WHAT WE KNOW ABOUT FAMILIES OF ASTEROIDS

V. ZAPPALA'
Astronomical Observatory of Torino
I-10025 Pino Torinese
Italy

ABSTRACT. Asteroid families are considered for the most to represent fragments of collisional breakup of precursor bodies. If true, this offers the unique possibility to examine the interiors of large bodies and to study the processes of collision on a scale much larger than can be done in laboratory. Indeed, the general features of the mass distributions and of the ejection velocities of the family members can be interpreted in terms of collisional disruption of a parent body followed by self-gravitational reaccumulation on the largest remnant. However, several problems remain open: a) the degree of fragmentation in real families is generally lower than that observed for experimental targets; b) the relative velocities computed including also proper eccentricity and inclination differences are higher by about a factor 4 than those derived from semiaxes differences only; c) only very few of the presently proposed families have distributions of inferred mineralogies consistent with cosmochemistry. Further studies are needed, including better proper elements computation, classification methods, and new investigations on the physics of hypervelocity impacts.

1. INTRODUCTION

The very identification of a family via the analysis of "clusters" of orbital elements in the phase space, presents a number of difficulties and ambiguities due to the arbitrary nature of some key assumptions of the analysis, i.e., separating family members from the "field" objects, and to inaccurate or unreliable proper elements. The often produced divergent results were analyzed by Carusi and Valsecchi(1982). Moreover, although the idea of the origin of families by collisional breakup of a parent body is now widely accepted, the details of this process are not fully understood. While the potential of physical studies to test

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and refine the collisional breakup theory is apparent, a wealth of information seems still to be hidden in the available data. In particular, a systematic coupling of orbital and physical data has to be more deeply investigated.

Obviously, one cannot exclude that some (or many) families have non collisional origin. In addition to the well known groups of Hungaria and Phocaea (Williams, 1971), other smaller groups can be separated from the field by secular resonances and can appear as true families. At the moment, however, this field of research is just at the beginning; therefore, the present paper will be devoted only to demonstrate that the collisional hypothesis is quite consistent with the data and that from these data one can extract some interesting information on the mechanism of collisional fragmentation. In addition, the major discrepancies which remain to be solved will be outlined.

2. MASS DISTRIBUTIONS

The knoweldge of the mass (or size) distribution of asteroids has been generally considered a powerful tool in understanding the evolutionary mechanisms which have been effective for the asteroid population as a whole. In particular,it is known that catastrophic collisions should result in a characteristic mass distribution of fragments. In this framework, the determination of the mass distribution of family members is crucial, since it allows direct comparison with laboratory experiments as well as numerical simulations of both the individual breakup process and the overall collisional evolution.

Gradie et al.(1979) made the first comprehensive attempt to "reconstruct" the parent bodies for some selected families. Fujiwara(1982) performed a detailed study of the mass distribution of the three "classical" Hirayama families (Koronis, Eos, and Themis), concluding that the three families were completely fragmented, but most of the fragments should have been reaccumulated by mutual gravitation, while the larger members could have rubble-pile structures, roughly fitting hydrostatic equilibrium figures. Zappala' et al.(1984) extended the analysis to the whole set of Williams'(1979) families. The first step of their work was to reconstruct the total mass of a family and, as a consequence, the mass of its parent body. They computed the missing mass of the unobserved smaller components using a differential mass distribution, with an assumed exponent (1.8) as suggested by the theoretical study of Dohnanyi(1971) for the whole sample of asteroids. Obviously, this procedure yelds only a crude estimate of the lower limit for the total mass of each individual parent body, but can be very useful in statistical analyses.

Zappala' et al. represented the mass distributions of specific families in terms of the "discrete mass distribution" introduced by Kresak(1977). Comparing the distribution tails, the best fit exponents, the mass ratios among the largest fragments, and the total masses of the precursor bodies, they found that - a part the very few largest fragments - the trend is quite similar among most of the families and it can be roughly fit by the usual exponent of about 1.8. A good agreement was also found with the results coming from laboratory experiments on hipervelocity breakups (Fujiwara, 1986).

The behaviour of the mass distribution among the largest bodies, in particular the mass ratios among the parent body, the largest fragment, and the second largest fragment, deserve further scrutiny. A few families show an unusual sudden mass drop from the largest and the second largest remnant, which is completely absent among catastrophic fragmentation experiments. This can be explained as a result of sub-catastrophic cratering impacts, which leave most of the parent body's mass intact, but also as a product of gravitational effects leading the reaccumulation of the slowest escaping fragments onto the largest remnant. The latter hypothesis is confirmed by the correlation existing between the M1/M0 ratio (M0=mass of the parent body, M1=mass of the largest remnant) and the size of the precursor body: larger mass ratios, implying more efficient reaccumulation, are associated to larger parent bodies. On the other hand, no correlation was found for the M2/M0 ratio (M2=mass of the second largest fragment), implying that no reaccumulation is effective for smaller remnants. The latter conclusion leads to a major discrepancy between the mass distributions of most families and the laboratory results. In fact, a scaling of the specific energy (E/M) from laboratory experiments to asteroid sizes predicts much more fragmentation for the asteroids than is seen: the specific energy necessary to disperse the fragments to infinity, overcoming the gravitational binding of the parent body, is considerably higher than the critical value for breakup observed in the laboratory. The problem is that any reasonable partition of energy would break a target body into innumerable tiny pieces, if the impact were sufficiently energetic to provide the kinetic energy necessary to disperse the fragments into a family. This dilemma could be resolved only if the effective strengths for asteroids were exceptionally high (Davis et al.,1985).

3. VELOCITY DISTRIBUTIONS

Another fundamental aspect of the families which can be compared with experimental data is the apparent ejection velocities of the fragments. In line of principle one could derive the relative velocities from the differences between semimajor axis, proper eccentricity, and proper inclination of the family asteroids, and those of a reference body (for which a natural choice is the largest asteroid of the family under scrutiny). However, even at this preliminary stage, there are some inescapable difficulties involving the retardation of an ejected fragment due to self-gravitation of the disrupted body; a possible further dispersion due to subsequent breakups of the members; the dependences of the velocities on some unknown angles at the moment of the breakup event. Nevertheless, assuming to have reconstructed quite accurately the mass of the parent body and that the subsequent impacts should have affected only very small "original" fragments, the problem of the unknown angular elements at the time of breakup can be partially overcome by using some mean value of the trigonometric functions or by exploring the resulting velocities with various assumptions. Obviously, this procedure cannot be taken into account in order to understand the dynamical history of individual families, but can be useful for statistical considerations. This was the approach of Zappala' et al.(1984), who studied the proper elements of Williams'(1979) families. For obtaining the relative velocity components vS, vW, and vT(S=along the direction toward the Sun, W= along the normal to the orbital plane, and T=WxS) from the differences in semimajor axis, eccentricity and inclination, they used the classical Gauss' perturbation equations (see, e.g., Brouwer and Clemence, 1961, p.299). Even with the most favourable assumptions about the unknown angles quoted before, the velocity distributions were found to be far from isotropy. In fact, the r.m.s. values of vS and vW exceed by a factor 4 or 5 that of vT. This trend exists even for the three largest classical families (Themis, Eos, and Koronis). There is no obvious physical explanation for this result within the collisional theory. Excluding at the moment any cosmogonic rather than strictly collision origin for families, one should point out that while vT depends mainly on the difference in semimajor axis, vW and vS depend more strongly on the differences between inclination and eccentricity. Therefore, it is possible to ascribe the asymmetry to poor reliability of the proper elements e' and i'(a is generally a more reliable parameter). At least within the linear theory, Carpino et al.(1986) confirmed this hypothesis, by simulating some "synthetic" families and performing numerical integrations for 10000 years. They found that e' and i', as computed with the aid of the linear theory, fluctuate widely in time, causing a systematic "noise" in e' and i', artificially increasing the resulting differences and thus the velocities vS and vW.The asimmetry found by Zappala' et al.(1984) indicates that probably such effect cannot be completely removed, even within a more refined perturbation theory.

Based on these considerations, Zappala' et al.(1984),following Ip(1979) restricted their interpretation of family velocities to the velocity vT, which depends on the most "reliable" orbital parameter, the semimajor axis. The resulting value was multiplied by a factor 3**0.5 to account for the other two neglected components, assuming overall isotropy. The ejection velocity was computed by correcting the above velocity for the gravitational slowing down of the fragments escaping from the parent body.

From a plot of the mean ejection velocity of each family versus the size of the largest remnant, Zappala' et al. did not find any correlation. This result is consistent with the fact revealed by laboratory impact experiments that the ejection velocity depends mainly on the specific energy delivered to the target by the collision (Fujiwara and Tsukamoto, 1980); this quantity, in turn, depends on the impact velocity and on the projectile-to-target mass ratio, and both these parameters are not correlated with the target asteroid's size. The mean of the ejection velocity for the used sample of families resulted in 145 m/sec, which agrees well with the values found in the experiments for projectile-to-target mass ratio in the range 0.001 to 0.01 (assuming an impact velocity of about 5 km/sec); it is also remarkable that, according to Farinella et al.(1982), this range is precisely the same as that expected for the largest collision endured by all asteroids of size larger than about 10 km.

It is less easy to understand another result of this analysis: there are no velocities lower than 60 m/sec even for small target bodies, for which gravitational reaccumulation should be negligible. This result seems discrepant from experimental breakups, for which fragment velocities are generally lower for the same degree of fragmentation. Similar evidence about larger ejection velocities consistent with a moderate degree of fragmentation has been discussed in terms of the supposed catastrophic breakup of the saturnian satellite Hyperion (Farinella et al.,1983). This problem of velocity scaling may be related to the E/M scaling problem mentioned in the previous Section: in both cases, the apparent degree of fragmentation seems inadequate for the evident energy.

Even limiting the analysis to the vT component, it is possible to evidence some symmetry propriety of the ejection velocity field. The distribution of the differences in semimajor axis was investigated by Ip(1979) and extended by Zappala' et al.(1984). It was possible to distinguish between "symmetric" (or" dispersed") and "asymmetric" families, the latter ones showing most fragment on the same "side". Asymmetric families generally correspond to larger ejection velocities and to larger objects. Possibly this is again related to self-gravitation effects, which could amplify any initial anisotropy of the velocity field.

4. COMPOSITIONS OF FAMILY MEMBERS

Another fruitful way to study the origin of families and to investigate the collisional hypothesis is related to the mineralogy of the members of a given family. In the collisional assumption the inferred mineralogies must be consistent with a reliable cosmochemical model of the parent body.

Based on the TRIAD taxonomic classifications available (Bowell et al.,1979), Gradie et el.(1979) discussed the compositions for 47 Williams'(1979) families for which two or more members were classified. They concluded that while many of the more populous families are homogeneous, and consistent with the breakup of a homogeneous precursor body, a significant fraction of less populous smaller families are not. In addition, the families composed of dissimilar members are often difficult to explain in terms of the prevailing interpretations of mineralogy and cosmochemical models of parent bodies.

More recent studies have taken advantage of the refiniments in asteroid taxonomy and of the much larger database that has been compiled over the past decade. Bell (1988) concludes that there are only five families that seem to be well-established and composed of genetically related asteroids. He doubts the "reality" of a large fraction of the remaining families. On the other hand, Chapman(1987) performed a study which arrives at somewhat different -less pessimistic- conclusions. He confirms the distinctiveness and probable reality for the classical families (Nysa, Maria, Koronis, Eos, Themis, and subsets of the Flora family), and finds that several additional Williams families are compositionally distinctive, and a dozen more are probably distinctive although statistics are poor.

A more detailed review of the arguments of the present paper can be found in Chapman et al.(1988).

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