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Asteroid family ages

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ABSTRACT

A new family classification, based on a catalog of proper elements with ~384,000 numbered asteroids and on new methods is available. For the 45 dynamical families with >250 members identified in this classification, we present an attempt to obtain statistically significant ages: we succeeded in computing ages for 37 collisional families.

We used a rigorous method, including a least squares fit of the two sides of a V-shape plot in the proper semimajor axis, inverse diameter plane to determine the corresponding slopes, an advanced error model for the uncertainties of asteroid diameters, an iterative outlier rejection scheme and quality control. The best available Yarkovsky measurement was used to estimate a calibration of the Yarkovsky effect for each family. The results are presented separately for the families originated in fragmentation or cratering events, for the young, compact families and for the truncated, one-sided families. For all the computed ages the corresponding uncertainties are provided, and the results are discussed and compared with the literature. The ages of several families have been estimated for the first time, in other cases the accuracy has been improved. We have been quite successful in computing ages for old families, we have significant results for both young and ancient, while we have little, if any, evidence for primordial families. We found 2 cases where two separate dynamical families form together a single V-shape with compatible slopes, thus indicating a single collisional event. We have also found 3 examples of dynamical families containing multiple collisional families, plus a dubious case: for these we have obtained discordant slopes for the two sides of the V-shape, resulting in distinct ages. We have found 2 cases of families containing a conspicuous subfamily, such that it is possible to measure the slope of a distinct V-shape, thus the age of the secondary collision. We also provide data on the central gaps appearing in some families. The ages computed in this paper are obtained with a single and uniform methodology, thus the ages of different families can be compared, providing a first example of collisional chronology of the asteroid main belt.

1. Introduction

One of the main purposes for collecting large datasets on asteroid families is to constrain their ages, that is the epoch of the impact event generating a collisional family. A collisional family not always coincides with the dynamical family detected by density contrast in the proper elements space. More complicated cases occur, such as a dynamical family to be decomposed in two collisional families, or the opposite case in which a collisional family is split in two density contrast regions by some dynamical instability.

Although other methods are possible, currently the most precise method to constrain the age of a collisional family (for the ages older than ~10 Myr) exploits non-gravitational perturbations, mostly the Yarkovsky effect (Vokrouhlický et al., 2000). These effects generate secular perturbations in the proper elements of an asteroid which are affected not just by the position in phase space, but also by the Area/Mass ratio, which is inversely proportional to the asteroid diameter D. Thus, the main requirements are to have a list of family members with a wide range of values in D, enough to detect the differential effect in the secular drift of the proper elements affecting the shape of the family, and to have a large enough membership, to obtain statistically significant results.

Recently Milani et al. (2014) have published a new family classification by using a large catalog of proper elements (with >330,000 numbered asteroids) and with a classification method

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improved with respect to past methods. This method is an extension of the Hierarchical Clustering Method (HCM) (Zappalá et al., 1990), with special provisions to be more efficient in including large numbers of small objects, while escaping the phenomenon of chaining. Moreover, the new method includes a feature allowing to (almost) automatically update the classification when new asteroids are numbered and their proper elements have been computed. This has already been applied to extend the classification to a source catalog with ~384,000 proper elements, obtaining a total of ~97,400 family members (Knežević et al., 2014). In this paper we are going to use the classification of Milani et al. (2014), as updated by Knežević et al. (2014), and the data are presently available on AstDyS.[1]

This updated classification has 21 dynamical families with >1000 members and another 24 with >250 members. The goal of this paper can be simply stated as to obtain statistically significant age constraints for the majority of these 45 families. Computing the ages for all would not be a realistic goal because there are several difficulties. Some families have a very complex structure, for which it is difficult to formulate a model, even with more than one collision: these cases have required or need dedicated studies. Some families are affected by particular dynamical conditions, such as orbital resonances with the planets, which result in more complex secular perturbations: these shall be the subject of continuing work. The results for families with only a moderate number of members (such as 250–300) might have a low statistical significance.

The age estimation includes several sources of uncertainty which cannot be ignored. The first source appears in the formal accuracy in the least square fit used in our family shape estimation methods. The uncertainty depends upon the noise resulting mostly from the inaccuracy of the estimation of D from the absolute magnitude H. The second source of error occurs in the conversion of the inverse slope of the family boundaries into age, requiring a Yarkovsky calibration: this is fundamentally a relative uncertainty, and in most cases it represents the largest source of uncertainty in the inferred ages. In Section 4.1 we give an estimate of this uncertainty between 20% and 30%.

As a result of the current large relative uncertainty of the calibration, we expect that this part of the work will be soon improved, thanks to the availability of new data. Thus the main result of this paper are the inverse slopes, because these are derived by using a consistent methodology and based upon large and comparatively accurate data set. Still we believe we have done a significant progress with respect to the previous state of the art by estimating 37 collisional family ages, in many cases providing the first rigorous age estimate, and in all cases providing an estimated standard deviation. The work can continue to try and extend the estimation to the cases which we have found challenging.

Since this paper summarizes a complex data processing, with output needed to fully document our procedures but too large, we decided to include only the minimum information required to support our analysis and results. Supplementary material, including both tables and plots, is available from the web site http://hamilton.dm.unipi.it/astdys2/fam_ages/.

2. Least squares fit of the V-shape

Asteroids formed by the same collisional event take the form of a V in the (proper a–$1/D$) plane. The computation of the family ages can be performed by using this V-shape plots if the family is old enough and the Yarkovsky effect dominates the spread of proper a, as explained in Milani et al. (2014, Section 5.2). The key idea is to compute the diameter D from the absolute magnitude H, assuming a common geometric albedo p_v for all the members of the family. The common geometric albedo is the average value of the known WISE albedos (Wright et al., 2010; Mainzer et al., 2011) for the asteroids in the family. Then we use the least squares method to fit the data with two straight lines, one for the low proper a (IN side) and the other for the high proper a (OUT side), as in Milani et al. (2014), with an improved outlier rejection procedure, see Carpino et al. (2003) and Section 2.4.

2.1. Selection of the fit region

Most families are bounded on one side or on both sides by resonances. Almost all these resonances are strong enough to eject most of the family members that fell into the resonances into unstable orbits. In these cases the sides of the V are cut by vertical lines, that is by values of a, which correspond to the border of the resonance. For each family we have selected the fit region taking into account the resonances at the family boundaries. The fit of the slope has to be done for values of $1/D$ below the intersection of one of the sides of the V affected by the resonance and the resonance border value of proper a. In Table 1 we report the values for a and D, and the cause of each selection.

The *cause* of each cut in proper a is a mean motion resonance, in most cases a 2-body resonance with Jupiter, in few cases either a 2-body resonance with Mars or a 3-body resonance with Jupiter and Saturn. When no resonance with this role has been identified, we use the label FB (for Family Box) to indicate that the family ends where the HCM procedure does not anymore detect a significant density contrast (with respect to the local background). This is affected by the depletion of the proper elements catalog due to the completeness limit of the surveys: the family may actually contain many smaller asteroids beyond the box limits, but they have not been discovered yet. On the contrary when the family range in proper a is delimited by strong resonances, the family members captured in them can be transported far in proper e (and to a lesser extent in proper $\sin I$) to the point of not being recognizable as members; over longer time spans, they can be transported to planet-crossing orbits and removed from the main belt altogether.

The tables in this paper are sorted in the same way: there are four parts, dedicated to families of the types fragmentation, cratering, young, one-sided; inside each group the families are sorted by decreasing number of members. In some cases the tables have been split in four sub-tables, one for each type.

In two cases we have already defined the fit region in such a way that we can include two families in a single V-shape. This *family join* is justified later, in Section 3, by showing that the two dynamical families can be generated by a single collision. This applies to the join of 10955 with 19466 and to the join of 163 with 5206. Note that the join of two families, justified by the possibility to fit together in a single V-shape with a common age, is conceptually different from the *merge* of two families due to intersections, discussed in Milani et al. (2014) and Knežević et al. (2014); however, the practical consequences are the same, namely one family is included in another one and disappears from the list of families.

For one-sided families we are also indicating the "cause" of the missing side. E.g., for 2076 the lack of the IN side of the V-shape is due to the 7/2 resonance; on the other hand, the dynamical family 883 could be the continuation of 2076 at proper a lower than the one of the resonance. However, the V-shape which would be obtained by this join would have two very different slopes, thus it can be excluded that they are the same collisional family.

For most families the "cause" of the delimitation in proper a, in the sense above, can be clearly identified. However, some ambiguous cases remain: e.g., for family 1128 the outer boundary could be

[1] http://hamilton.dm.unipi.it/astdys/index.php?pc=5.