families that likely have different ages, and show different stages of evolution. Understanding the complicated interplay of the different evolutionary tracks will certainly help in understanding the properties of families, and will possibly help in determining their current ages, with important implications for the studies of the collisional evolution of the asteroid belt.

### 3.2. Size Distributions and Asteroid Inventory

In many cases the slopes of the power-law distributions fitting the size frequencies of asteroid families turn out to be very steep. According to Tanga et al. (1999), the resulting exponents of the cumulative size distributions reach often values beyond −3. In these cases, it is easy to show that integrations of the size distributions would lead to infinite reconstructed masses for the corresponding parent bodies. For this reason, it is clear that the size distributions must change slope somewhere at small sizes. A difficult problem is thus determining the exact value of this transition size, and whether this is generally constant or varies for different families. Some general indications come from different kinds of evidence.

First, some families in the inner region of the main belt are complete down to sizes on the order of 5–6 km. This means that any change in slope of the size distributions must occur at smaller sizes for these particular families. Of course, this does not imply that the same is necessarily true for all the families in the main belt. Second, Campo Bagatin and Petit (2001) explored some generalizations of the Tanga et al. (1999) model, and found analytical reasons to predict that the value of the power-law exponent should asymptotically converge toward a fixed value, found to be around −2.8, for any model based on a similar treatment of the geometric constraints affecting the production of fragments. The authors stressed that the above result can be a pure artifact of the assumed geometric model, and there is not any proof that the model is really representative of the actual physics of the phenomena of catastrophic disruption. If proven to be adequate to represent the real world, the above result would in any case prevent the possibility of obtaining distributions diverging to infinity in terms of reconstructed mass.

Another very important consideration is that further collisional evolution experienced by the freshly formed family members should lead to changes of the size frequencies. According to Marzari et al. (1995), the family size distributions should be expected to converge progressively, starting from the low-size end of the distribution, toward the equilibrium value expected for a collisionally relaxed population, being equal to −2.5 according to classical results by Dohnanyi (1969, 1971). The convergence should take place over timescales depending on the size, the smallest members being expected to run into relaxation in shorter times (Marzari et al., 1995). The problem in this scenario can be that the Dohnanyi-predicted value of the slope was model-dependent (the outcomes of the collisions were assumed to be independent of size), and it seems to be unconfirmed by general analyses of the overall size distribution of main-belt asteroids (Cellino et al., 1991; Jedicke and Metcalfe, 1998). In particular, it turns out that nonfamily asteroids, for instance, exhibit a size frequency much shallower than the predicted Dohnanyi slope.

Apart from causing some uncertainty about the exact value of the slope to which families should be expected to converge, the above fact should also be taken into account when another controversial consequence of the steepness of the family size distributions is discussed. The subject here is that of the possible predominance of family members in the general asteroid inventory at small sizes. According to Zappalà and Cellino (1996), family members increasingly dominate the asteroid population going toward smaller sizes. This conclusion is a consequence of both the steep slopes of the family size distributions and the apparently shallow slopes of the nonfamily population. The situation is controversial also because family members should be expected to become dominant at values of size (~1 km) for which the current asteroid inventory is severely incomplete. Many authors tend to dislike the idea that 99% of the main-belt asteroids larger than 1 km should be family members (Zappalà and Cellino, 1996). On the other hand, avoiding this type of conclusion is not trivial, if we can believe in extrapolations (even moderate in some cases) of the observed family size frequencies. Allowing for some important change of slope in the size frequencies of families somewhere between 1 and 5 km is reasonable. However, even in this case, families could hardly become so shallow as to not give a predominant contribution to the main-belt asteroid inventory at small sizes.

Only observations will definitely clarify the real situation. Models of the general asteroid inventory based on the dominance of families down to sizes of 1 km are currently being developed. Some definite predictions on the number and apparent magnitudes of the asteroids that should be found in any given sky field can be made, and observations will soon confirm or rule out these models (see, e.g., Tedesco and Désert, 1999).

### 3.3. Ejection Velocities and Comparison with Hydrocodes

The results mentioned in sections 2.1 and 2.2 concerning the derivation of the original ejection velocity fields of families, and the discovery of a defined size-velocity relationship, can certainly in principle be affected by subsequent evolutionary effects experienced by family members (section 3.1). However, it seems difficult to reconcile the expectation of very important evolutionary changes with the
conservation of regular patterns such those that are observed for the velocity field structures and the size-velocity relations of the most robust families. Figure 3 shows a typical example concerning the Eos family. The existence of defined, “triangular” trends in the diameter vs. proper semi-major axis, eccentricity, and inclination plots can be easily recognized in spite of any level of noise possibly affecting the proper elements.

In particular, we should note that in principle a size-dependent spreading in semimajor axis can be interpreted in terms of the Yarkovsky effect. What seems more difficult to explain, however, is the size-dependent spreading in eccentricity and inclination. For this, effects like Yarkovsky can be only indirectly effective, by moving objects into narrow resonant zones. The resulting distribution of the objects in the proper elements space should be due to a complicated interplay of the residence times in the resonances experienced by bodies of different sizes, and the relative rate of variation of the proper elements under the influence of the size-dependent Yarkovsky effect and the size-independent resonant behavior. It seems fairly difficult to expect that the final result of the evolution should be such a regular behavior like the one shown in Fig. 3.

Although conclusions are certainly premature at the present stage, it seems that if the current interpretation of the data at our disposal is not grossly wrong, we should conclude that either the evolutionary effects are weaker than currently believed, or the families themselves are relatively young, and still poorly affected by the above effects. Of course, this conclusion would have important consequences for our understanding of the collisional evolution of the asteroid belt (see Davis et al., 2002).
From the point of view of the physics of collisions, the ejection velocities that are derived from application of the Gaussian formulas constitute another debated subject. Generally speaking, the problem is that according to the most sophisticated hydrocode models of catastrophic breakup processes (Love and Ahrens, 1996; Nolan et al., 1996; Asphaug et al., 1998), the impact energies that are apparently needed to disperse the family members with the observed speeds should have been sufficiently high as to completely pulverize the family parent bodies.

In particular, the reconstructed velocity fields of families indicate that ejection velocities well beyond 100 m/s are not rare for the smallest fragments. As a comparison, typical speed values in laboratory experiments are 5–10x smaller, velocities of 100 m/s being only typical of pulverized fragments produced very close to the impact point (Martelli et al., 1994). This is a well-known problem. When trying to reproduce the reconstructed ejection velocity field of the Maria family using the Paolicchi et al. (1996) semi-empirical model (SEM) of catastrophic disruption events, which is generally able to give a good fit to laboratory experiments, Zappalà et al. (1997) found that SEM gives maximum velocities a factor of 5 too low to reproduce the family data.

According to hydrocode results, the observed velocities are not possible unless we assume that the observed family members are essentially reaccumulated rubble piles. In this scenario, all asteroids larger than some hundreds of meters should be rubble piles. Pisani et al. (1999), however, made some quantitative tests, and concluded that reaccumulation cannot be sufficiently efficient to justify the observed size distributions of several known families. In particular, important phenomena of reaccumulation were found to be possible for the largest remnant alone, but certainly not for a large number of objects. Moreover, preliminary results of the in situ exploration of the near-Earth asteroid 433 Eros, a 31 × 13 × 13-km object, thought to be a collisional fragment from the disruption of a larger parent body, indicate that it is very unlikely that this asteroid can be a rubble-pile [for the meaning of terms like “rubble pile,” see Cheng (2002) and Richardson et al. (2002)].

Of course, a possible dynamically induced spreading of families in the proper elements space might artificially increase the apparent ejection velocities of family members. Taking this into account one could conclude that the real ejection velocities at the epoch of formation were lower, as required by hydrocode results. However, there is not yet any conclusive evidence of a dominating role played by post-formation dynamical evolution, as mentioned above. It is true that when observations do not fit theory, scientists tend to believe that observations are likely wrong. But at this stage we think that the self-consistency of much observational data is very notable, and would tend to indicate that something can be wrong in current theoretical models of collisional processes. Of course, this is another field in which new observational and theoretical activities are needed to achieve some reliable interpretation of what is observed.

3.4. Formation of Binaries

Strictly related to the modeling of family formation is the problem of the possible formation of binaries. This subject is currently very hot, after the recent discoveries of several binary systems among both near-Earth and main-belt asteroids (see Merline et al., 2002). Interestingly enough, the first convincing discovery of an asteroid satellite came from the Galileo flyby of the Koronis family member 243 Ida. More recently, the asteroid 90 Antiope, a member of the Themis family, has also been found to be an outstanding example of a binary system with components of comparable size (Merline et al., 2000; Weidenschilling et al., 2001). It is clear that the formation of binaries in collisional processes is an interesting field of research for which we can expect to have important results in the near future. This subject is discussed extensively in Paolicchi et al. (2002).

3.5. Collision Probabilities

The formation of big asteroid families is not only an interesting phenomenon per se, but it also has a number of important consequences. Dell’Oro et al. (2001) have found that a long-term increase of the collision probabilities in the region of the main belt swept by the orbital motion of the newly formed family members must be expected. Again, this is due to the huge numbers of kilometer-sized members that are apparently produced by these events. When a large family is produced, its members will cross the orbits of the majority of the main-belt population, apart from objects located far enough in terms of semimajor axis and eccentricity (mostly the low-eccentricity asteroids orbiting close to the inner and outer edges of the belt). In this respect, it is not unlikely that major collisional events like those that produced the big Eos and Themis families can trigger the subsequent collisional regime over substantial timescales. This is just another example of family-related mechanisms that should be taken into account by modern models of the overall collisional evolution of the asteroid belt (see Davis et al., 2002).

Another fact that should be mentioned is that according to recent investigations (Dell’Oro et al., 2002), the very early times after formation of any given family are characterized by a larger impact probability among members of the same family, with respect to the typical values controlling the steady collisional regime in the main belt. Although these epochs of enhanced interfamily collisions were found to be short, and were on average characterized by low impact velocities, there is still the possibility that the freshly formed surfaces of family members can have been marked in a significant way, with consequences on the cratering record observed by in situ exploration by space probes (243 Ida and 951 Gaspra were observed by Galileo). We should also note that, according to Weidenschilling et al. (2001), the existence of binary asteroids like 90 Antiope (a member of the Themis family), characterized by components of comparable size, might also be explained by the occurrence of
relatively mild interfamily collisions likely occurring during the very early history of a newly born family.

4. FAMILIES AS POSSIBLE SOURCES OF NEAR-EARTH ASTEROIDS

Families have been found to also play an important role in the production of near-Earth asteroids and meteorites. The first indications were found by Morbidelli et al. (1995), who convincingly showed that a number of well-known families (such as Themis) are sharply cut by the edges of important mean-motion resonances with Jupiter. This qualitatively showed two important things: First, the formation of families in several cases led to the immediate injection of substantial numbers of sizeable fragments into resonant orbits. Many of them (mostly in the case of resonances located in the inner belt, like the 3:1 mean-motion resonance or the \( \nu_6 \) secular resonance; a smaller fraction in the case of resonances located in the outer belt) achieved near-Earth-like orbits. This process was quantitatively analyzed by means of numerical integrations of the orbits by Gladman et al. (1997). The results showed that the transfer times are extremely short for resonances like 3:1 and 5:2, on the order of a couple of million years. Based on these results and on a preliminary assessment of the numbers of objects actually injected by several families at the epochs of their formation, Zappalà et al. (1998) found that in the past several episodes of paroxysmal near-Earth-asteroid production, with consequent enhancements in the collision rate with the terrestrial planets, took place, with durations on the order of several million years in most cases. This also indicates that the inventory of near-Earth objects is not steady, and can be strongly influenced by the occurrence of important collisional events in the main belt.

Second, family-forming events left groupings of objects that are very close to the borders of several important resonances. This fact is important, because it can be expected that the normal collisional evolution experienced by these objects can likely produce a steady rate of production of small fragments directly injected into the most efficient dynamical routes to the inner solar system (see also Zappalà and Cellino, 2001). A good example is given by the Maria family, whose reconstructed ejection velocity field, sharply cut by the 3:1 resonance with Jupiter, is shown in Fig. 4 (Zappalà et al., 1997).

An important result obtained by Morbidelli et al. (1995) was the discovery that several objects are currently located into the 9:4 mean-motion resonance with Jupiter. This relatively thin resonance cuts across the big Eos family, and was shown by Gladman et al. (1997) to give a modest but not fully negligible contribution to the near-Earth population. The reason is that the dynamical evolution inside the 9:4 resonance is relatively slow, with eccentricity being pumped up over timescales sufficiently long to allow Mars to capture some objects before they become dominated by Jupiter (with subsequent ejection from the solar system). Most of the 9:4 resonant objects cannot be recognized as Eos family members on the basis of their orbital elements, but it was straightforward to assume that these objects might be original members of this family, observed during the early stages of a dynamical evolution that will decouple them from the asteroid main belt. This conjecture was fully confirmed by subsequent observations by Zappalà et al. (2000) (see also Cellino et al., 2002).

Another fact that should be mentioned when speaking about the relation between near-Earth objects and families is the following: If direct collisional injection into some of the dynamically unstable regions in the main belt (such as the 3:1 resonance with Jupiter, the \( \nu_6 \) secular resonance, and the region of Mars-crossing) is assumed to be the most effective mechanism for supplying kilometer-sized NEAs, some constraints must be respected. In particular, direct injection cannot be accepted if it can be shown that it necessarily predicts the formation of too many observable families. The reason is simply that the number of known families in the main belt is limited. This is a strong constraint for any mechanism of steady NEA supply, mainly for sizeable objects having diameters beyond 1 or 2 km. According to Zappalà et al. (2002), it does not seem trivial to explain the currently observed number of NEAs larger than 2 km only by means of steady collisional injection into chaotic regions in the main belt. Many candidate parent bodies exist (the most effective ones have been listed in Table 1), but the ranges of “permitted” impact energies that satisfy the nonfamily formation constraint for most of them are fairly narrow.
TABLE 1. A list of the most effective NEA candidate parent bodies found by Zappalà et al. (2001).

<table>
<thead>
<tr>
<th>ID Number</th>
<th>a' (AU)</th>
<th>e'</th>
<th>sin i'</th>
<th>Transfer Region</th>
<th>Diameter (km)</th>
<th>Taxonomic Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>304</td>
<td>2.404</td>
<td>0.122</td>
<td>0.257</td>
<td>ν6</td>
<td>68</td>
<td>C</td>
</tr>
<tr>
<td>313</td>
<td>2.376</td>
<td>0.236</td>
<td>0.201</td>
<td>MC</td>
<td>96</td>
<td>C</td>
</tr>
<tr>
<td>495</td>
<td>2.487</td>
<td>0.118</td>
<td>0.045</td>
<td>3:1</td>
<td>39</td>
<td>—</td>
</tr>
<tr>
<td>512</td>
<td>2.190</td>
<td>0.199</td>
<td>0.142</td>
<td>MC</td>
<td>23</td>
<td>S</td>
</tr>
<tr>
<td>753</td>
<td>2.329</td>
<td>0.214</td>
<td>0.153</td>
<td>MC</td>
<td>24</td>
<td>S</td>
</tr>
<tr>
<td>877</td>
<td>2.487</td>
<td>0.142</td>
<td>0.059</td>
<td>3:1</td>
<td>38</td>
<td>F</td>
</tr>
<tr>
<td>930</td>
<td>2.431</td>
<td>0.121</td>
<td>0.265</td>
<td>ν6</td>
<td>36</td>
<td>—</td>
</tr>
<tr>
<td>1080</td>
<td>2.420</td>
<td>0.243</td>
<td>0.086</td>
<td>MC</td>
<td>23</td>
<td>F</td>
</tr>
<tr>
<td>1715</td>
<td>2.400</td>
<td>0.249</td>
<td>0.181</td>
<td>MC</td>
<td>23</td>
<td>—</td>
</tr>
<tr>
<td>2143</td>
<td>2.281</td>
<td>0.194</td>
<td>0.130</td>
<td>MC</td>
<td>19</td>
<td>—</td>
</tr>
</tbody>
</table>

5. FUTURE DEVELOPMENTS

From the facts discussed in the previous sections, it is easy to see that the physical properties of asteroid families play an important role in our current understanding of the collisional and dynamical evolution of the asteroid population. The interpretation of the data at our disposal is not straightforward, and a coordinated observational and theoretical effort will be needed in order to confirm or rule out a number of conclusions that are suggested by the data that are currently available. A determination of the times needed to collisionally erode and dynamically disperse a newly formed family will certainly be a primary field of investigation in the near future. At the same time, trying to understand how families can achieve their steep size distributions, and how long they can keep them unchanged in the range of sizes covered by current datasets, will be another major field of research. If families evolve rapidly, and those that are currently observed can be shown to be really young, this will deeply influence current ideas of the collisional evolution of the main belt, and will provide new important constraints in addition to those currently recognized, like the preservation of the basaltic crust of 4 Vesta; the existence of metallic meteorites; the scarcity of taxonomic types directly interpreted in terms of mantle material from differentiated parent bodies; the observed cratering records of Ida, Gaspra, Mathilde, and Eros, etc. In general, it will be possible to obtain a better and more reliable estimate of the asteroid inventory at small sizes. Two hundred years after the discovery of the first asteroids, we are still far from fully understanding these interesting objects. As the direct outcomes of mutual collisions, families certainly represent a very important piece of the asteroid puzzle.

REFERENCES


