ON THE ORIGIN AND EVOLUTION OF VESTA AND THE V-TYPE ASTEROIDS. W.F. Bottke[1], [1]Southwest Research Institute, Boulder, CO, USA (bottke@boulder.swri.edu)

Introduction. Vesta is one of the most fascinating and best studied asteroids in the asteroid belt. Our insights not only come from DAWN data, but also from decades of in-depth studies of both the HED meteorites, almost certainly from Vesta, and Vesta asteroid family members. Together, they provide powerful constraints describing how Vesta reached its current state. The problem facing collisional and dynamical modelers is to assemble a self-consistent story from these clues that can plausibly match what we know of the origin and evolution of the asteroid belt, meteorites, and the surfaces of inner solar system bodies.

Here we explore several intriguing issues regarding the origin of Vesta, same-sized differentiated bodies, and smaller V-type asteroids (bodies with spectra like Vesta). To address this work, we need the look at many questions, such as: (i) how, where, and how fast did differentiated planetesimals like Vesta grow? (ii) how were they affected by collisional evolution within a primordial disk that also contains protoplanets? (iii) how did the differentiated fragments of these collisions survive to the present? The constraints available to solve these problems are diverse but cryptic; they 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, in situ studies of (4) Vesta, and so on.

What We Think We Know. A possible starting point for this discussion concerns the iron meteorites, many which may have come from the cores of differentiated asteroids like Vesta [e.g., 1, 2]. Core formation for some of these bodies appears to be ancient and may be nearly contemporaneous with the origin of the CAIs [3,4]. Iron meteorites may also represent two-thirds of the 100-150 unique asteroid parent bodies sampled among all meteorites [2]. Taken at face value, these factors suggest that differentiated parent bodies and their fragments should be common today in the main asteroid belt. If so, one might argue the main belt was once teeming with several tens or more of Vesta-like bodies, many which were disrupted.

Evidence supporting this scenario, however, is surprisingly 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 [5]. 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 an apparent paucity of asteroids that might come from the exposed mantles of disrupted differentiated bodies.

For the V-type asteroids, almost all of them are $D < 10$ km, consistent with fragments from cratering events on very large asteroids [6]. Most in the inner main belt have similar inclinations to Vesta, and are most easily explained as Vesta family members dispersed in semimajor axis by (i) high ejection velocities and (ii) a billion years or more of Yarkovsky evolution. More puzzling are the smattering of V-types in the central/outer main belt; they are scattered over a wide range of eccentricities and inclinations, and have no obvious dynamical association with Vesta. Recent spectra work also suggests they are unrelated to Vesta.

Taken together, we have a conundrum. Somehow, 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. How can this be done?

Pathway to a Solution. As a possible solution, consider that planetesimals are predominantly heated, overall, by the decay of short-lived radionuclides like ^{26}Al [7]. This means that only the fastest and/or largest growing bodies have a chance to melt globally [8]. According to planetesimal formation models, faster-growing bodies are those that form closer to the Sun. This may suggest that many iron meteorite parent bodies formed in the terrestrial planet region [1]. These differentiated planetesimals may have also evolved side-by-side with larger and similar-sized protoplanets. Collisions between these bodies were inevitable, and their accretion was inefficient [9]. Hit and run collisions were presumably common, with the fragments often forming core-enriched bodies. Repeated hit and run collisions could leave naked molten cores or core fragments buried by remnant mantle and crustal silicates [10]. Collisional evolution in the terrestrial region was also intense [1], and only the largest, strongest, or most fortunate bodies survived for very long.

Capturing Objects in the Main Belt. In this view, only a modest number of fully and partially differentiated bodies were likely to be indigenous to the main belt. The rest may be hit and run byproducts from the terrestrial planet region that were captured in the main belt region by early dynamical processes. This could explain why the asteroid belt has a number of sizable but isolated fragments that look like they came from differentiated protoplanets. We hypothesize that central/outer main belt V-types are potentially small fragments from “Vesta’s sisters” that were scattered into the main belt from the terrestrial planet region. There is some evidence for this, with a few eucrites having different oxygen isotopes than standard eucrites [11].

There are many dynamical scenarios that could move terrestrial planet region material (TPM) onto 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 [12]. In Fig. 1 we evaluate

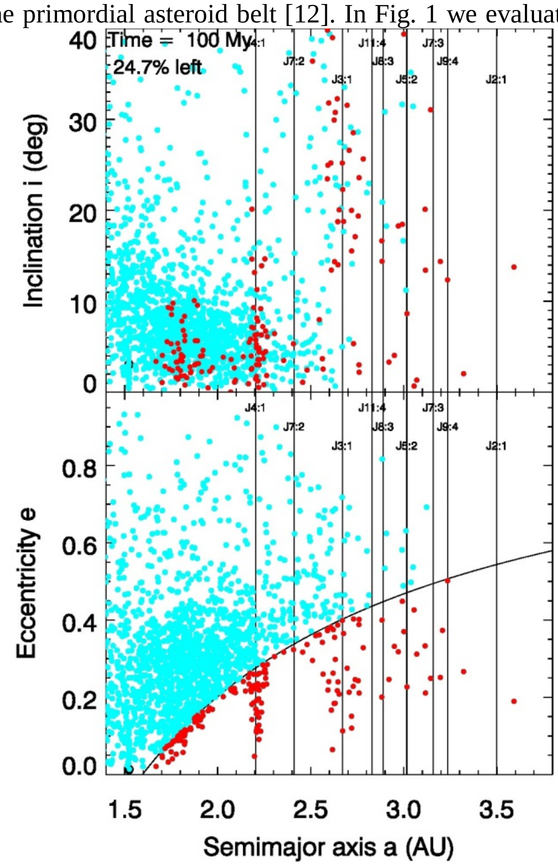

Fig. 1. Objects scattering off of Mars (blue dots) enter into non-Mars-crossing orbits (red dots) through primordial mean motion resonances of giant planets. Giant planets orbits defined by [23]. Most red objects have inclinations < 20°. Many are on stable orbits within the main belt region after 300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

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) [13]. 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, possibly at ~4.1-4.2 Ga.

Indigenous Vestas in the Primordial Main Belt?. These results also suggest a second possible scenario to explain fragments of differentiated bodies in the main belt. Let us suppose that Vesta once had "sister" objects in the main belt. This idea would be consistent with dynamical models predicting the asteroid belt had considerably more mass long ago that was eventually eliminated by a dynamical depletion process (e.g., sweeping resonances caused by planetary migration [13,14], ejection by planetary embryos [1] or Jupiter interacting with the asteroid belt [10]).

To investigate these issue, we used *Boulder*, a collisional code capable of simulating the dynamical depletion and collisional fragmentation of multiple planetesimal populations using a statistical particle-in-the box approach [15]. We input into *Boulder* an estimate of the primordial main belt size distribution stretched across many semimajor axis zones as well as a number of Vesta-like objects. We tracked these populations and their fragments for hundreds of My until the time of the late giant planet migration ~4 Ga. We then assumed the populations dynamically lost sufficient mass that collisional grinding over the next 4 Gy could produce the current main belt population.

Our preliminary results suggest the history of Vesta and her putative sisters can be used to constrain main belt history. We find that an excited primordial main belt with more than 3-4 Vestas after the first few My produces too many V-type fragments; collisions/dynamics cannot get rid of all of the evidence. Thus, only a very few Vestas ever existed in the main belt region. Collisions on these bodies prior to their dynamical removal might be responsible for the V-types seen in the central/outer main belt. These results would also be consistent with dynamical work indicating that the primordial asteroid belt only lost a factor of 3-4 of its mass during late giant planet migration [16].

Vesta's Family. We find that Vesta's observed family of $D < 10$ km objects has such a steep size distribution that it has an 80% probability of being < 1 Gy old. If true, Vesta's largest basin Rheasilvia, the presumed source of much of the Vesta family, is similarly young, as suggested by superposed crater counts [17]. This result fits with growing evidence that most of the prominent meteorite classes were produced by young asteroid families.

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