Asteroids were born big

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Received ____________________; accepted ____________________

The classical model of terrestrial planet and Jovian core formation assumes two steps take place. In the first, solid grains grow into small, kilometer-sized planetesimals, whereas in the second, collisional coagulation among the planetesimals allows them to agglomerate into planet-size bodies. Here we show, using simulations of this second step, that an initial population of kilometer-sized planetesimals cannot evolve into a size distribution that is consistent with our current understanding of the post-accretion state of the asteroid belt. Instead, we find compelling evidence that the early asteroid belt was largely comprised of 100–1,000 km diameter bodies. This implies that main belt planetesimals, and possibly those across the solar system, were produced by a mechanism other than standard collisional coagulation (e.g. (1)). Accordingly, these results suggest that planet formation followed a path different from what is usually assumed and the classical model, despite its simplicity and appeal, should be reconsidered.

This classical model is appealing because it explains the accretion of Mercury- to Earth-sized bodies in the inner Solar System (2; 3; 4; 5) and, possibly, of super-Earth cores in the Jovian planet region (6; 7). A self-consistent accretion model, however, must also be able to reproduce the size-frequency distributions (SFDs) of small body populations. Here we test the classical model by simulating the stage where Moon- to Mars-mass planetary embryos grow. We focus on this occurring in the asteroid belt, the best-understood reservoir of leftover planetesimals in the Solar System.

The asteroid belt has changed significantly since the planet formation epoch. Numerical models of its collisional and dynamical history, however, allow us to both interpret a wide range of observations in the current asteroid belt and deduce what its original (e.g., post-accretion) nature was like. According to our best models (see the Supplementary

Materials for a detailed review), the reconstructed main belt had the following properties: (i) The shape of its SFD for diameter $D > 100$ km bodies was the same as the current main belt SFD (8). (ii) The SFD experienced a significant change in slope to shallower power law values near $D \sim 100$ km. This left a "bump" that can still be seen in the current main belt SFD (8) (Fig. 1). (iii) There probably were $\sim$ 1,000 times as many $D =$ 100-1,000 km objects than they are now. In fact, the primordial mass of solids originally in this region is believed to have been $\sim$ 1,000 times larger than the current total mass (i.e., 6×10^{-4} Earth masses) (e.g. (9)). This mass was probably eliminated mainly by a size-independent dynamical depletion mechanism, not collisional grinding (e.g. (8; 10)). (iv) The main belt is believed to have once included 0.01-0.1 Earth mass planetary embryos. Our models require these embryos to explain both the dynamical sculpting of the asteroid belt and the formation of the terrestrial planets (11; 12; 13). They were eliminated from the asteroid belt during the events described in (iii).

We are confident that the reconstructed belt is a good approximation of reality because it was worked out within the confines of a comprehensive model that not only explains the major properties of the observed asteroid belt but also those of the terrestrial planets (12; 13). Therefore, we argue it is reasonable to use the reconstructed belt to test predictions from planetary accretion simulations.

For this purpose, we model the temporal evolution of the early main belt SFD using `Boulder`, a statistical coagulation/fragmentation code of the collisional accretion process that we constructed along the lines of previous codes (e.g., (2; 14; 15)). The description of `Boulder`, as well as its validation tests are reported in the Supplementary Materials.

Our simulations account for eccentricity e and inclination i excitation due to mutual planetesimal perturbations as well as (e, i) damping due to dynamical friction, gas drag and mutual collisions. Our nominal simulations start with 1.6 Earth masses of solid material within an annulus between 2-3 AU. By assuming a nominal gas/solid mass ratio of 200, this corresponds to the Minimum Mass Solar Nebula defined in (16). The bulk mass density of the planetesimals is set to 2g/cm^3, the average value between those measured for S-type and C-type asteroids (17). Unless specified, the simulations cover a time-span of 3 My, consistent with the mean lifetime of nearby proto-planetary disks (18) and hence the probable formation timescale of Jupiter. The initial velocity dispersion of the planetesimals is assumed to be equal to their Hill speed ($v_{\rm orb}[M_{\rm obj}/(3M_\odot)]^{1/3}$, where $v_{\rm orb}$ is the orbital speed of the object, $M_{\rm obj}$ is its mass, and $M_\odot$ is the solar mass). The lower size limit of planetesimals tracked in our simulation is diameter $D = 0.1$ km.

In our first simulation, we start with a population of 1.2×10^{12} planetesimals with $D = 2$ km, typical initial conditions for classical accretion simulations (Fig. 1a). We find the resulting SFD does not satisfy reconstructed belt properties (i)-(iii): the SFD between $D = 300$ and 1,000 km is too steep, there is no turn-over to a shallower slope at $D \sim 100$ km, and the number of $\sim 1,000$ km "Ceres-size" objects is too small by more than an order of magnitude. Increasing the simulation timescale to 10 My does not improve matters, with the largest bodies growing to 0.5 Mars masses without significantly modifying the SFD in the 10-1,000 km range. Other variations around our initial conditions lead to comparable and equally unsatisfying results (see Fig. 1 caption and Supplemental Materials for additional discussion).

We believe that the above mismatch is robust and will naturally occur in any system which starts with only small objects. The shape of our model SFD, particularly the shallow slope in the interval 500 km$< D <$2,000 km and the paucity of objects of these sizes (Fig. 1a), is diagnostic of the well-known process of runaway growth, where large objects grow faster than small ones due to gravitational attraction (19; 20). Runaway growth is particularly effective if the bulk of the mass is initially in small objects and, therefore, it is unlikely that any simulation which starts with only small objects will ever produce a SFD significantly different from Fig. 1a (21).

If true, what alternatives can potentially replace the classical accretion model? A possible solution comes from a recent conceptual breakthrough; new models show that large planetesimals can form directly from the concentration of meter-sized boulders (1) or chondrule-size particles (22) in the turbulent structures of the gaseous component of the protoplanetary disk. These results imply that physical processes other than collisional coagulation might have formed large planetesimals early on. Thus, the original planetesimals were not necessarily small, but might have had a variety of sizes. Hence, in what follows, we assume that the initial planetesimal SFD is a free parameter of our model and we simulate how this SFD evolves under mutual planetesimal collisions. By tuning the initial SFD, we attempt to reproduce our reconstructed asteroid belt. These simulations should allow us to glean insights into the processes that produced the first planetesimals.

In our next simulation, we attempt to satisfy property (ii), the turnover of the size distribution at $D \sim 100$ km, by inputing into `Boulder` 9.4×10^6 bodies with $D = 100$ km (Fig. 1b). A sharp turnover of the SFD at the initial planetesimal size is obtained, but properties (i) and (iii) are not satisfied. Still, this run shows the way forward —the turnover at $D = 100$ km may be indicative of the minimal size of the initial planetesimals. However, the planetesimals might need to span a wide range of sizes to match the other constraints.

Thus, we next start with $D =$ 100-500 km planetesimals in a main belt-like SFD. In order to place 1.6 Earth masses in these bodies, we have to assume they were $\sim 10,000$ times more numerous than current asteroids in the same size range. The results are shown in Fig. 1c. On the positive side, we find that the slope of the input SFD is now preserved. On the negative side, the slope of the SFD beyond the initial planetesimals' maximal size ($D > 500$ km) is once again too steep and we end up with too many 100-500 km objects.

We conclude that the initial planetesimals had to range in size all the way up to (at least) Ceres-size objects, and that only a fraction of a Minimal Solar Nebula mass could have been incorporated into these large planetesimals.

Therefore, in our last simulation in this series, we input a range of 100-1,000 km planetesimals in quantities that are 2,000-4,000 times the main belt population from the small to the large end (i.e., they have a SFD slightly shallower than the current main belt SFD). The remaining mass, which is about 45% of the total, is placed in $D = 2$ m bodies. Our results are shown in Fig. 1d. We find that $\sim 10\%$ of the meter-size boulders coagulate with the large planetesimals, while the rest are lost via collisional grinding. The final SFD is now consistent with properties (i)-(iv) of the reconstructed post-accretion asteroid belt. Our scaled results are also consistent with those found by direct N-body simulations (23) (i.e., we reproduce the mass of their largest body and their total number of $D > 2,000$ km objects).

In the above calculations we made two simplifying assumptions: i) We postulated that the large planetesimals formed so quickly that they essentially existed from the beginning of the simulation. However, theoretical considerations and meteorite data indicate that planetesimals should form sporadically over the lifetime of the gas disk (22; 24). ii) We have assumed that the nebula was not turbulent. However, recall that the works that motivated us to start with large planetesimals assumed a turbulent disk. Turbulence should enhance the velocity dispersion of the planetesimals (25) and this might abort growth if the latter becomes considerably larger than the escape velocity of the largest objects.

Thus, we now perform more sophisticated calculations where we relax the above assumptions. In particular, to account for (i) we randomly introduce planetesimals in `Boulder` over a 2 My timespan in two different ways. In case-A, we assume all the mass was initially in small bodies. Every time a large planetesimal is injected in the simulation, we remove an equal amount of mass from the small bodies. In case-B, we inject equal mass proportions of small bodies and planetesimals. This method accounts for the possibility that planetesimal formation is regulated by the availability of 'building blocks'. Note that chondrules may be such building blocks; they are an essential component of many meteorites and they appear to have formed progressively over time (24). In addition, we account for turbulence by including velocity stirring of the planetesimals; see Supplemental Materials for implementation. Additional computational details can be found in the Fig. 2 caption.

Fig. 2a shows the results obtained when all input planetesimals have $D = 100$ km (as in Fig. 1b). Our starting conditions are reminiscent of the model in (22) that, as published, can form only $D < 100$ km bodies from self-gravitating clumps of chondrules in low vorticity regions of the disk. Without turbulent stirring, the availability of small bodies promotes runaway growth among early-forming planetesimals. This leads to very large planetary embryos and a SFD that does not match the reconstructed main belt. If turbulent stirring is turned on, accretion is inhibited and the largest objects do not exceed $D = 250$ km. These and additional tests (see Supplemental Materials) indicate it is difficult to reproduce the reconstructed main belt using $D \leq 100$ km planetesimals.

In Fig. 2b, we input the same SFD used in Fig. 1d. Without turbulent stirring, in case-A large planetesimals gobble up the small bodies and form embryos larger than Mars via runaway growth. In fact, this happens so quickly that mass conservation prevents us from injecting the same number of D = 100-1,000 km planetesimals as in Fig. 1d. Consequently, the net number of asteroids in this size range is a factor of ~ 2 lower than that estimated for the post-accretion main belt, i.e. property (iii). Considering that this estimate is probably uncertain by this factor and the slope of the main belt SFD is reproduced in the simulation, we believe that this run may still be valid. In case-B, a signature of runaway growth is still visible and the planetary embryos that form are slightly larger and more numerous than in Fig. 1d. All main belt constraints are reproduced. In presence of turbulent stirring, the same simulations lead to nearly identical results because the largest initial planetesimals have escape velocities higher than the velocity dispersion induced by turbulence.

We conclude that the planetesimals in the asteroid belt had to be born big (i.e., from $D = 100$ km to *at least* 1,000 km), so that they had to form by processes other than collisional coagulation. As far as we know, Ref. (1) is the only model that can produce planetesimals this large, via gravitational instabilities inside turbulent eddies. Our results may help us explain several interesting puzzles about small body evolution across the solar system. For example, if we assume the asteroid belt was initially deficient in $D < 100$ km asteroids, its early collisional activity may have been much lower than previously thought. This could explain the paucity of meteorite shock degassing ages recorded between 4.1-4.4 Gy ago (28) and, for extra-solar systems, the deficit of hot dust observed in young proto-planetary disks (29). Moreover, if planetesimals formed in the same way in the Kuiper belt, it is likely that the turn-over observed in its SFD at $D \sim 100$ km (30) is a signature of accretion and not one of collisional grinding. Finally, our results should have full implications for the formation of the cores of the Jovian planets that have yet to be explored. The presence of large planetesimals in a massive disk of boulders might boost accretion of these cores, thus helping us to solve one of the major problems in planetary science.

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Figure Captions

Fig. 1: An exploration of accretion in the asteroid belt region. The gray lines show the reconstructed (i.e., post-accretion) main belt SFD. The solid gray lines show the observed main belt SFD for $100 < D < 1,000$ km asteroids scaled up 1,000 times. The dashed lines show the upper and lower bound of the main belt power law slope in the 20-100 km range (8). The upper bound corresponds to the current SFD slope. The vertical dotted lines show the sizes of Lunar/Martian-sized objects for bulk density 2 g cm^{-3}. These size embryos are assumed to have formed across the inner Solar System (11; 13). The dots and black lines show the input and output SFD, respectively. In (a), we start with 1.5 $M_\oplus$ of $D = 2$ km planetesimals. Several distinctive runaway growth features are shown: the existence of massive bodies, a shallow-sloped SFD down to $D \sim 700$ km (showing the paucity of bodies in the $D =$ 700-4,000 km range) and a steep-sloped SFD down to the original planetesimal size of $D \sim 2$ km. In (b), we start from $D = 100$ km planetesimals. The SFD for $D > 100$ km is still steep compared to observations and the number of Ceres-size bodies is too low. In (c), we start from 10,000 times the current $D =$ 100-500 km asteroid population. The SFD for $D > 500$ km is too steep and too many objects exist in the original size range. In (d), we start from 1,000-2,000 times the current $100 < D <$1,000 km asteroid population. The final SFD satisfies all the properties of the post-accretion asteroid belt. Note that simulations using different starting masses led to similar results multiplied by a scaling factor related to the initial mass. For example, in (a), the production of 1,000 Ceres would require an unrealistic starting mass of 16 $M_\oplus$, though this still would still not produce property (ii).

Fig. 2: Results of accretion simulations including a spread for planetesimals formation times and turbulence stirring. In the left panel the input planetesimals have $D = 100$ km, as in Fig. 1b. In the right panel, they follow the input SFD used in Fig. 1d. In both panels, the grey lines sketch the main belt constraints, as in Fig. 1. The black curves reproduce the results of Fig. 1b and 1d, for reference. In the case-A simulations the initial mass that has not yet been incorporated in the large planetesimals is modeled with $D = 2$ m particles, which cannot destroy or accrete each other through collisions. These particles can only be accreted by the planetesimals, or are removed when a new large planetesimal is created. They might be considered as representing a population of smaller bodies of the same total mass. Simulations where these particles are fully coupled with the gas lead to similar results (see Supplementary Material). In the case-B simulations, $D = 2$ m particles are introduced together with the input planetesimals, in 1/1 mass proportion. These particles can now mutually accrete or break in collisions. In the simulations with turbulent stirring, we assumed that the parameter governing "turbulence strength" in the `Boulder` code, γ (see Supplemental Materials for details), was equal to 2×10^{-4}. This value is on the low end of the range corresponding to the amplitude of the fluctuations of the disk's surface density observed in magnetohydrodynamic simulations (26; 27). Still, it inhibits accretion if all input planetesimals have $D = 100$ km (panel a). Instead, if input planetesimals range up to 1,000 km (panel b), this value of γ has no visible effects. See Supplementary Material for a discussion of how much turbulent stirring can be tolerated in this case.

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