ON THE ORIGIN AND EVOLUTION OF DIFFERENTIATED PLANETESIMALS.

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Introduction. The origin and evolution of differentiated planetesimals is intimately tied to several challenging planet formation questions: How, where, and how fast do planetesimals grow? How are they affected by collisional evolution within a primordial disk that also contains protoplanets? How did the differentiated fragments of these collisions survive to the present? The constraints available to solve these problems [1] include meteorite samples (e.g., irons, HEDs), remote observations of unusual asteroids like (16) Psyche, which may be an exposed core of a Vesta-like asteroid, and in situ studies of (4) Vesta and the weird asteroid (21) Lutetia. It is no easy task to pull together a simple story from this odd assortment of clues.

What We Think We Know. Consider that most iron meteorites are pieces from the cores of distinct, differentiated asteroids [2]. Core formation for these bodies was nearly contemporaneous with the origin of the CAI inclusions and likely predated the birth of most of the chondrules found in ordinary and carbonaceous meteorites by one to several million years [3,4]. Iron meteorites also currently represent over two-thirds of the 100-150 unique asteroid parent bodies sampled among all meteorites [1]. Both factors would seem to suggest that differentiated parent bodies and their fragments are common in the main asteroid belt.

Evidence supporting this idea, however, is meager. Spectroscopic observations of many tens of asteroid families show few signs that their parent bodies once had distinct iron cores nor mantles/crusts derived from melted rock [6]. Instead, we see the opposite: most asteroid families investigated to date are made up of members with remarkably similar spectroscopic signatures and albedos. There is also a paucity of olivine-rich asteroids and meteorites that would be derived from the exposed mantles of disrupted differentiated bodies. Solving this “great dunite shortage” has long been a holy grail of small body studies.

Even studies of M-type asteroids, long thought to be simple exposed iron cores, have become complicated. Rosetta observations of (21) Lutetia, an asteroid probably representative of this class, indicates it is an enstatite or CV chondrite with perhaps a small iron core [7,8]. Perhaps only M-types like (16) Psyche and (212) Kleopatra can still be considered exposed iron cores from the interpretation of radar observations [9]. Understanding the M class has thus become a fundamental and achievable goal of small body exploration.

Cores may be hidden. Magnetic field traces in the Allende CV chondrite may be telling us that some primitive- and not so primitive-looking main belt asteroids experienced partial differentiation [10]. Consider the Eos family, probably derived from the catastrophic disruption of a ~400 km diameter partially differentiated parent body [11, 12]. The spectroscopic signatures of Eos family members are consistent with CV/CK chondrites [2, 12], a possible match to the fossil magnetic field signature in Allende.

Regardless, we have a conundrum. We need to make lots of differentiated bodies, extract material from their deep interiors, yet hide or eliminate most of the expected traces that would come from extraction.

Pathway to a Solution. Advances in planet formation processes and asteroid belt evolution models allow us to glean new insights. First, consider that planetesimals are predominantly heated, overall, by the decay of short-lived radionuclides like ^{26}Al [13]. This means that only the fastest and/or largest growing bodies have a chance to melt globally [14]. According to planetesimal formation models, in the inner solar system, the faster-growing bodies are closer to the Sun. It may then be deduced that most iron meteorite parent bodies formed in the terrestrial planet region [1].

Second, consider that differentiated planetesimals in the terrestrial planet region evolved side-by-side with larger and similar-sized protoplanets. Collisions between these bodies were inevitable, and their accretion was inefficient [15]. Hit and run collisions were common; here a differentiated projectile can lose its exterior somewhat like a rubber-coated bullet fired into a solid target. Crust and mantle are removed by mechanical shearing and tides as it passes through the target body. Hit and run can also form chains of core-enriched bodies, fragments of the projectile interior. Repeated hit and run collisions could leave naked molten cores or core fragments buried by remnant mantle and crustal silicates [16]. According to [17], this disruption/reaccumulation of melted planetesimals may result in chondrule formation.

Degrees of mantle stripping might explain the range of cooling rates seen among the main classes of iron meteorites (e.g., IVA irons) [18]. It might also explain why so few crust and mantle fragments remain from the iron meteorite parent bodies: much of it could have been pulverized by disruptive hit and run events [15] and altered beyond recognition by the associated hydrostatic unloading, shock, reduction and depletion.

Collisional evolution in the terrestrial region was intense [1], and only the largest, strongest, or most fortunate bodies survived for very long. Differentiated planetesimals and their fragments were evidently once plentiful. Were they also populous in the main asteroid belt? We believe this is unlikely, because modeling shows the asteroid belt experienced limited collisional evolution, not enough to disrupt numerous differentiated bodies down to their cores and erase the fragments [19]. The survival of Vesta's crust provides support for this. It appears likely that only a modest number of fully and partially differentiated bodies were indigenous to the main belt, and most of these (like Vesta) were large enough to survive intact to recent times. This, however, does not solve our conundrum.

Capturing Objects in the Main Belt. One idea is that some hit and run byproducts from the terrestrial planet region found their way into the main belt region by early dynamical processes. Hit and run collisions could lead to core-enriched gravitational accumulations [15]; migrating these sub-parent-bodies to the main belt during terrestrial planet formation could explain why the asteroid belt has a larger-than-expected number of sizable fragments that look like they came from differentiated protoplanets.

There are many dynamical scenarios that could move terrestrial planet region material (TPM) to stable orbits within the main belt region. One involves gravitational scattering among planetary embryos [1]. Another involves scattering/capture opportunities within the Grand Tack model when Jupiter migrates across the primordial asteroid belt [20]. In Fig. 1 we evaluate TPM capture within the Nice model, with the giant planets residing for hundreds of My on nearly-circular, co-planar orbits in a much more compact configuration than they have today (all between 5-12 AU) [21, 22]. We simulated how planetary perturbations affected test bodies started outside the primordial main belt region. We found that many bodies scattering off of Mars were able to enter into the primordial main belt via "fossil" mean motion resonances, where they stayed for 100s of My. These bodies were permanently captured when the host resonances moved via late giant planet migration ~4.1-4.2 Ga.

Intriguingly, many large E-, M-, and K-type asteroids, including (21) Lutetia, can be found near primordial Jovian resonances like the J4:1 (2.2 AU), J7:2 (2.42 AU), and J3:1 (2.67 AU). If they were captured, Jupiter had to be located at 5.55 AU prior to the onset of late giant planet migration. This could mean that the unusual properties of M-type asteroids might be explained as the captured byproducts of hit and runs collisions. If so, this population could include both exposed cores (e.g., Psyche) and "hodge-podge" worlds made of leftover debris (e.g., Lutetia).

Open Questions. While the asteroid belt is a mixture of indigenous and foreign material, sorting out one from the other is difficult. No known genetic marker yet exists that can tell us where a given meteorite formed. Our understanding of planet formation is highly incomplete, and we may still be missing big things about planetesimal, planet and main belt evolution. These will have to be addressed with a targeted mission to one or more of these remnant core bodies. Until then, the ideas presented here should be considered a best guess about the current state of the art.

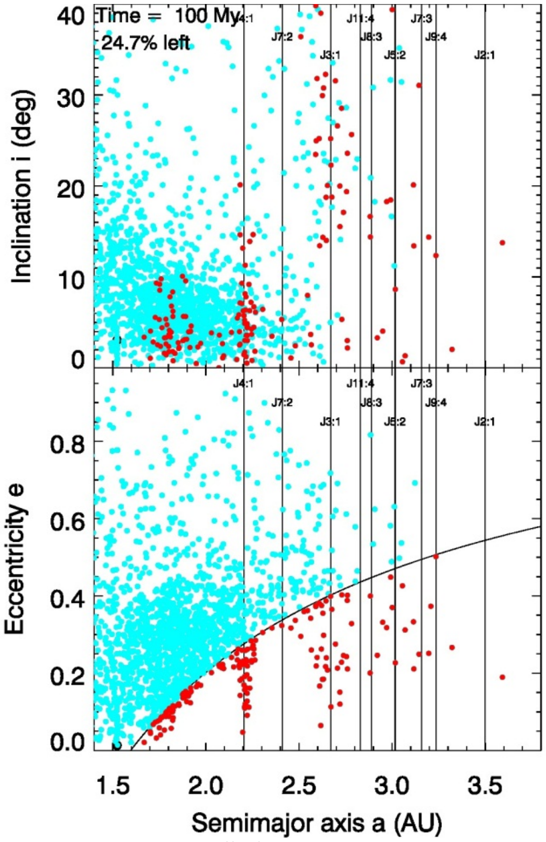

Fig. 1. Objects scattering off of Mars (blue dots) enter into non-Mars-crossing orbits (red dots) through primordial mean motion resonances of giant planets. Giant planets orbits defined by [23]. Most red objects have inclinations < 20°. Many are on stable orbits within the main belt region after 300 My, the end of the simulation.

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