Supplementary Discussion for:

Iron Meteorites As Remnants of Planetesimals Formed in the Terrestrial Planet Region

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Summary

We argue that the presence of intact asteroid (4) Vesta, the spectroscopic homogeneity seen among individual asteroid families, and the paucity of small intact differentiated bodies in the main belt means that Vesta was close to the minimal size for differentiation in its formation region. The observed differentiated fragments in the main belt and the iron meteorites, however, provide clear evidence that differentiated bodies once existed. We reconcile these two aspects by postulating that the parent bodies of many iron meteorites did not form in the main belt but instead formed closer to the Sun, where planetesimal accretion is faster and hence differentiation is more likely to occur among small bodies. After their parent bodies experienced extensive melting and comminution early in Solar System history, the fragments were scattered into the main belt via interactions with planetary embryos. Iron meteorites, representing core fragments from differentiated planetesimals, are common because they are hard to disrupt, they migrate slowly by Yarkovsky drift, and their immediate precursors are predominately located near resonances that efficiently deliver material to Earth. Conversely, crust and mantle fragments, being stones, are both weaker than irons and more susceptible to Yarkovsky drift; few survive 4.6 Gy. Thus, some asteroids and meteorites escaping the main belt today may not actually be indigenous to the main belt zone (see also [1]). Moreover, it is possible that Vesta itself is a main belt interloper, although perhaps from a region closer to the main belt than the iron meteorite parent bodies.

1. Where do most meteorites come from in the main belt, and how is this related to iron meteorite record?

Most meteorites are fragments of main belt asteroids that have reached Earth through combination of processes that includes collisions, slow semimajor axis drift

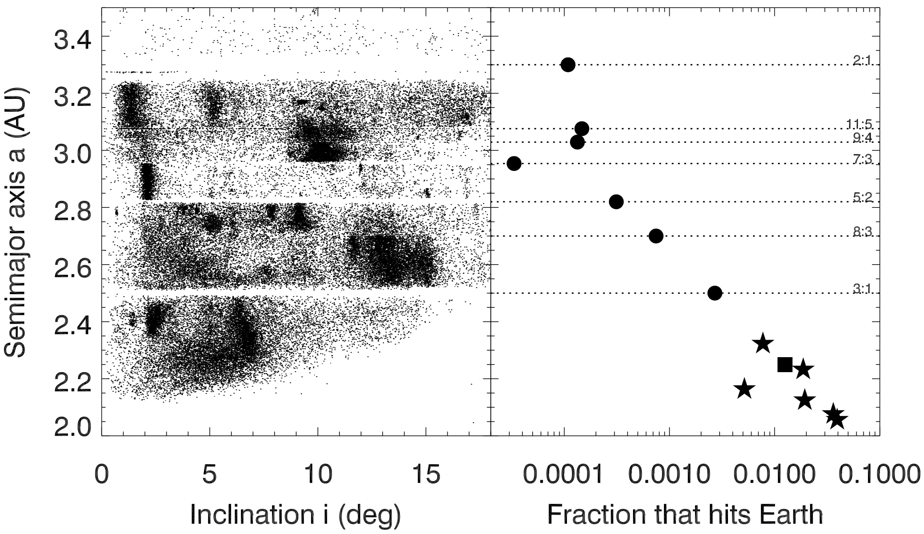

Figure S1: The delivery efficiency of test bodies from various main belt resonances striking the Earth. To create this plot, we updated the work of [4] and tracked the dynamical evolution of thousands of test bodies started in all major main belt resonances. For reference, we have also plotted the proper semimajor axis a and inclination i of 71,323 numbered asteroids with absolute magnitude $H < 15$ [5]. The stars represent values taken from test bodies started in the ν_6 secular resonance. In order of increasing a, we gave them $i = 2.5°$, 5°, 7.5°, 10°, 12.5°, and 15.0° [6]. The filled square represents test bodies placed in the intermediate-source Mars-crossing region located adjacent to the main belt between $a =$ 2.0-2.5 AU [6]. Most objects in this zone escape the main belt via numerous tiny mean motion resonances (MMR) with Mars or three-body MMRs. The filled circles are values from tests bodies placed in numerous MMRs with Jupiter. Here we supplemented our impact statistics by applying Öpik-like collision probability codes to the evolutionary paths of our test bodies [7, 8]. Objects escaping the main belt with $a \leq 2.3$ AU are more than 2 orders of magnitude more likely to strike Earth than those with $a \geq 2.8$ AU. This implies that that our meteorite collection is significantly biased toward the innermost regions of the main belt.

via thermal radiation (Yarkovsky) forces, dynamical resonances, and close encounters with the terrestrial planets [2, 3]. To determine where these objects come from in the main belt, we updated results from [4] and tracked the dynamical evolution of thousands of test bodies started in all major main belt resonances.

The results, shown in **Fig. S1**, indicate that meteoroids escaping from $a <$ 2.3 AU have a 1-4% chance of striking the Earth. This fraction drops by 2 orders of magnitude, however, as we move to resonances in the central and outer main belt. Thus, if the material flux escaping out of various main belt resonances are within a factor of several of one another, as suggested by numerical experiments [6], the meteorite collection should be strongly biased toward inner main belt material.

The connection to iron meteorites can be seen **Fig. 1** in the main text, which shows that most interlopers are delivered to the innermost region of the main belt. This may explain why two-thirds of the unique parent bodies sampled in worldwide meteorite collections are represented by iron meteorites (i.e., 27 chondritic, 2 primitive achondritic, 6 differentiated achondritic, 4 stony-iron, 12 iron groups, and 60 ungrouped irons) [9, 10]. For reference, there are currently more than 20,000 known stony and iron meteorites [9].

2. How much differentiated material exists in the main belt that is not associated with Vesta?

Fragments of putative differentiated bodies have been identified in the main belt, but so far only in limited numbers. For example, only one asteroid is known to sample the crust of a Vesta-like but non-Vesta differentiated asteroid: (1459) Magnya, a $D = 20$-30 km V-type asteroid located in the outer main belt [11]. Note that this body could also be an intact differentiated body. Similarly, main belt spectroscopic surveys have only identified 22 A-type asteroids, which many believe are mantle fragments from Vesta-like bodies, out of a sample of 950 objects [12]. This material, which is likely composed of olivine-rich metal-free silicates, is mostly missing from our meteorite collection; this deficiency is colloquially known as the "great dunite shortage" (e.g., [13]). There have been spectroscopic searches for the exposed cores of differentiated asteroids, which many believe are analogous to M-type asteroids. The majority of large M-types ($D > 65$ km), however, show evidence for hydrated minerals, low densities, and/or radar signatures inconsistent with iron-rich material (e.g., [14, 15]). The most prominent examples of differentiated core material may be (16) Psyche and (216) Kleopatra, $D = 250$ and 120 km M-type asteroids, respectively, with metal-like radar signatures [15, 16] (see also [17, 18]).

Note that some differentiated material may deviate from our preconceived notions of what such asteroids should look like. For example, recent work indicates that S-type asteroids with a high-calcium pyroxene component and minor amounts of olivine may have experienced igneous differentiation [19]. To date, several asteroids in the central main belt have been found with this spectral signature (i.e., 17 Thetis, 847 Agnia, 808 Merxia, and members of the Agnia and Merxia families). A close examination of Agnia and Merxia family members, however, shows that they have nearly identical spectra. Sunshine et al. claim this homogeneity means they are likely secondary families formed from the breakup of basaltic fragments from a primary asteroid parent body [19]. Note that neither family is particularly large (i.e., the Agnia parent body was $D \sim 40$ km; Merxia was $D \sim 100$ km; Durda, Bottke et al., in preparation), which would be consistent with this scenario.

While high-calcium pyroxene S-type asteroids (and putative meteorites from these bodies) need to be further investigated, lets assume for the moment that they are indeed fragments from differentiated asteroids. Where did these objects come from? Using insights gleaned from collisional and dynamical models, it is possible to make some interesting connections. Consider the following:

- The Agnia and Merxia parent bodies in the central main belt presumably were derived from large differentiated bodies. Given their spectral similarities, they may have even come from the same parent body [19]. The disruption event(s) that produced the Agnia and Merxia parent bodies had to occur prior to the last dynamical depletion event that shaped the main belt (e.g., [20, 21]) or the family members would be dynamically related to other asteroids in proper element space. We can infer from this that the high-calcium pyroxene S-type fragments produced by this large disruption event (or events) were scattered throughout the central main belt (and perhaps further) by the last dynamical depletion event. While many of these objects would have been ejected from the main belt, some must have survived.

- The asteroids (16) Psyche and (216) Kleopatra, if they are indeed iron cores, had to have been produced by the disruption at least one very large differentiated asteroid (i.e., possibly Vesta-sized). These objects, like Agnia and Merxia, are located in the central main belt and are not associated with any known family. For this reason, we can assume that the breakup event that produced these objects, like the one that produced the Agnia and Merxia families, occurred prior to the last dynamical depletion event that shaped the main belt (e.g., [20, 21]). Note that the location of the crust and mantle material associated with these iron cores has long been a mystery [16].

Given this information, we postulate that the largest M-type asteroids and high-calcium S-type asteroids represent the core, mantle, and crust of a putative Vesta-size body that disrupted long ago. If true, some meteorites may be linked to this material (i.e., a few HEDs may not come from Vesta [19]). Because meteorites from central/outer main belt asteroids are unlikely to reach Earth (**Fig. S1**), however, the total number should be small. For this and other reasons, we believe that only a limited number of unique iron meteorites are derived from this source material.

Finally, we point out that unidentified remnants of other differentiated planetesimals may still be found in the inner main belt. At present, 5-color data from the Sloan Digital Sky Survey suggests there are some asteroids in the inner main belt with Vesta-like colors that are unassociated with either (4) Vesta or the Vesta family [22]. These objects are prime candidates for new observations.

3. Could space weathering effects help "hide" a population of small differentiated bodies in the main belt?

Space weathering is thought to be caused by the formation of nanophase iron particles in asteroid regolith, where silicate vapor is deposited on surrounding grains via micrometeorite impact heating and/or solar wind sputtering [23]. This process, while reddening and diminishing the band depths of S-type asteroid spectra, does not significantly affect the spectral features of Vesta-like bodies, whose surface is dominated by pyroxene rather than olivine (and thus has a lower abundance of nanophase metallic iron; [24]). This explains why basaltic material over a vast size range (i.e., Vesta, multi-km members of the Vesta family, km-sized V-type asteroids in the near-Earth asteroid population, HED meteorites) are spectroscopically similar to one another [25]. For this reason, we expect non-Vesta but Vesta-like basaltic material to be similarly unaffected by space weathering (though see **#2** and [19]).

4. Why does the meteorite record contain so few non-Vesta samples of crust/mantle from differentiated asteroids?

The model presented in the main text implies that disrupted differentiated planetesimals from the terrestrial planet region should have injected representative samples of crust, mantle, and core material in the main belt. The meteorite record, however, is deficient in meteorites made of basaltic or olivine-rich material other than those believed to be linked with (4) Vesta and its family [9, 13]. A possible explanation for the missing crustal material could be that it was never there to begin with; basaltic melts on small asteroids may contain enough entrained volatiles that they are readily vented into space by volcanism [26]. This scenario, however, does not explain what happened to the mantle material.

To investigate this apparent shortage, we modeled the evolution of a hypothetical population of olivine (A-type) asteroids in the inner main belt using a code designed to track how comminution and dynamical depletion via the Yarkovsky thermal drag and chaotic resonances affect size-frequency distributions (SFDs) evolving inside the main belt population [27]. **Fig. S2** shows our results. For testing purposes, we chose an extreme example; we assumed these bodies followed a power-law SFD, with the low-D end containing the same number of $D \sim 1$ m bodies as the current main belt and the high-D end set to a diameter twice the size of the largest known A-type asteroid in the inner main belt (i.e., (1126) Otero; $D \sim 12$ km).

Following the evolution of this SFD from 4 Ga to today, we find the population of potential olivine meteoroids drops by ~ 3 orders of magnitude (**Fig. S2**). This occurs because there are not enough large A-type asteroids in the inner main belt to keep the population of meter-sized olivine bodies replenished through a collisional cascade. Instead, the meteoroids are steadily eroded over time by comminution and dynamical depletion. Thus, while olivine-rich A-type asteroids clearly exist in the inner main belt, they are statistically unlikely to produce a significant number of present-day meteorites. The same analysis can be used to explain what happened to the non-Vesta crustal fragments from differentiated asteroids (though see [26]); they too lack a reservoir of large bodies capable of sustaining a large meteoroid flux over several Gy.

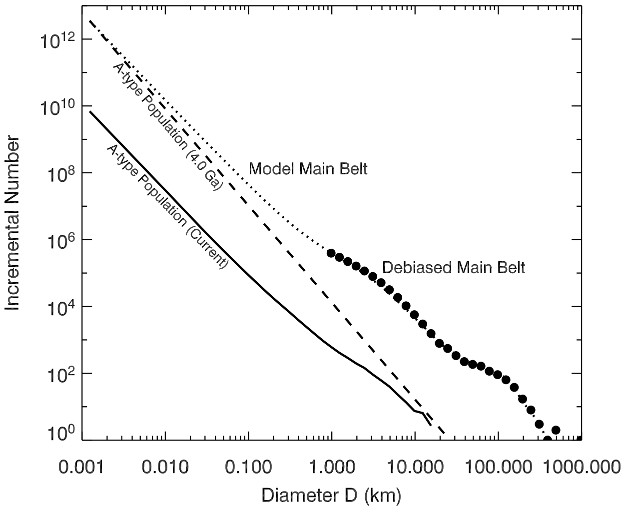

Figure S2: Collisional and dynamical evolution for a hypothetical population of olivine-rich A-type asteroids placed in the inner main asteroid belt. For our initial A-type asteroid population, we chose the largest body to be twice the size of the largest known A-type asteroid in the inner main belt (i.e., (1126) Otero; $D \sim 12$ km), while we set the number of meter-sized objects equal to those in the main belt. The latter, while an exaggeration, is useful for demonstration purposes. Linking the low and high ends, the rest of the population was given a power-law SFD with differential index $q = -3.9$. The solid line shows what happens to the A-type population after 4 Gy of evolution. The population of meteoroids, represented by bodies in the $D \sim 0.001$ km size bin, decreases by ~ 3 orders of magnitude, mainly because there are too few collisions among larger A-type asteroids to keep them replenished. Thus, our "extreme" population is statistically unlikely to produce many meteoroids, consistent with the absence of olivine-rich meteorites in our collection.

5. Could small differentiated asteroids (iron meteorite parent bodies) have formed in the main belt zone and then been eliminated by collisional and dynamical processes?

We argue the answer is 'no'. The accepted view is that iron meteorites come from small differentiated bodies ($D \sim$ 20-200 km) that formed in the main belt early in Solar System history. These bodies were then almost entirely eliminated by (i) dynamical interactions with planetary embryos and sweeping resonances (e.g., [20, 21]) and (ii) main belt collisions (e.g., [13]). Thus, the iron meteorites would be one of the few surviving remnants of this putative population. When this scenario is considered in detail, however, several potential problems come to light:

- Collision evolution models, now calibrated against a wide range of constraints (e.g., the wave-shaped main belt size-frequency distribution, the number and distribution of asteroid families produced by the disruption of $D > 100$ km parent bodies over the last 3-4 Gy, the single $D \sim 400$ km basin observed on asteroid (4) Vesta, the cosmic ray exposure history of stony meteorites, the relatively constant crater production rate of the Earth and Moon over the last 3 Gy), indicate that only a limited fraction of $D \sim$ 20-200 km bodies ever disrupted in the primordial main belt population [17, 18]. These results suggest it would be difficult to eliminate a substantial population of differentiated asteroids without violating numerous constraints (i.e., producing a main belt size-frequency distribution with a shape different than that observed; creating too many asteroid families over the last 4 Gy, etc.).

- Dynamical models of main belt evolution are more successful at eliminating objects than collisions, with $\sim 99.5\%$ of the primordial main belt population ejected prior to or during the so-called Late Heavy Bombardment that occurred ~ 3.9 Gy ago [17, 20, 21, 18]. These model results imply the number of intact differentiated bodies in the primordial main belt was limited to roughly 200 (i.e., 1/0.5%). The problem, however, is that this makes Vesta's survival a remarkable fluke; dynamical removal mechanisms should not have a preference for Vesta over its smaller and more numerous brethren (assuming these bodies follow a reasonable size distribution).

- The paucity of differentiated material in the main belt is discordant with expectations based on planetesimal formation and meteoritical data. Isotopic chronometers indicate that core formation among most iron meteorite parent bodies occurred 1-2 My before the formation of the ordinary chondrite parent bodies [28, 29]. If small bodies differentiated in the main belt at these early times, it is reasonable to expect larger bodies forming near the same locations to have differentiated as well (e.g., [30]). Hence, if iron meteorites are indigenous to the main belt, large numbers of differentiated bodies and their fragments should reside there today. At the least, chondrites and asteroid families should show some signs that their parent bodies were significantly heated or that their parent bodies agglomerated some of these differentiated planetesimals during accretion. None of these conspicuous items has yet been observed. (See main text for additional details: for families, see [31]; for chondrites and other meteorites, see [9, 10, 32, 33]).

6. What are some of the limitations of this model?

The model presented here, while the best that can be done with current planet formation codes, can still be improved. Here we briefly discuss how the inclusion of dynamical friction and gas drag in future planet formation/planetesimal evolution codes might impact our conclusions. We also describe why we do not predict in the main text the fraction of interloper material existing in the current main belt.

Dynamical Friction. Preliminary results by our team using codes that include dynamical friction between planetary embryos and a limited number of smaller bodies suggest: (i) the disruption rate of small differentiated planetesimals in the terrestrial planet zone is somewhat diminished when compared to the results in the main text and (ii) the length of time the fragments have to become trapped in the main belt in increased. Because these two effects roughly balance one another, the overall story presented here should remain the same, albeit with longer timescales. Potential constraints on these timescales may be found in iron meteorite cooling rate data [32, 34].

Gas Drag. The effects of gas drag on our scenario have yet to be modeled. Still, insights gleaned from numerical results and observational data allow us to predict its importance.

- Our model results are consistent with the (limited) degree of semimajor axis mixing observed among large S- and C-type asteroids in the main belt (see main text and [20, 35]). For this reason, we believe the effects of gas drag in the inner Solar System were similarly limited; either it did not significantly affect planetesimal mixing, or the gas went away early enough that planetary embryos still had time to stir the remaining planetesimals before being removed from the inner Solar System.

- Planet formation models invoking strong gas drag models are likely to produce results that are inconsistent with the taxonomic stratification seen among main belt and Hungaria asteroids [35]. For example, if gas drag dominates planetesimal evolution, the main belt should be literally overrun with bodies formed beyond the snowline (e.g., [36]). Asteroids made from this material are much more likely to resemble the primitive C-type asteroids that dominate the outer main belt (analogous to carbonaceous chondrites) than the water-poor and metamorphosed S- and E-type asteroids that dominate the inner main belt and Hungaria regions, respectively (analogous to ordinary and enstitite chondrites).

Thus, main belt observations not only place strong constraints on the effects of gas drag in the inner Solar System, but they also suggest that leaving gas drag out of our model runs may not significantly impact our conclusions.

Other Model Limitations. A common question asked about our model results is why we do not estimate the fraction of interloper material existing in the current main belt. This calculation, while admittedly important, is difficult to do correctly; it requires the construction of a coupled collisional and dynamical simulation capable of tracking individual planetesimals and their fragments as they experience both comminution and interactions with planetary embryos. There is also the issue of constraining such a model when we have yet to attain a thorough understanding of the physical and spectroscopic properties of smaller main belt asteroids. For these reasons, we leave this critical but computationally expensive problem for future work.

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