Spectroscopic Properties of Asteroid Families

A. Cellino
Istituto Nazionale di Astrofisica, Osservatorio Astronomico di Torino

S. J. Bus
University of Hawai'i

A. Doressoundiram
Observatoire de Paris–Meudon

D. Lazzaro
Observatório Nacional, Rio de Janeiro

Asteroid families have been the target of several dedicated campaigns of spectroscopic observations during the last 10 years. Preliminary studies were mainly devoted to obtain a confirmation of the cosmochemical reliability of groupings identified by purely statistical analyses of the distributions of objects in the space of the orbital proper elements. These early attempts led to some spectacular confirmations of the common collisional origin of some families, like that associated with 4 Vesta. Subsequently, spectroscopic investigations started to be mostly focused on the issue of characterizing the overall mineralogical compositions of different families, at the same time looking for possible evidence of thermal differentiation of the original parent bodies and for possible evidence of ongoing space-weathering processes. Spectroscopy has also proven to be crucially needed to identify likely interlopers that can seriously affect the derived size distributions of families and the reconstruction of the original fields of ejection velocity of the fragments. At the same time, spectroscopic properties have been recognized as an invaluable tool to assess the real memberships of families mutually overlapping in the space of proper elements. Moreover, spectroscopic surveys have in general been found to be an excellent complement to conventional family searches purely based on the identification of concentrations of objects in the proper-element space. A challenging unsolved problem comes from the fact that several families have been found to exhibit peculiar spectroscopic properties. This opens up new exciting possibilities for future developments in the interpretation of asteroid taxonomic classes.

1. INTRODUCTION

In the early 1990s, the availability of large datasets of asteroid proper elements (*Milani and Knežević,* 1990, 1992) and the simultaneous development of new statistical techniques for the identification of asteroid families (*Zappalà et al.,* 1990; *Bendjoya et al.,* 1991; *Bendjoya,* 1993; *Zappalà et al.,* 1994, 1995) promised to open new perspectives for the physical studies of these groupings, thought to be the direct outcomes of collisional events that occurred in the asteroid belt. Previously, extensive physical studies of families had been prevented or seriously slowed down by strong discrepancies in the family lists proposed by different authors [see the review chapter by *Valsecchi et al.* (1989) in the *Asteroids II* book], and by cosmochemical inconsistencies in some of the proposed family memberships (*Chapman et al.,* 1989).

In that uncertain situation, the first important goal to be pursued was to find some convincing evidence that the most recently identified families could really be considered as "true" collisionally originated groups, and not simply statistical flukes. In this respect, it was immediately clear that some definite answer could come from spectroscopy. Spectroscopy was able to find, through the observations performed by *Binzel and Xu* (1993), the first spectacular confirmation of the collisional origin of a family, the one associated with the large asteroid 4 Vesta (see Fig. 1). In that case, a spectroscopic check was particularly suitable, due to the fact that 4 Vesta was a unique (at that time) case of an object belonging to the V taxonomic class, characterized by spectroscopic properties similar to those of basaltic achondrites. Subsequently, the activities of spectroscopic monitoring of families have been steadily increasing. From the point of view of spectroscopy, families provide a unique opportunity to obtain information on the inner layers of their parent bodies. As a consequence, intense observational activity has been devoted to family members in order to characterize their plausible mineralogical composition. At the same time, spectroscopy has been used as a very important tool for identifying random interlopers within families. These objects share by chance the same orbital properties as "true" family members, but they were not produced by the disruption of the family's parent body. Interlopers can be identified when they are characterized by spectroscopic properties

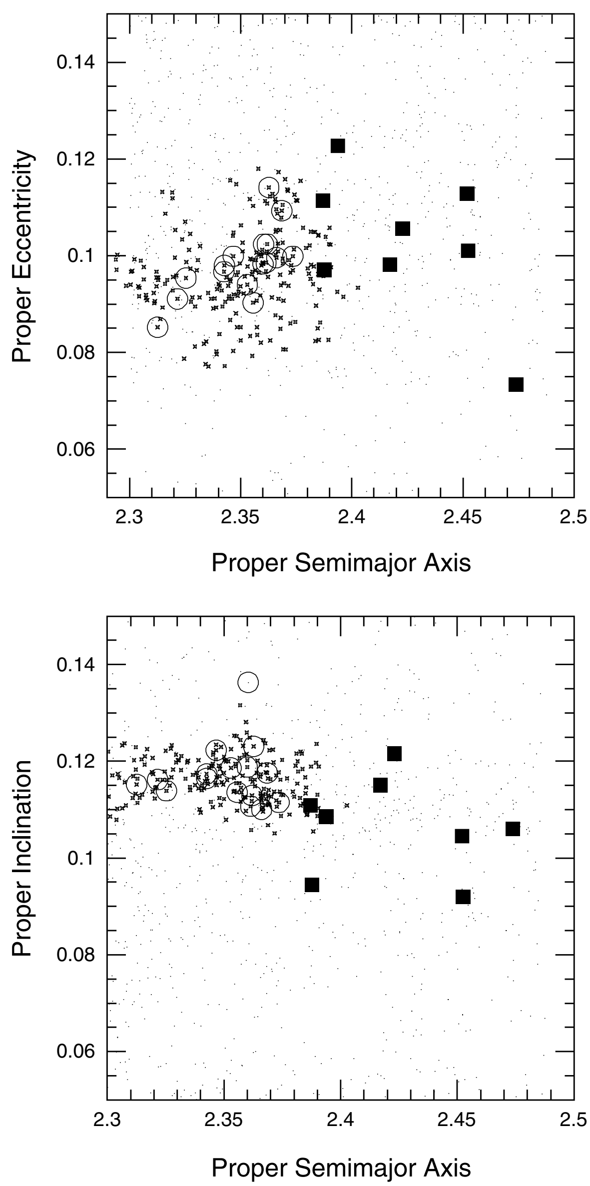

Fig. 1. Plot of the asteroids located around the family of Vesta in the space of the proper elements. Crosses indicate family members. Open circles identify the basaltic objects found by *Binzel and Xu* (1993). Filled squares indicate the basaltic objects not belonging to the nominal family identified by the same authors in the region between the family and the border of the 3:1 mean-motion resonance with Jupiter.

incompatible with those of their family. For instance, an S-type object belonging to a family of C-type members should be considered as a very likely interloper. The presence of interlopers and their plausible numbers can be predicted in purely statistical terms (*Migliorini et al.,* 1995), but it is clear that direct observations can quantify not only how many nominal members are actual interlopers, but they can also identify which ones. In turn, this is very useful for investigations concerning the physical properties of the families (size distributions, ejection velocity fields, etc.) described in *Zappalà et al.* (2002).

Spectroscopic properties can also be used to enlarge the nominal membership of some families, in cases in which some peculiar spectral features can be found to characterize their members. In this way, objects sharing the same feature, but located beyond the nominal family borders, can be added to the list of plausible members. A good example of this was given, again, by the quoted spectroscopic observations of the Vesta family by *Binzel and Xu* (1993). In particular, these authors discovered a number of genetically related objects (belonging to the V taxonomic class) well beyond the nominal borders of the family, all along the region separating the family from the 3:1 mean-motion resonance with Jupiter (Fig. 1). In this way, it was convincingly shown for the first time that large ejection velocities of the fragments, of the order of several hundred meters per second, are possible in family-forming events.

Since then, several families have been extensively observed, including the most important groupings identified by statistical investigations, like Koronis (*Binzel et al.,* 1993), Eos (*Doressoundiram et al.,* 1998a; *Zappalà et al.,* 2000), Eunomia (*Lazzaro et al.,* 1999), Veritas (*Di Martino et al.,* 1997), Hoffmeister (*Migliorini et al.,* 1996), Flora (*Florczac et al.,* 1998), Maria (*Zappalà et al.,* 1997), Nysa/Polana (*Doressoundiram et al.,* 1998b; *Cellino et al.,* 2001), and Hygiea (*Mothé-Diniz et al.,* 2001). In addition to the above specific campaigns, a major observational contribution has also been produced by the SMASS (*Xu et al.,* 1995) and SMASSII (*Bus,* 1999) surveys. The infrared JHK spectrophotometry performed by *Veeder et al.* (1995) for members of the Eos, Koronis, and Maria families also deserves a mention in this context.

The general results of these investigations, as well as a number of problems they were expected to solve, are briefly summarized in the following sections.

2. STATE OF THE ART

A first point deserves mention here. Spectroscopy of asteroids has profited in recent years from improvements in instrumental performance because of the availability of larger telescopes and increasingly better CCDs. Wide spectral windows have been sampled, with an extension of the traditional wavelength range of the classical UBVRI photometry toward longer wavelengths in the near-IR (see *Bus et al.,* 2002). However, this does not mean that, on average, the wavelength coverage in single observing campaigns has been steadily increasing. In most cases, spectra have been obtained for asteroid families in the interval from 5000 Å up to 9,500–10,000 Å. This means that, with respect to the older spectrophotometric investigations based on UBV filters, something has been generally lost at the ultraviolet end of the obtained spectra, whereas the longest wavelengths covered have been rarely beyond 1 µm. This is all because of the limitations of the instruments. Although this did not prevent the observers from obtaining important results, as we shall see, it is important to stress that in several cases family investigations suffered from a less than ideal coverage of the spectra, mainly around the region of the silicate absorption bands around 1 μm and beyond, or shortward of 5000 Å, an important region for objects belonging to the "primitive" taxonomic classes (C, B, F, and G).

In spite of the above limitations, spectroscopy of families has produced a wealth of useful data in recent years. A summary of the current situation is given in Table 1, listing for each family (ordered according to the proper semimajor axis of the lowest-numbered member) the number of members observed spectroscopically, the identified interlopers (by purely spectroscopic means; this does not include interlopers already known on the basis of taxonomic classification), the general spectral properties characterizing the members, and possible analogs among the near-Earth asteroid (NEA) population and/or the meteorite classes. Some additional notes are also included when appropriate, mainly dealing with possible indications of evidence of space-weathering phenomena and/or the inferred properties of the original parent bodies. All these data have been obtained by several dedicated observing campaigns (see section 1), and the main references are also listed in Table 1. Taxonomic information is also given, and is very relevant to the subject of this chapter. For this reason, we have summarized the main taxonomic classes identified by the classical Tholen classification (*Tholen,* 1984) and the most recent SMASSII-based classification (*Bus,* 1999) in Table 2, together with a (forcedly synthetic) description of the main features characterizing each class. Note also that the W taxonomic class mentioned in Table 1 corresponds to M-type objects exhibiting hydration features around 3 μm (*Rivkin et al.,* 2000).

Spectroscopy of family members has been carried out by many authors with the purpose of finding some answers to a number of important questions (listed in no particular order): (1) Did some families originate from a differentiated parent body? (2) Can some peculiar spectroscopic features be identified for different families, allowing us to improve the member lists beyond those derived from the nominal statistical procedures? (3) If the answer to the previous question is "yes," can we use these spectroscopic features to disentangle the memberships of different, mutually overlapping families? (4) Can we identify families by purely spectroscopic means? (5) Is there any evidence of some ongoing space-weathering processes affecting the members of different families? (6) Can some families be identified as likely sources of NEAs, based on comparisons of spectroscopic properties and closeness to some dynamical transfer region? (7) Can we draw conclusions about the mixing of different taxonomic types in the main belt as a consequence of collisional events?

Currently, we cannot say that we have found definitive answers to all the above questions, but a large body of evidence has been collected, allowing us to draw at least some clear indications of the likely solutions.

2.1. Spectral Homogeneity

A first important result of the spectroscopic campaigns carried out so far is that, apart from the peculiar case of Vesta, no convincing evidence of any other family originating from a differentiated parent body has been found. A possible exception might be a tentative association of the Bellona and Phaeo groupings, whose members belong to the S and X taxonomic classes respectively. This possible association has been proposed by *Bus* (1999), but it is not firmly established, being at most a tentative conjecture according to the same author. Another tentative candidate might be the Lydia family, but in this case the evidence is also quite weak.

As a general rule, spectroscopic properties turn out to be fairly homogeneous among members of the same family. This fact can look disappointing from the point of view of the observers (finding evidence of members coming from a metallic core, an olivine-rich mantle, and a basaltic crust might be *a priori* much more exciting!), and certainly it has important implications that will be extensively discussed in the next section. On the other hand, spectral homogeneity of the families has been found to be useful for some applications. In particular, it is possible to characterize in a reliable way the average reflectance properties and surface albedos of different families. This allowed, for instance, *Zappalà and Cellino* (1996) to derive an estimate of the limit of completeness of the asteroid inventory in the main belt, based on the behavior of the distributions of apparent magnitudes for families at different heliocentric distances. These estimates have been later confirmed by independent studies (*Jedicke and Metcalfe,* 1998).

However, the above findings do not mean that all the members of any given family are essentially equal in terms of spectral reflectance. Some limited variations are certainly present, and are in some cases beyond the instrumental uncertainties. Some examples of the typical ranges of spectroscopic properties (from very homogeneous to mildly dispersed) observed in different families are shown in Fig. 2.

Apart from the cases of macroscopic differences related to the presence of random interlopers [the identified C-type members of the Eunomia family being a good example; see *Lazzaro et al.* (1999)], in some cases the differences can be qualitatively ascribed to mild variations in the mineralogical properties of the parent body, and/or to possible phenomena of space weathering. No convincing quantitative analysis has yet been performed regarding this particular subject. In particular, the occurrence of space weathering has so far been demonstrated mainly in the case of asteroids belonging to the S taxonomic class (see *Chapman,* 2002), but little is known about possible space-weathering processes affecting different taxonomic classes. In this respect, data from families like Eos (*Doressoundiram et al.,* 1998a; *Zappalà et al.,* 2000) might indicate that space weathering also affects at least the K class.

2.2. Spectroscopy as a Tool for Family Identification

The generally homogeneous spectral properties of families can be usefully applied to extend family memberships beyond the nominal lists found by purely statistical techniques of family identification. In this respect, a major advance has been the extensive SMASSII spectroscopic sur-

TABLE 1. Summary of spectroscopic studies of families.

Family	Number of Observed Spectra*	Identified Interlopers	Spectral Characteristics	Meteorites and/or NEA Analogs	Notes†	References
Flora‡	47	298, 2093, 3533, 3875, 4278	S type Max. ~750 nm Range of slopes	L3, L4, L5, LL	Homogeneous PB. Evidence of SW	*Florczak et al.* (1998)
Vesta‡	20		V type	HED V-type NEAs	Differentiated PB with basaltic surface. Cratering event.	*Binzel and Xu* (1993)
Nysa/Mildred‡,§	11	Nysa? (E type) Hertha? (W type)	S type		Likely young family	*Cellino et al.* (2001)
Polana‡,§	11	Nysa? (E type) Hertha? (W type) 3881, 3997, 4797	F type	Metamorphic CI/CM F-type NEA?	Possible links with Nysa and/or 135 Hertha	*Cellino et al.* (2001)
Henan‡	16	3430	L type		Uncertain boundaries	*Bus* (1999)
Maria‡	12	4167?	S type Similar spectral slope and 1-µm band Max. ~770 nm	Ordinary chondrites.	Possible source of big NEAs, like 433 Eros and 1036 Ganymede.	*Zappalà et al.* (1997)
Eunomia‡	44 + 10	85, 141, 546	S type Max. ~750 nm Slope spanning a continuous but limited range		Some degree of differentiation of PB?	*Lazzaro et al.* (1999), *Bus* (1999)
Weringia§	4		S type		Very dispersed family	*Bus* (1999)
Eugenia‡	12	2715	Spectra span the boundary between C and X type			*Bus* (1999)
Chloris‡	9		C type Steep UV drop-off Absorption band at 0.7 µm			*Bus* (1999)
Lydia‡	10		Spectra span the boundary between C and X type		Differentiated PB?	*Bus* (1999)
Liberatrix‡	9	6704	C type Steep UV drop-off		Uncertain boundaries	*Bus* (1999)
Merxia‡	10	1987 UF5	S type			*Bus* (1999)
Watsonia§	8	1659	L type	CO3/CV3 affinities	Spinel-bearing PB. Dispersed family. Old?	*Burbine et al.* (1992) *Bus* (1999)
Coelestina‡	8	127	S type Decrease of spectral slope for smaller objects		Uncertain boundaries possible SW	*Bus* (1999)
Thisbe§	5	2730	B type			*Bus* (1999)
Pallas‡	16		B or C type		One or more cratering events	*Bus* (1999)
Phaeo‡	4		X type		Moderate robustness	*Bus* (1999)
Bellona§	14	322, 1427, 1730 2879, 5467	S type		Uncertain boundaries Might include Phaeo	*Bus* (1999)
Astrid‡	5		C type Moderate spectral slopes			*Bus* (1999)
Agnia‡	17		S type Decrease of spectral slope for smaller objects		Size-dependent resurfacing or SW	*Bus* (1999)
Gefion‡	36		S type		Interlopers known from taxonomy/radiometry: 1, 255, 374	*Bus* (1999)

TABLE 1. (continued).

Family	Number of Observed Spectra*	Identified Interlopers	Spectral Characteristics	Meteorites and/or NEA Analogs	Notes†	References
Hoffmeister‡	9		C or F type Small concave absorption feature around 0.9 µm		Carbon-rich PB	*Migliorini et al.* (1996) *Bus* (1999)
Dora‡	33	7081 6907?, 9970?	C type Absorption band at 0.7 µm			*Bus* (1999)
Koronis‡	8		S type Range of 1-µm band depth and center.		Modest degree of defferentiation of PB	*Binzel et al.* (1993)
Eos‡	45 + 7	1910, 4455	K type Max ~800–850nm. Range of 1-µm band depth and center. Range of slopes	CO/CV First evidence of a dynamical route through the 9:4 resonance	Modest degree of internal differentiation within PB. Possible SW	*Doressoundiram et al.* (1998a) *Zappalà et al.* (2000)
Themis‡	36	461, 1171	C type Mostly with absorption band at 0.7 µm		Slight heterogeneity of PB	*Florczak et al.* (1998)
Hygiea‡	11	100, 1109, 1209, 1599	C (10 Hygiea) and B type		Possible inhomogeneities in PB	*Mothé-Diniz et al.* (2001)
Veritas‡	8		C, P, and D type Wide range of spectral slopes		Stratified PB and/or SW. Presence of hydrated members. Dynamical instabilities	*Di Martino et al.* (1997)

*From the studies referenced in the last column; for more details on each family refer to *Zappalà et al.* (2002).
†PB and SW indicate parent body and space weathering respectively.
‡Family identified by means of proper-element analysis.
§Family identified mainly by means of spectroscopy.

TABLE 2. Summary of asteroid taxonomic classes.

Tholen Class	Bus Class	Albedo	Spectral Features
A	A	Moderate	Very steep red slope shortward of 0.75 µm; moderately deep absorption feature longward of 0.75 µm.
B, C, F, G	B, C, C_b, C_h, C_g, C_{hg}	Low	Linear, generally featureless spectra. Differences in UV absorption features and presence/absence of narrow absorption feature near 0.7 µm.
D	D	Low	Relatively featureless spectrum with very steep red slope.
E, M, P	X, X_c, X_e, X_k	From low (P) to very high (E)	Generally featureless spectrum with reddish slope; differences in subtle absorption features and/or spectral curvature and/or peak relative reflectance.
Q	Q	Moderate	Reddish slope shortward of 0.7 µm; deep, rounded absorption feature longward of 0.75 µm.
R	R	Moderate	Moderate reddish slope downward of 0.7 µm; deep absorption longward of 0.75 µm.
S	S, S_a, S_k, S_l, S_q, S_r	Moderate	Moderately steep reddish slope downward of 0.7 µm; moderate to steep absorption longward of 0.75 µm; peak of reflectance at 0.73 µm. Bus subgroups intermediate between S and A, K, L, Q, R classes.
T	T	Low	Moderately reddish shortward of 0.75 µm; flat afterward.
V	V	Moderate	Reddish shortward of 0.7 µm; extremely deep absorption longward of 0.75 µm.
—	K	Moderate	Moderately steep red slope shortward of 0.75 µm; smoothly angled maximum and flat to blueish longward of 0.75 µm, with little or no curvature.
—	L, L_d	Moderate	Very steep red slope shortward of 0.75 µm; flat longward of 0.75 µm; differences in peak level.
—	O	—	Peculiar trend, known so far only for asteroid 3628.

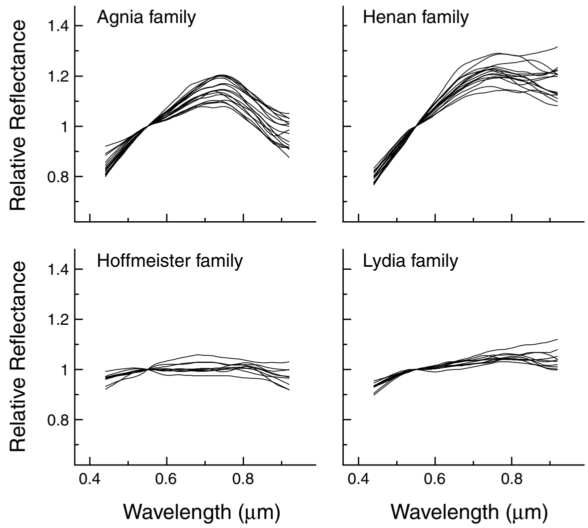

Fig. 2. Available spectra for the Agnia, Henan, Hofmeister, and Lydia families (from *Bus,* 1999). While in some cases families appear to be very homogeneous in terms of spectral properties, in some other cases there is some range of heterogeneity (like in the case of the Agnia family plotted here) that might be explained in terms of possible space-weathering processes and/or in terms of possible mild variations in the mineralogical properties of the parent body.

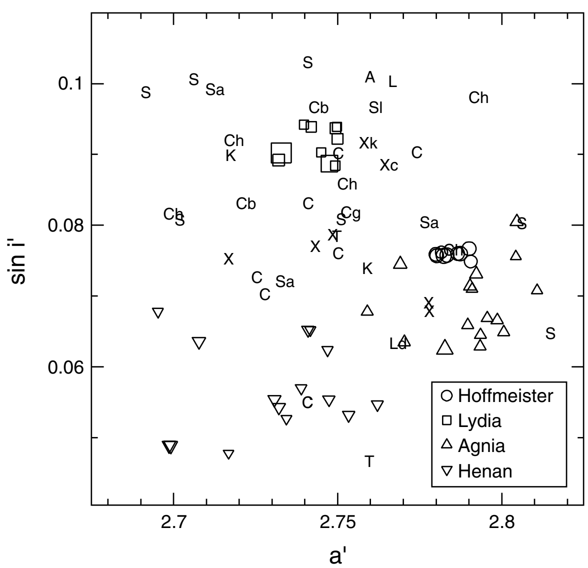

Fig. 3. Plot of the location of the spectroscopically observed members of the Hoffmeister, Lydia, Henan, and Agnia families in the proper inclination vs. semimajor axis plane (from *Bus,* 1999). Different symbols are used for each family, while nonfamily, background objects located in the same region of the sin i'–a' plane are also indicated using their corresponding taxonomic type. The sizes of the family symbols are proportional to the corresponding diameters of the objects. It can be seen that in this region of the belt several families are found to mutually overlap, and spectroscopy is an essential tool for discriminating among the members of different groupings.

vey carried out by *Bus* (1999). In particular, spectroscopic features have made it possible to disentangle the memberships of a number of families identified by means of purely statistical techniques, and found to mutually overlap in the region of the main belt between 2.7 and 2.8 AU in heliocentric distance. For instance, the location in the proper inclination vs. semimajor axis of the spectroscopically observed members of the Lydia, Liberatrix, Henan, and Hoffmeister families (spectra shown in Fig. 2) are plotted in Fig. 3. It is easy to see that, apart from the very compact Hoffmeister grouping, the other families shown are noticeably spread, and it is not surprising that the classical techniques of family identification gave uncertain results, due to the difficulty in separating mutually overlapping groupings (we should take into account, however, that family identification is made by also considering a third dimension, given by the location of the objects in proper eccentricity).

Of course, specroscopy is a powerful tool when the overlapping families are distinct in terms of reflectance spectra. Luckily enough, this happens in several cases of interest. A very nice example, in this respect, is the big Nysa family, which has recently been found to be composed by two mutually overlapping families (named after the asteroids Mildred and Polana) whose members belong to the S and F taxonomic class respectively (*Cellino et al.,* 2001).

In cases like those mentioned above, spectroscopy is decisive for enabling any further analysis of the physical properties of these families, since this would be impossible without reliable indications about the real memberships of the groupings. Even in cases in which the membership is already well established, however, spectroscopy is very important to identify random family interlopers. This task is more important than would appear at first glance. The reason is that interlopers can strongly affect the apparent physical properties of families. Figure 4 shows a good example of this effect. The figure shows the relation between the sizes of the nominal members of the Dora family and the corresponding values of the proper elements (semimajor axis, eccentricity, and inclination) of the same objects. This type of plot is very important, since the differences in proper elements can be interpreted in terms of differences in ejection velocities (see *Zappalà et al.,* 2002). In particular, Fig. 4 shows a typical "triangular" trend in the three plots, indicating that smaller fragments were ejected at higher speeds in the original disruption of the family's parent body. A few objects do not follow the general trend in the plots shown in Fig. 4 (indicated by full circles). *A priori*, this might indicate that the size-velocity relation does not actually exist, or it is fairly weak. However, the discrepant objects were observed by *Bus* (1999) in the SMASSII spectroscopic survey. One of them (a K-type asteroid) turned out to be certainly an interloper. The other three objects were found to be separated by the core of the family in terms of spectroscopic properties. Though not being certain interlopers, they must be considered suspect. In particular, two of them do not belong to the same subset of the big C taxonomic complex (Ch), which characterizes the core of the Dora family (*Bus,* 1999). This

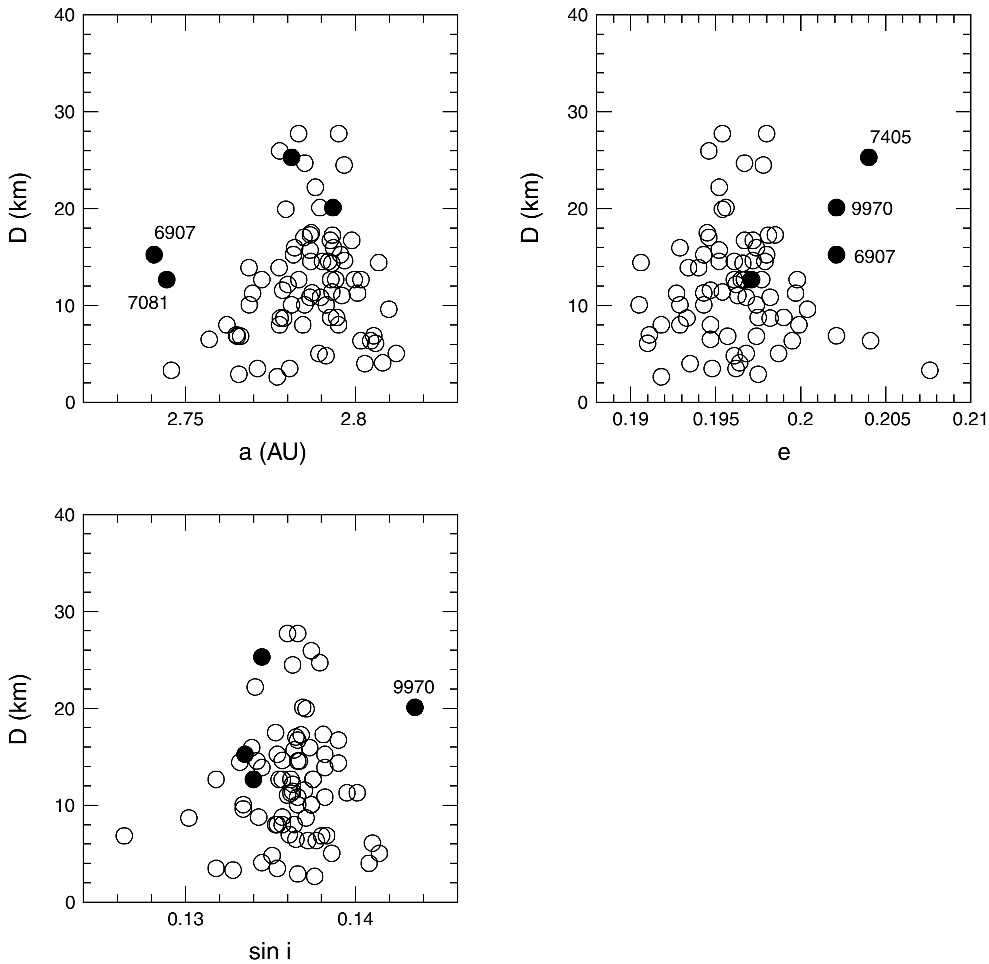

Fig. 4. Plots of the diameter vs. proper semimajor axis, eccentricity, and inclination for the Dora family. Four objects, indicated by their identification numbers and full circles, do not fit the general trend exhibited by the other family members. These objects were observed by *Bus* (1999). One (7081) is surely an interloper. The other three are separated by the core of the family in terms of spectroscopic properties. Though not being certain interlopers, they must be considered suspect.

example shows that the spectroscopic data are a very important element for any physical analysis of the identified families. At the same time, we also have here a potential method for identifying some lists of likely candidate interlopers for different families, to be confirmed by future spectroscopic observations.

The first serious attempt to identify new families by purely spectroscopic means has been made by *Bus* (1999). In particular, he found a number of groupings including objects that would suggest a common collisional origin primarily on the basis of spectroscopic properties. This does not mean that the location in the proper-element space is not taken into account. Instead, a hybrid metric was defined, in which the distance between the objects is defined according to both the distance in the proper-element space and the spectral similarity (quantitatively defined). In this way, it was possible to identify some groupings not previously considered by family searches based on proper elements alone. These new candidate families (listed in Table 1) are associated with the asteroids Thisbe, Watsonia, Weringia, and Bellona. Of course, more detailed physical analyses will be useful to confirm or reject these identifications.

As a general comment, it should be mentioned that spectroscopy can be effective for identifying families formed a long time ago, and subsequently eroded and dispersed by collisional and dynamical evolution. We certainly know that the families that we see today are only the most recent and/or populous groupings among those that necessarily have been produced during the history of the solar system (*Marzari et al.,* 1999). The older, "ghost" families no longer can be found by looking at pure concentrations in the proper-element space. On the other hand, spectroscopic properties can be the only possible diagnostics of the existence of such groupings. Some examples are given by the proposed Watsonia family (*Bus,* 1999), a possible L-type family associated with the asteroids 387 Aquitania and 980 Anacostia as

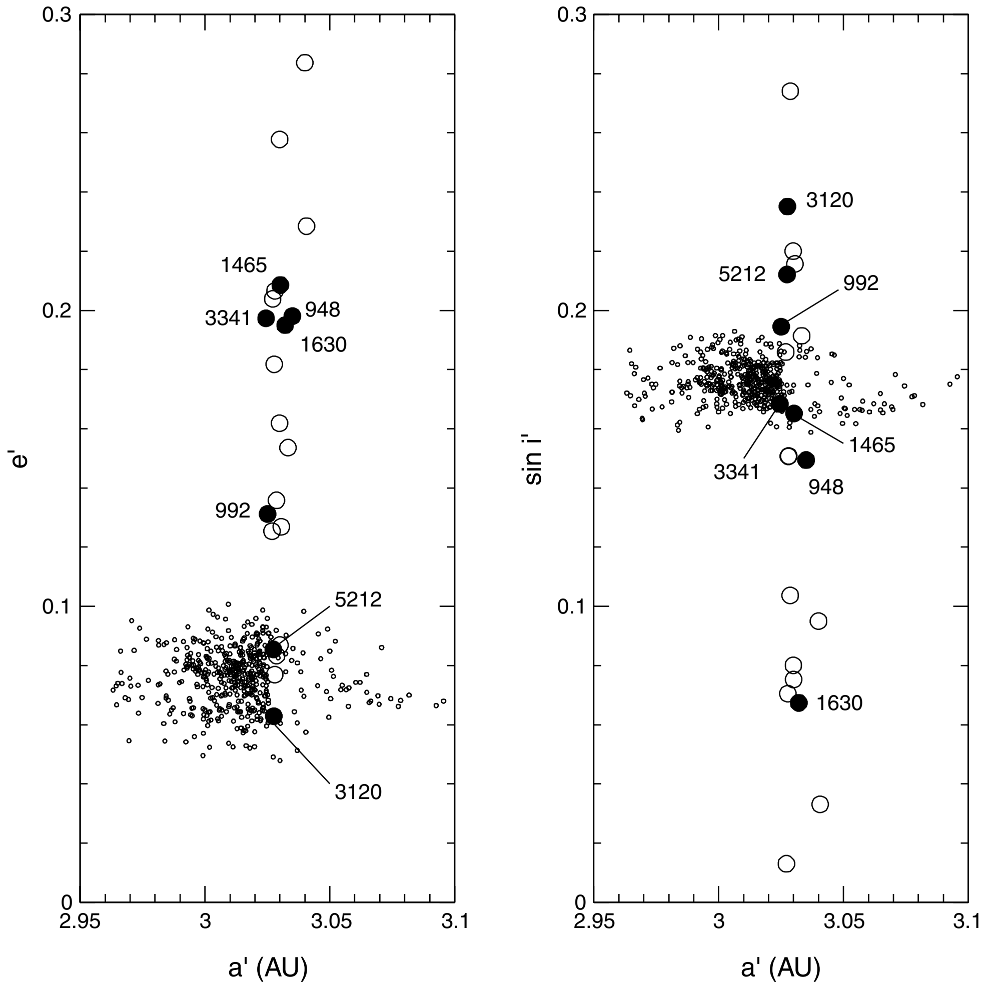

Fig. 5. Location in the proper eccentricity–proper semimajor axis (left) and proper inclination–proper semimajor axis (right) planes of the Eos family, and a group of asteroids currently located into the 9:4 mean-motion resonance with Jupiter. Several of the resonant objects were spectroscopically observed by *Zappalà et al.* (2000) (full circles and numbers) and were found to share the same characteristic spectral features of common Eos family members. This means that the resonant objects were originally Eos members, and are currently observed during the first stages of a dynamical evolution that would lead most of them out of the solar system. A fraction of these objects, however, can be captured by Mars and achieve typical near-Earth orbits.

first suggested by *Burbine et al.* (1992) and an anomalous concentrations of F-type asteroids around, but well beyond the borders of, the Polana family (*Cellino et al.,* 2001).

2.3. Spectroscopic Features

Having been produced by the disruption of "normal" asteroids in the main belt, families are not expected *a priori* to exhibit any exceptional spectroscopic feature. Spectroscopic campaigns have been devoted to observe families discovered by analyses of the clusterings of objects in the space of the proper elements (see *Bendjoya and Zappalà,* 2002) without any *a priori* bias in favor of exotic spectroscopic properties. However, actual observations have shown that, surprisingly, rare features are found fairly often. Apart from the quoted example of the basaltic Vesta family, three other outstanding cases are those of the Eos, Polana, and Henan families. The latter was found by *Bus* (1999) to belong to his newly proposed L taxonomic class. As already mentioned above, the Polana family is a major subcluster of the Nysa clan (*Zappalà et al.,* 1995), and has been found to constitute a single, distinct family composed of objects belonging to the fairly rare F taxonomic class (*Cellino et al.,* 2001).

The case of the Eos family, one of the most populous families in the current main belt, is even more interesting. The members of this family belong to the (elsewhere) rare K taxonomic class, characterized by a well-defined spectroscopic behavior, somewhat intermediate between C- and S-type asteroids (*Gaffey et al.,* 1993). This fact led *Zappalà et al.* (2000) to identify some asteroids presently located into the 9:4 mean-motion resonance with Jupiter as likely Eos members, observed well beyond the family's borders, during the first phases of a dynamical evolution that will remove these asteroids from the main belt (Fig. 5). Some of these objects might be perturbed by Mars and forced to achieve typical near-Earth orbits (*Zappalà et al.,* 2000; *Gladman et al.,* 1997). This is a first example of a positive answer to the question about a possible role of family-forming events in contributing to the flux of NEAs and meteorites. In this respect, we should also quote the results of the spectroscopic analysis of the Maria family performed by *Zappalà et al.* (1997), showing that this family can be considered as a likely source of ordinary chondrite-like material, and a possible parent of the "giant" near-Earth asteroids 433 Eros and 1036 Ganymed. This latter hypothesis has been more recently questioned by *Zappalà and Cellino* (2001) because of the difficulty in reconciling the very short lifetimes of objects injected into the 3:1 mean-motion resonance, with the idea that Eros and/or Ganymede were directly injected into the 3:1 mean-motion resonance during the Maria family-forming event.

3. DISCUSSION

Spectroscopy of families has so far been able to supply a great deal of useful information, as discussed in the previous section. From the point of view of the most general concepts we have learned about the asteroid population, a couple of facts should probably be emphasized at this stage. First, the lack of any clear evidence of differentiated parent bodies is interesting. The occurrence in the past of extensive phenomena of melting and thermal differentiation among asteroids has been inferred basically by three kinds of observational evidence: the basaltic crust of 4 Vesta, the existence of iron and stony-iron meteorites, and the existence of the M-type asteroids, generally interpreted as the metal-rich cores of differentiated parent bodies. These facts have always constituted a delicate constraint for our understanding of the likely origin and subsequent collisional evolution of the asteroid belt. If iron meteorites come from M-type asteroids, and the latter are really the cores of large differentiated parent bodies, the apparent lack of objects having spectroscopic properties that should be expected for fragments originating in the mantle (like the fairly rar olivine-rich A-type asteroids) is a long-debated problem (*Burbine et al.,* 1996). If collisional evolution was sufficiently intense to pulverize the supposedly weak mantle-originating bodies, how can we explain the presence of the intact basaltic crust of Vesta? Moreover, the disruption of the very large bodies that should have been the parents of some large M-type objects observed today (like 16 Psyche) should have produced families that should be still observable (*Davis et al.,* 1999).

More generally, the melting mechanisms are not so obvious for objects as small as asteroids. If radiogenic heating is the natural process to explain the differentiation of a large body like Vesta, how can we explain that 1 Ceres, which is twice as large, apparently has a primitive composition and likely never experienced important heating episodes? These are long-debated problems that are not yet solved. Some plausible mechanisms are mentioned in *McSween et al.* (2002). The lack of any convincing evidence of differentiated family parent bodies, as well as recent discoveries of hydration features in a large fraction of M-type asteroids, could be the first steps toward a new kind of understanding of the likely thermal history of asteroidal bodies. Of course, the existence of iron meteorites indicates that in any case several sources of metallic material must have been produced during the history of the asteroid belt.

The second important fact that we have learned from family spectroscopy has already been noted in the previous section, and is the surprisingly high number of cases in which families are characterized by unusual spectroscopic features. This is true not only in literal terms, but also from the point of view of the general distribution of the taxonomic classes in the main belt. A major example is given by the Eos family. The fact that this family accounts for the vast majority of the K-type asteroids (non-Eos K-type objects being very rare) is puzzling. The existence of the Eos family should imply that a unique prototype of a K-type asteroid existed in the outer belt, in a region where the vast majority of objects exhibits very different spectroscopic properties. This unique parent body was also fairly large [around 220 km according to *Tanga et al.* (1999)] and suffered a collision able to produce this huge family of K-type fragments. All this looks like a sequence of unlikely coincidences. Another example is given by the quoted case of the Polana family in the inner belt, characterized by an F-type taxonomic classification, generally interpreted as altered primitive bodies (*Bell et al.,* 1989), but located in a region in which primitive bodies are not very abundant. The newly proposed L-type class is another example, since most of the identified objects belonging to this class are interpreted as family members (*Bus,* 1999).

In other cases, some families do not belong to unusual taxonomic classes, but they exhibit some spectral reflectance features that are somewhat unusual within their classes, and can be used to characterize their members. Some examples are given by the Maria (*Zappalà et al.,* 1997), Chloris, and Lydia (*Bus,* 1999) families (see also Table 1).

An explanation of the observational evidence is not straightforward, but some simple ideas can already be proposed. One possibility is that we observe relatively young objects, since they were more recently produced. Their spectroscopic features might be due to a shorter exposure to space-weathering phenomena. An alternative explanation might be that we are possibly observing features that are more directly due to thermal and/or physical metamorphism produced by the energetic collisional events responsible of the formations of families. There is not any real proof that this might be true, apart from some preliminary analyses by *Rubin* (1995), and some further work is needed in order to analyze in more detail the problem.

Another relevant fact appears to be reasonably established according to present evidence. Family-forming events were likely able to eject fragments at high speeds, as indicated by the quoted *Binzel and Xu* (1993) observations of the Vesta family (Fig. 1). According to recent results (*Cellino et al.,* 1999), the smallest fragments in family-forming events can achieve the maximum velocities produced in these events. This means that families, and more generally collisional events, have likely been responsible (mainly at small sizes) for a significant mixing of different taxonomic types in the main belt, partly destroying a possible more regular gradient in composition inherited by the original protoplanetary disk (*Cellino,* 2000). Other mechanisms possibly affecting the composition gradient in the asteroid main belt (scattering events produced by massive planetary embryos during the first few million years of the solar system's history) are also discussed in *Petit et al.* (2002).

4. FUTURE DEVELOPMENTS

Family spectroscopy is a vigorous field of research, and its importance is not going to decrease in the near future. The next steps will probably be an extension of the wavelength coverage of the surveys, in order to analyze more satisfactorily the full range of important spectral features, both at short wavelengths, and, probably more important, up to 2 or 3 μm. This will allow the observers to obtain data much more directly diagnostic of the true mineralogical assemblages present on the surfaces of the objects, including very important clues on the presence or absence of hydrated materials (*Jones et al.,* 1990; *Rivkin et al.,* 1995, 2000). An important development will also be an extension of the observations to smaller family members. Observations of these objects can potentially be used to derive possible inferences about the role of space-weathering phenomena related to the different collisional lifetimes of objects of different sizes. It is known, for instance, that S-type NEAs exhibit spectra much more similar to those of ordinary chondrites, with respect to the bigger S-type objects in the main belt (see *Binzel et al.,* 2002). A comparison with family members in the same size ranges might confirm that small main-belt objects surviving over longer timescales exhibit the same "weathered" surface properties of bigger objects of the same taxonomic class. At the same time, observations will likely be extended also to the families that were found by statistical analyses, but with a lesser degree of statistical confidence. Moreover, new examples of families identified by mostly spectroscopic means will be possible. In all these cases, we can expect some important discoveries in the future. In particular, it will be extremely important to see whether the frequency of "strange," "peculiar" spectroscopic features will increase when new families will be analyzed. If this will be the case, we will have probably to modify some of the general ideas we have on the meaning of taxonomic classes, and the importance of space weathering and collisionally induced thermal metamorphism effects.

REFERENCES

Bell J. F., Davis D. R., Hartmann W. K., and Gaffey M. J. (1989) Asteroids: The big picture. In *Asteroids II* (R. P. Binzel et al., eds.), pp. 921–945. Univ. of Arizona, Tucson.

Bendjoya Ph. (1993) A classification of 6479 asteroid into families by means of the wavelet clustering method. *Astron. Astrophys. Suppl., 102,* 25–55.

Bendjoya Ph. and Zappalà V. (2002) Asteroid family identification. In *Asteroids III* (W. F. Bottke Jr. et al., eds.), this volume. Univ. of Arizona, Tucson.

Bendjoya Ph., Slézak E., and Froeschlé C. (1991) The wavelet transform: A new tool for asteroid family determination. *Astron. Astrophys., 272,* 651–670.

Binzel R. P. and Xu S. (1993) Chips off asteroid 4 Vesta: Evidence for the parent body of basaltic achondrite meteorites. *Science, 260,* 186–191.

Binzel R. P., Xu S., and Bus S. J. (1993) Spectral variations within the Koronis family: Possible implications for the surface colors of asteroid 243 Ida. *Icarus, 106,* 608–611.

Binzel R. P., Lupishko D. F., Di Martino M., Whitely R. J., and Hahn G. J. (2002) Physical properties of near-Earth objects. In *Asteroids III* (W. F. Bottke Jr. et al., eds.), this volume. Univ. of Arizona, Tucson.

Burbine T. H., Gaffey M. J., and Bell J. F. (1992) S-asteroids 387 Aquitania and 980 Anacostia: Possible fragments of the breakup of a spinel-bearing parent body with CO3/CV3 affinities. *Meteoritics, 27,* 424–434.

Burbine T. H., Meibom A., and Binzel R. P. (1996) Mantle material in the main belt: Battered to bits? *Meteoritics & Planet. Sci., 31,* 607–620.

Bus S. J. (1999) Compositional structure in the asteroid belt: Results of a spectroscopic survey. Ph.D. thesis, Massachusetts Institute of Technology.

Bus S. J., Vilas F., and Barucci M. A. (2002) Visible-wavelength spectroscopy of asteroids. In *Asteroids III* (W. F. Bottke Jr. et al., eds.), this volume. Univ. of Arizona, Tucson.

Cellino A. (2000) Minor bodies: Spectral gradients and relationships with meteorites. *Space Sci. Rev., 92,* 397–412.

Cellino A., Michel P., Tanga P., Zappalà V., Paolicchi P., and Dell'Oro A. (1999) The velocity-size relationship for members of asteroid families and implications for the physics of catastrophic collisions. *Icarus, 141,* 79–95.

Cellino A., Zappalà V., Doressoundiram A., Di Martino M., Bendjoya Ph., Dotto E., and Migliorini F. (2001) The puzzling case of the Nysa-Polana family. *Icarus, 152,* 225–237.

Chapman C. R. (2002) Cratering on asteroids from *Galileo* and *NEAR Shoemaker*. In *Asteroids III* (W. F. Bottke Jr. et al., eds.), this volume. Univ. of Arizona, Tucson.

Chapman C. R., Paolicchi P., Zappalà V., Binzel R. P., and Bell J. F. (1989) Asteroid families: Physical properties and evolution. In *Asteroids II* (R. P. Binzel et al., eds.), pp. 386–415. Univ. of Arizona, Tucson.

Davis D. R., Farinella P., and Marzari F. (1999) The missing Psyche family: Collisionally eroded or never formed? *Icarus, 137,* 140–151.

Di Martino M., Migliorini F., Zappalà V., Manara A., and Barbieri C. (1997) Veritas asteroid family: Remarkable spectral differences inside a primitive parent body. *Icarus, 127,* 112–120.

Doressoundiram A., Barucci M. A., and Fulchignoni M. (1998a) Eos family: A spectroscopic study. *Icarus, 131,* 15–31.

Doressoundiram A., Cellino A., Di Martino M., Migliorini F., and Zappalà V. (1998b) The puzzling case of the Nysa-Polana family finally solved? *Bull. Am. Astron. Soc., 30,* 505.

Florczac M., Barucci M. A., Doressoundiram A., Lazzaro D., Angeli C. A., and Dotto E. (1998) A visible spectroscopic survey of the Flora clan. *Icarus, 133,* 233–246.

Gaffey M. J., Burbine T. H., and Binzel R. P. (1993) Asteroid spectroscopy: Progress and perspectives. *Meteoritics, 28,* 161–187.

Gladman B. J., Migliorini F., Zappalà V., Michel P., Cellino A., Froeschlé Ch., Levison H., Bailey M., and Duncan M. (1997) Dynamical lifetimes of objects injected into asteroid belt resonances. *Science, 277,* 197–201.

Jedicke R. and Metcalfe T. S. (1998) The orbital and absolute magnitude distributions of main belt asteroids. *Icarus, 131,* 245–260.

Jones T. D., Lebofsky L. A., Lewis J. S., and Marley M. S. (1990) The composition and origin of the C, P and D asteroids: Water as a tracer of thermal evolution in the outer belt. *Icarus, 88,* 172–192.

Lazzaro D., Mothé-Diniz T., Carvano J. M., Angeli C., Betzler A. S., Florczac M., Cellino A., Di Martino M., Doressoundiram A., Barucci M. A., Dotto E., and Bendjoya P. (1999) The Eunomia family: A visible spectroscopic survey. *Icarus, 142,* 445–453.

Marzari F., Farinella P., and Davis D. R. (1999) Origin, aging and death of asteroid families. *Icarus, 142,* 63–77.

McSween H. Y. Jr., Ghosh A., Grimm R. E., Wilson L., and Young E. D. (2002) Thermal evolution models of asteroids. In *Asteroids III* (W. F. Bottke Jr. et al., eds.), this volume. Univ. of Arizona, Tucson.

Migliorini F., Zappalà V., Vio R., and Cellino A. (1995) Interlopers within asteroid families. *Icarus, 118,* 271–291.

Migliorini F., Manara A., Di Martino M., and Farinella P. (1996) The Hoffmeister family: Inferences from physical data. *Astron. Astrophys., 310,* 681–685.

Milani A. and Knežević Z. (1990) Secular perturbation theory and computation of asteroid proper elements. *Cel. Mech., 49,* 316–330.

Milani A. and Knežević Z. (1992) Asteroid proper elements and secular resonances. *Icarus, 98,* 211–232.

Mothé-Diniz T., Di Martino M., Bendjoya P., Doressoundiram A., and Migliorini F. (2001) Rotationally resolved spectra of 10 Hygiea and a spectroscopic study of the Hygiea family. *Icarus, 152,* 117–126.

Petit J-M., Chambers J., Franklin F., and Nagasawa M. (2002) Primordial excitation and depletion of the main belt. In *Asteroids III* (W. F. Bottke Jr. et al., eds.), this volume. Univ. of Arizona, Tucson.

Rivkin A. S., Howell E. S., Britt D. T., Lebofsky L. A., Nolan M. C., and Branston D. D. (1995) Three-micron spectrometric survey of M- and E-class asteroids. *Icarus, 117,* 90–100.

Rivkin A. S., Howell E. S., Lebofsky L. A., Clark B. E., and Britt D. T. (2000) The nature of M-class asteroids from 3-μm observations. *Icarus, 145,* 351–368.

Rubin A. E. (1995) Petrologic evidence of collisional heating of chondritic asteroids. *Icarus, 113,* 156–167.

Tanga P., Cellino A., Michel P., Zappalà V., Paolicchi P., and Dell'Oro A. (1999) On the size distribution of asteroid families: The role of geometry. *Icarus, 141,* 65–78.

Tholen D. J. (1984) Asteroid taxonomy from cluster analysis of photometry. Ph.D. thesis, Univ. of Arizona, Tucson. 150 pp.

Veeder G. J., Matson D. L., Owensby P. D., Gradie J. C., Bell J. F., and Tedesco E. F. (1995) Eos, Koronis and Maria family asteroids: Infrared (JHK) photometry. *Icarus, 114,* 186–196.

Valsecchi G., Carusi A., Knežević Z., Kresák Ľ., and Williams J. G. (1989) Identification of asteroid dynamical families. In *Asteroids II* (R. P. Binzel et al., eds.), pp. 368–385. Univ. of Arizona, Tucson.

Xu S., Binzel R. P., Burbine T. H., and Bus S. J. (1995) Small main-belt asteroid spectroscopic survey: Initial results. *Icarus, 115,* 1–35.

Zappalà V. and Cellino A. (1996) Main belt asteroids: Present and future inventory. In *Completing the Inventory of the Solar System* (T. W. Rettig and J. M. Hahn, eds.), pp. 29–44. ASP Conference Series 107.

Zappalà V. and Cellino A. (2001). Formation of asteroid families and delivery of NEO showers from the main belt. In *Collisional Processes in the Solar System* (M. Marov and H. Rickman, eds.), pp. 303–321. Kluwer, Dordrecht.

Zappalà V., Cellino A., Farinella P., and Knežević Z. (1990) Asteroid families. I. Identification by hierarchical clustering and reliability assessment. *Astron. J., 100,* 2030–2046.

Zappalà V., Cellino A., Farinella P., and Milani A. (1994) Asteroid families II: Extension to unnumbered multiopposition asteroids. *Astron. J., 107,* 772–801.

Zappalà V., Bendjoya Ph., Cellino A., Farinella P., and Froeschlé C. (1995) Asteroid families: Search of a 12487 asteroid sample using two different clustering techniques. *Icarus, 116,* 291–314.

Zappalà V., Cellino A., Di Martino M., Migliorini F., and Paolicchi P. (1997) Maria's family: Physical structure and possible implications for the origin of giant NEAs. *Icarus, 129,* 1–20.

Zappalà V., Bendjoya P., Cellino A., Di Martino M., Doressoundiram A., Manara A., and Migliorini F. (2000) Fugitives from Eos family: First spectroscopic confirmation. *Icarus, 145,* 4–11.

Zappalà V., Cellino A., Dell'Oro A., and Paolicchi P. (2002) Physical and dynamical properties of asteroid families. In *Asteroids III* (W. F. Bottke Jr. et al., eds.), this volume. Univ. of Arizona, Tucson.