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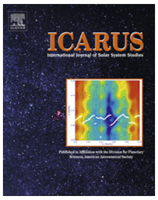

A six-part collisional model of the main asteroid belt

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ABSTRACT

In this work, we construct a new model for the collisional evolution of the main asteroid belt. Our goals are to test the scaling law of Benz and Asphaug (Benz, W., Asphaug, E. [1999]. Icarus, 142, 5–20) and ascertain if it can be used for the whole belt. We want to find initial size–frequency distributions (SFDs) for the considered six parts of the belt (inner, middle, "pristine", outer, Cybele zone, high-inclination region) and to verify if the number of synthetic asteroid families created during the simulation matches the number of observed families as well. We used new observational data from the WISE satellite (Masiero et al., 2011) to construct the observed SFDs. We simulate mutual collisions of asteroids with a modified version of the Boulder code (Morbidelli, A., et al. [2009]. Icarus, 204, 558–573), where the results of hydrodynamic (SPH) simulations of Durda et al. (Durda, D.D., et al. [2007]. Icarus, 498–516) and Benavidez et al. (Benavidez, P.G., et al. [2012]. 219, 57–76) are included. Because material characteristics can significantly affect breakups, we created two models — for monolithic asteroids and for rubble-piles. To explain the observed SFDs in the size range $D = 1$ to 10 km we have to also account for dynamical depletion due to the Yarkovsky effect. The assumption of (purely) rubble-pile asteroids leads to a significantly worse fit to the observed data, so that we can conclude that majority of main-belt asteroids are rather monolithic. Our work may also serve as a motivation for further SPH simulations of disruptions of smaller targets (with a parent body size of the order of 1 km).

1. Introduction

The collisional evolution of the main asteroid belt has been studied for more than 60 years (Dohnanyi, 1969; Davis et al., 1979 etc.). The first collisional model was created by Dohnanyi (1969) and his important result was that a size–frequency distribution for a population of mutually colliding asteroids will reach an equilibrium. If the cumulative distribution is described by a power law, the corresponding slope (exponent) will be close to -2.5. An overview of previous modeling of the main belt and subsequent advances can be found in a relatively recent paper by Bottke et al. (2005), so that we shall not repeat it here. Nevertheless, it is worth to mention another development, which is an attempt to merge a classical particle-in-a-box collisional model with (parametrized) results of smooth-particle hydrodynamic (SPH) codes as done in Morbidelli et al. (2009). We are going to use this kind of method in this work.

Every collisional model should comply with two important constraints: (1) the size–frequency distribution (SFD) of main belt at the end of a simulation must fit the observed SFD; (2) the number of asteroid families created during this simulation must fit the observed number of families. It is important to note, that the models were improved in the course of time not only due to the progress of technology or new methods but also thanks to an increasing amount of observational data. In this work, we could exploit new data obtained by the WISE satellite (Wide-field Infrared Survey Explorer; Masiero et al., 2011), specifically, diameters and geometric albedos for 129,750 asteroids.

Moreover, several tens of asteroid families are observed in the main belt as shown by many authors (Zappalà et al., 1995; Nesvorný et al., 2005, 2010; Brož et al., 2013; Masiero et al., 2013; Milani et al., 2013). The lists of collisional families are also steadily improved, they become more complete and (luckily) compatible with each other.

In order to fully exploit all new data, we created a new collisional model in which we divided the whole main belt into six parts (see Section 2 for a detailed discussion and Section 3 for the description of observational data). Our aims are: (1) to check the number of families in individual parts of the belt — we use the list of families from Brož et al. (2013) (which includes also their physical properties) with a few modifications; (2) to verify whether a single scaling law (e.g. Benz and Asphaug, 1999) can

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be used to fit the *whole* asteroid belt, or it is necessary to use two different scaling laws, e.g. one for the inner belt and second for the outer belt; (3) and we also test a hypothesis, if the main belt is mostly composed of monolithic or rubble-pile objects.

In this paper, we assume that *all* families observed today were created in the last ~4 Gyr (without any influence of the late heavy bombardment dated approximately 4.2 to 3.85 Gyr ago).[1] We thus focus on an almost steady-state evolution of the main belt, without any significant changes of collisional probabilities or dynamical characteristics. This is different from the work of Bottke et al. (2005). We must admit here that the assumption of the steady-state evolution could be disputable, since Dell'Oro et al. (2001) showed that the formation of big asteroid families may influence the impact probability.

We model collisions with the statistical code called Boulder (Morbidelli et al., 2009) that we slightly extended to account for six populations of asteroids (Sections 5 and 6). As mentioned above, the Boulder code incorporates the results of the SPH simulations by Durda et al. (2007) for *monolithic* $D_{\rm PB} = 100$ km parent bodies, namely for the masses of the largest remnant and fragment and an overall slope of fragment's SFD. For asteroids larger or smaller than $D_{\rm PB} = 100$ km a scaling is used for sake of simplicity.

Material characteristics definitely have significant influence on mutual collisions (e.g. Michel et al., 2011; Benavidez et al., 2012). Therefore, we also run simulations with *rubble-pile* objects, which are less firm (refer to Section 7). A set of simulations analogous to Durda et al. (2007) for rubble-pile targets with $D_{\rm PB} = 100$ km was computed by Benavidez et al. (2012).

First, we try to explore the parameter space using a simplex algorithm while we keep the scaling law fixed. Considering a large number of free parameters and the stochasticity of the system, we look only for some local minima of χ^2 and we do not expect to find a statistically significant global minimum. Further possible improvements and extensions of our model are discussed in Sections 8 and 9.

2. A definition of the six parts of the main belt

We divided the main belt into six parts (sub-populations) according the synthetic orbital elements (the semimajor axis a and the inclination I, Fig. 1). Five parts separated by major mean-motion resonances with Jupiter are well-defined — if an asteroid enters a resonance due to the Yarkovsky effect (Bottke et al., 2006), its eccentricity increases and the asteroid becomes a near-Earth object. Consequently, vast majority of large asteroids do not cross the resonances[2] and we do not account for resonance crossing in our model. The sixth part is formed by asteroids with high inclinations, $\sin I_{\rm p} > 0.34$. This value corresponds approximately to the position of the ν_6 secular resonance.

Namely, the individual parts are defined as follows:

1. inner belt – from $a = 2.1$ to 2.5 AU (i.e. the resonance 3:1);
2. middle belt – from 2.5 to 2.823 AU (5:2);
3. "pristine" belt – from 2.823 to 2.956 AU (7:3; as explained in Brož et al. (2013));
4. outer belt – from 2.956 to 3.28 AU (2:1);
5. Cybele zone – from 3.3 to 3.51 AU;
6. high-inclination region – $\sin I > 0.34$.

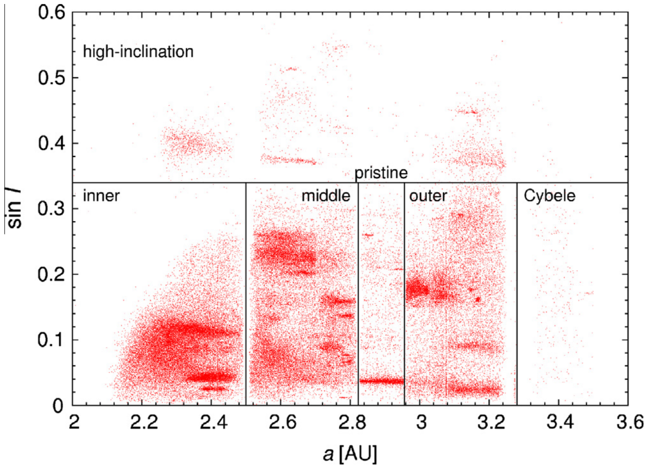

Fig. 1. A definition of the six parts of the main asteroids belt according to the semimajor axis a and the inclination I: inner, middle, "pristine", outer, Cybele zone and high-inclination region. The numbers of objects in these parts are the following: 177,756; 186,307; 23,132; 121,186; 1894 and 25,501, respectively.

For a and $\sin I$ we preferentially used the proper values from the AstDyS catalog (Asteroids Dynamic Site; Knežević and Milani, 2003).[3] For remaining asteroids, not included in AstDyS, we used osculating orbital elements from the AstOrb catalog (The Asteroid Orbital Elements Database).[4]

More precisely, we used proper values from AstDyS for 403,674 asteroids and osculating values from AstOrb for 132,102 not-yet-numbered (rather small) asteroids, which is a minority. We thus think that mixing of proper and osculating orbital elements cannot affect the respective size–frequency distributions in a significant way. Moreover, if we assign (erroneously) e.g. a high-inclination asteroid to the outer main belt, then it is statistically likely that another asteroid from the outer main belt may be assigned (erroneously) to the high-inclination region, so that overall the SFDs remain almost the same.

3. Observed size–frequency distributions

To construct SFDs we used the observational data from the WISE satellite (Masiero et al., 2011)[5] — for 123,306 asteroids. Typical diameter and albedo relative uncertainties are ~10% and ~20%, respectively (Mainzer et al., 2011), but since we used a statistical approach (10^4 to 10^5 bodies), this should not present a problem. For asteroids not included there we could exploit the AstOrb catalog (i.e. data from IRAS; Tedesco et al., 2002) — for 451 bodies. For remaining asteroids (412,019), we calculated their diameters according the relation (Bowell et al., 1989)

$$D = 10^{0.5(6.259 - \log p_V) - 0.4H}, \tag{1}$$

where H denotes the absolute magnitude from the AstOrb catalog and p_V the (assumed) geometric albedo. We assigned albedos to asteroids without a known diameter randomly, by a Monte-Carlo method, from the distributions of albedos constructed according

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[1] This is an approach different from Brož et al. (2013), where (at most) 5 large ($D_{\rm PB} > 200$ km) catastrophic disruptions were attributed to the LHB. Nevertheless, there was a possibility (at a few-percent level) that all the families were created without the LHB. So our assumptions here do not contradict Brož et al. (2013) and we will indeed discuss a possibility that the number of post-LHB families is lower than our 'nominal' value.

[2] For very small asteroids ($D \lesssim 10$ m) we must be more careful. Nevertheless, if an asteroid is able to cross the resonance between e.g. the pristine and the middle belt (i.e. increasing the population of the middle belt) then another asteroid is able to cross the resonance between the middle and the inner belt (decreasing the population of the middle belt). The crossing of the resonances essentially corresponds to a longer time scale of the dynamical decay, which we shall discuss in Section 8.

[3] http://hamilton.dm.unipi.it/astdys/.

[4] ftp://ftp.lowell.edu/pub/elgb/astorb.html.

[5] http://wise2.ipac.caltech.edu/staff/bauer/NEOWISE_pass1/.