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Reconstructing the size distribution of the primordial Main Belt

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ABSTRACT

In this work we aim to constrain the slope of the size distribution of main-belt asteroids, at their primordial state. To do so we turn out attention to the part of the main asteroid belt between 2.82 and 2.96 AU, the so-called "pristine zone", which has a low number density of asteroids and few, well separated asteroid families. Exploiting these unique characteristics, and using a modified version of the hierarchical clustering method we are able to remove the majority of asteroid family members from the region. The remaining, background asteroids should be of primordial origin, as the strong 5/2 and 7/3 mean-motion resonances with Jupiter inhibit transfer of asteroids to and from the neighboring regions. The size-frequency distribution of asteroids in the size range $17 < D(\mathrm{km}) < 70$ has a slope $q \simeq -1$. Using Monte-Carlo methods, we are able to simulate, and compensate for the collisional and dynamical evolution of the asteroid population, and get an upper bound for its size distribution slope $q = -1.43$. In addition, applying the same 'family extraction' method to the neighboring regions, i.e. the middle and outer belts, and comparing the size distributions of the respective background populations, we find statistical evidence that no large asteroid families of primordial origin had formed in the middle or pristine zones.

1. Introduction

One of the reasons for which asteroids are subject of many studies is that they represent what is left over of the original population of planetesimals in the inner Solar System. Among the many properties of asteroids, their size-frequency distribution[1] (SFD) may be diagnostic of the processes by which planetesimals formed. The current cumulative SFD of asteroids is characterized by a quite steep slope in the size range $100\,\mathrm{km} < D < 1000\,\mathrm{km}$ (with an exponent q of about −2.5), and a shallower slope for $D < 100\,\mathrm{km}$ (with $q \sim -1.8$ down to $D \sim 10\,\mathrm{km}$). The current SFD of the asteroids, however, is presumably not identical to the SFD that planetesimals had at the time of their formation, but has evolved over the age of the Solar System as a consequence of various phenomena: collisions between asteroids produce a plethora of small fragments from only two original bodies, directly altering the SFD of the total population. Moreover, dynamical depletion is constantly removing asteroids from the main belt: The interplay between the Yarkovsky thermal force and the strongest resonances (mean-motion and secular ones), is the most important depletion mechanism, and since the Yarkovsky effect is size-dependent the SFD is modified accordingly.

Using several observational constraints, Bottke et al. (2005) concluded that the original SFD of planetesimals below $D = 100\,\mathrm{km}$ had to be equal to or shallower than the current one. However, they could not constrain what the original slope had to be. Considering the possibility of a very shallow primordial slope, Morbidelli et al. (2009) suggested that asteroids formed big, with characteristic sizes in the 100 km–1000 km range. The model emerging at the time about planetesimal formation from massive self-gravitating clumps of dust (Cuzzi et al., 2008) and pebbles (Johansen et al., 2007) seemed to support, at least qualitatively, that claim.

More recently, Johansen et al. (2015) studied in details the formation of planetesimals by streaming instability (Youdin and Johansen, 2007; Johansen and Youdin, 2007), using hydrodynamical simulations with multiple resolutions. They found that the planetesimals formed by this process have a characteristic cumulative SFD with exponent $q = -1.8$. Because this slope is very close to that currently observed for asteroids with $D < 100\,\mathrm{km}$, Johansen et al. (2015) proposed that 100 km is the maximal size of the planetesimals formed by the streaming instability. The asteroids currently larger than 100 km would have grown from primordial

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[1] The size-frequency distribution of asteroids is usually approximated by a power law, with a characteristic exponent q: $N(D) \sim D^q$.

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sizes smaller than this upper limit in a subsequent process named "pebble accretion" (Lambrechts and Johansen, 2012). Klahr and Schreiber (2015) instead, found that the characteristic size of the planetesimals formed by the streaming instability is $D \sim 100\,\mathrm{km}$, but with the wings of the size probability function extending to smaller and larger bodies. Cuzzi et al. (2010) had obtained a similar result, but for the turbulent concentration of clumps of small particles, rather than the streaming instability.

It is clear that the papers quoted above about planetesimal accretion, present quite different views on the characteristic sizes of the first planetesimals. In order to discriminate among them, it would be important to have an observational assessment of the primordial planetesimal SFD below 100 km in size. But, as said above, the asteroid SFD has evolved through collisions and dynamical depletion.

In principle, asteroids (tens of km in diameter) produced in collisions should be identifiable as members of asteroid families. Thus, if one removes the asteroid families from asteroid catalogs, one should be left with the population of these bodies which have not been produced by collisions through the lifetime of the Solar System: namely the primordial population. However, this procedure is not so easy to implement. The Hierarchical Clustering Method (Zappala et al., 1990) the most used procedure for the identification of asteroid family members usually succeeds in linking only the compact core of the family. This has been shown by Parker et al. (2008), who demonstrated that each nominal family identified by HCM is surrounded by a halo sharing the same spectral properties. Recent upgrades of the HCM (Milani et al., 2014; 2016) attempt to identify the family halos through a multi-step approach. However, it is unlikely that the entire family population can be identified with confidence even with this more sophisticated approach. The situation may be better for relatively large asteroids that we are interested here, but this is not certain.

Here, we assess the fraction of the background asteroid population (i.e. the population not belonging to any family) that is made of rogue family members and the characteristic size at which this contamination starts to be relevant. To do so, we focus in a zone of the asteroid belt, with semi-major axis $2.82 < a < 2.96$ AU, which contains much fewer asteroids than any other zone. The explanation for this deficit of asteroids, according to Brož et al. (2013), is due to the bordering of the 5/2 and the 7/3 mean motion resonances with Jupiter, which prevent the influx of asteroids migrating due to the Yarkovsky effect (Bottke et al., 2002) from the neighboring regions. Also, because the region is quite narrow, only few asteroid families formed in it. For these reasons, Brož et al. (2013) dubbed this region as the "pristine zone", as it is probably the one that reflects the best the primordial distribution of asteroids.

In this region it is fairly easy to subtract the family members, given the small number of families and the low orbital density of the overall population. We can also try to subtract all family members from the two regions that border the pristine zone, which contain a larger number of asteroids. This procedure is explained in Section 2. In principle, there is no reason that the primordial orbital densities of asteroids were different in neighboring regions. Thus, in Section 3, by comparing the nominal background population in the pristine zone with those in neighboring regions with the same semi major axis width, we can get statistical information on which fraction of these neighboring background populations should be in reality made of rogue family members that we cannot identify as such.

We then go further in our analysis in Section 4. To gain confidence that the background population in the pristine zone really represents the primordial SFD of asteroids and to determine up to which absolute magnitude this is true, we compare it with those in the neighboring regions. We require that at least in one of the neighboring zones the SFD of the background population is the same as in the pristine zone (e.g. same shape, same slopes, number of asteroids within a factor of ~ 2). We find that this is the case in the inner neighboring region up to absolute magnitude H $\sim$ 12, while we explain why the outer neighboring zone is different. Moreover we verify that the background SFD for $H < 12$ in the pristine zone is different from those of the families in these two regions, as suggested by Cellino et al. (1991).

Based on these results, in Section 5 we measure the slope of the SFD of the background population in the pristine zone between $9 < H < 12$. However, this is not yet the slope of the SFD of the primordial planetesimals below 100 km in size, because some original asteroids in this magnitude range might have been destroyed by collisions, even if, in principle, none of the current background asteroids was produced by collisions (by definition of background, if selected correctly). Thus, we correct the SFD slope by the size-dependent probability to have been catastrophically disrupted over the age of the Solar System, given in Bottke et al. (2005). Finally, we compare this slope with that expected by the streaming instability in the Johansen et al. (2015) simulations.

The conclusions of this work are summarized and discussed in Section 6.

2. Identification of family members

The first step of our study is to obtain the background population of the pristine zone. To do so we simply remove from the catalog of proper elements of numbered and multi-opposition asteroids[2] those asteroids that have been identified as family members following the classification of Milani et al. (2014) and Milani et al. (2016). However due to the fact that the focus of their study was to obtain a good classification of families, the authors of these works adopted a conservative approach in the selection of their Quasi Random Level (QRL)[3] for the hierarchical clustering analysis (Zappala et al., 1990), in order to avoid background objects from being incorrectly identified as family members and maintain good separation in orbital elements between families. Moreover they used the same QRL parameter for the pristine zone as for the rest of the outer belt. This resulted in a statistically significant family identification, which however left as background a lot of asteroids that should belong to the halos of asteroid families. This can be appreciated by looking at Fig. 1 panel b, where we see that even after removing all family members according to the Milani et al. classification, most of the very same families are still recognizable by the density contrast in the proper element space. For our purpose, which is to obtain as clear of a background as possible this is not the optimal solution. Therefore we decided to proceed with a modified application of the hierarchical clustering method, trying to get rid of as many family members as possible. We perform the hierarchical clustering method to the catalog of proper elements of the pristine zone, starting with the parent bodies identified by Milani et al. (2014). Moreover we also consider the parent bodies of asteroid families identified in Brož et al. (2013) which are not present in the Milani et al. (2014) classification, to make sure we remove as many family members as possible. We obtain for each asteroid family the number of associated members as a function of the cut-off velocity. We vary the latter, in increments of 2 m/s, from very small values where no close neighbor is found, up to

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

[3] The Quasi Random Level is a measure of the statistical significance when identifying asteroid families. It sets a threshold on the cut-off velocity, the maximum distance in the proper elements space between asteroids belonging to the same group, above which there is no statistical difference between an actual family and a statistical fluke of a random distribution of asteroids. For more see: Zappala et al. (1990).

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