METEORITIC CONSTRAINTS ON COLLISION RATES IN THE PRIMORDIAL ASTEROID BELT AND ITS ORIGIN. Edward R. D. Scott, Hawai'i Institute of Geophysics and Planetology, University of Hawai'i at Manoa, Honolulu, Hawai'i 96822, USA. (escott@hawaii.edu)

Introduction:

Two widely held scenarios for the formation of the asteroid belt appear to be totally incompatible. **1)** Limited cooling rate data for meteorites and other petrographic constraints suggest that the original parent bodies of chondrites and differentiated meteorites were ~50-250 km in radius, no larger than current asteroids. Several are thought to have cooled peacefully after they accreted without being disrupted by impacts [e.g., 1]. Asteroid family statistics and Vesta's intact crust suggest that the mass of main-belt asteroids was no more than 5x its current mass when "the present collisionally erosive environment was established" [2]. **2)** By contrast, the standard model for planetary accretion leads naturally to a scenario in which a hundred or more Mars- and Moon-sized bodies formed in the asteroid belt and were extracted in <100 Myr through mutual gravitational perturbations, close encounters and planetary resonances [3-5]. This scenario implies that the asteroids are trivial remnants from a vast population of asteroidal and planetary bodies, which survived an early violent epoch.

Here we examine meteorite and other data to try and reconcile these very different scenarios. Could any meteorite parent body be a fragment of a lunar-sized planetary embryo or a Ceres-sized body? Were meteorite parent bodies bombarded soon after they formed by a greatly enhanced flux of projectiles?

Chondrites:

Age data for a limited set of H chondrites suggest their parent body cooled peacefully for ~100 Myr after accretion [1]. However, metallographic cooling rates of brecciated and unbrecciated chondrites suggest that H, L, and LL bodies were disrupted and reassembled during metamorphism. Few impact melted or shocked chondrites have Ar-Ar ages >4.3 Gyr (e.g., Shaw and MIL 99301), but some may have subsequently metamorphosed. Rubin infers from chromite-plagioclase intergrowths, Cu grains, troilite veins, and other indicators that many OCs were shocked, and annealed prior to 4.3 Ga [6]. However, these features reflect may high temperatures rather than shock.

Carbonaceous chondrites. Some volatile-poor CK and CV chondrites were appreciably shocked but impact ages are lacking. CI and CM chondrites were not shock heated or melted at any time but the absence of such samples probably reflects destruction during impact-induced volatile loss [7]. Thus the impact history of volatile-rich asteroids cannot be inferred from meteorite samples.

E chondrites have preserved strong evidence for very early impact melting and impact-induced quenching. EHs have sulfide compositions indicating cooling in days. Many EHs are impact melts like Abee [8], which crystallized a few Myr after CAI formation [9]. I-Xe and Ar ages show that other impact-melts formed at 4.5 Ga [10]. An impact-melted clast in Hvittis (EL6) has an Ar age of ~4.47 Ga [11].

Differentiated meteorites:

Isotopic constraints show that the HED body, Vesta, melted at 4,565 Ma (2-3 Myr after CAI formation) [12]. Some basalts formed 3-5 Myr after CAI formation but igneous activity probably continued for tens of Myr. Vesta is thought to have accreted to its current diameter and escaped significant impact damage when cooling [1, 12]. However, we cannot exclude the possibility that Vesta was scrambled by impact before crust formation ended. Extreme depletion of moderately volatile elements in eucrites as in the Moon could indicate similar impact-induced losses, but nebular processes cannot be excluded as some CB-CH-CR clan chondrites are similarly depleted. Vesta experienced early brecciation of the crust and some impact-induced melting of hot material 50 Myr after accretion [13]. However, impacts at ~3.4-4.2 Ga reset nearly all eucrite Ar ages partly or totally. The nearly intact basaltic crust of Vesta and the lack of olivine in howardites that were lithified <3.5 Ga suggest that the olivine-rich mantle wasn't excavated by impact until the Vesta family formed.

Mesosiderites formed when a Vesta-like asteroid was impacted causing molten metal from the core of the target (less plausibly from the projectile) and solid silicate to be thoroughly mixed , probably 100-150 Myr after CAIs formed [see 14]. Core excavation of the target would require a 50-150 km projectile. Petaev et al. [15] conclude from cordierite-chromite barometry that after metal-silicate mixing, the mesosiderites cooled in a body >600 km in radius, assuming an H chondrite density.

All ureilites have pyroxene microstructures and other features indicative of cooling at ~10°C/hr from 1250 to <650°C [16]. They formed at depth in a large (>200 km diameter body that was catastrophically ruptured and dispersed, presumably around 4.5 Ga. Meter-sized pieces reaccumulated to make another body. Brachinites are coarse-grained, igneous rocks with high Ca (0.1-0.3 wt.%) in olivine showing that they did not cool slowly at depth in the body where they crystallized. The Shallowater aubrite formed when a magma was mixed by impact with cool chondritic material. Its complex cooling history requires another major impact before it cooled [16].

Many groups of irons contain silicate clasts and inclusions that require impact mixing of materials in partly molten bodies [17]. The IVA irons, which have heterogeneous cooling rates and some quenched silicate inclusions, was disrupted by impact when the core had cooled to ~1200 °C and reaccreted with metal at diverse depths. The group IAB body was scrambled by an impact before the molten metal crystallized, and the molten core of the IIE body was mixed with molten silicate and chondritic clasts by impacts or tidal distortion during close approaches to embryos [18].

Discussion:

The two scenarios for the asteroid belt could be easily reconciled if the embryos were cleanly removed by dynamical and the total mass of asteroid-sized bodies was 100x less than the mass of embryos. However, this seems unlikely. The mass ratio of asteroidal bodies to embryos was probably near unity [19], possibly in the range 0.1-0.7 [20]. Numerical models suggest that relatively few embryos collided with each other in the asteroid belt [3], but even a few such collisions, a similar number of close approaches [17], and a larger number of collisions between embryos and Vesta-sized bodies should have left an imprint in the meteorite record.

Rapid removal of embryos on timescales of ~1 Myr after Jupiter formation would also minimize the impact damage on the lucky survivors, especially as smaller bodies with more eccentric orbits are removed preferentially [4]. For example with the current population of asteroids, Vesta should be hit by a 35 km diameter projectile every 3 Gyr [see 2]. Even if there were 1000x as many 35 km diameter projectiles in the primordial asteroid belt, they might not have affected Vesta if the embryos and asteroid-sized bodies were removed in a few Myr. However, it may take up to several hundred Myr to clear the asteroid belt of embryos [3]. Thus, if an Earth-mass of embryos and planetesimals formed in the belt, we should have tangible evidence in some, but not necessarily all, meteorite groups.

Anomalous thermal histories and other petrologic features suggest that many bodies were disrupted as they crystallized and cooled. Among achondrites, the HED samples appear to be unique in that they lack evidence for exceptional early impact processing. We suggest that the major early impacts recorded by ureilites, brachinites and many iron meteorite groups are more representative of conditions in the asteroid belt during the first hundred Myr. Vesta was probably very fortunate to escape a catastrophic impact after its crust formed.

E chondrites and achondrites show the strongest evidence for an early period of intense bombardment: many were extensively melted and reheated by impacts <100 Myr after CAI formation and more recent impact melts from these groups are lacking. Impact heating may have been more important for E than O chondrites because they accreted later or formed closer to the sun where mean impact velocities were higher.

The most plausible explanation for an early intense period of bombardment in the asteroid belt appears to be an Earth-mass of planetary embryos and planetesimals, as most planet makers have inferred. The best candidates for meteorites from disrupted Vesta-to-Ceres sized bodies are mesosiderites and ureilites. The lack of material from lunar-sized bodies does not require that such bodies were never present in the belt as few planetary embryos collided in the belt and little ejecta may have accreted into meteorite parent bodies. Constraints on the time that Jupiter reached its present mass and position and started to clear the asteroid belt may be derived from the meteorite record of early impacts.

References:

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