THE EFFECT OF GIANT PLANET FORMATION ON THE ORIGIN AND SCATTERING OF IRON METEORITES PARENT BODIES. N. Haghighipour[1] and E. Scott[2], [1]Institute for Astronomy and NASA Astrobiology Institute, 2680 Woodlawn Drive, Honolulu, HI 96822, nader@ifa.hawaii.edu, [2]Hawaii Institute for Geophysics and Planetology, University of Hawaii, Honolulu, HI 96822, escott@hawaii.edu.

Introduction: Iron meteorites, which are derived from over ~60 parent bodies [1], provide the best clues to the nature of the collisions among planetesimals and the initial stage of accretion and growth of small bodies, particularly in the inner part of the solar system. They also provide the critical evidence that many differentiated bodies formed before the parent bodies of the chondrites. Recent advances in dating meteorites using both long-lived and short-lived isotopes have established that the parent bodies of meteorites accreted over a period of several million years, approaching the lifetime of the solar nebula [2]. Iron meteorites that were only briefly exposed in space to cosmic rays have $^{182}W/^{184}W$ isotopic ratios that closely match the inferred initial $^{182}W/^{184}W$ isotopic ratio of CAIs implying that most iron meteorites come from bodies that melted to form metallic cores 0.3±1.2 Myr after the formation of CAIs.

The parent bodies of iron meteorites were traditionally, assumed to have formed, differentiated, and subsequently been disrupted in the main asteroid belt. However, observational evidence is in disagreement with this assumption. If the parent bodies of iron meteorites had formed and differentiated in the main asteroid belt, we should have seen many metallic asteroids composed of debris from cores, as well as numerous olivine-rich asteroids and meteorites composed of mantle material. The most likely explanation for the lack of olivine-rich and metal-rich asteroids is that the differentiated asteroids were simply battered to bits over 4.5 Gyr [3] and only small strong metallic fragments survived. But this explanation appears inconsistent with the survival of Vesta's basaltic crust, and the presence of some unrelated V-type asteroids [4] as well as basaltic meteorites that are not from Vesta.

In an attempt to overcome these difficulties and to explain the absence of asteroid families formed from differentiated asteroids, Bottke et al [5] suggested that the parent bodies of iron meteorites might have formed in the region interior to 2 AU, and that they or their surviving fragments were scattered into the main belt as a result of the collisions and interactions between the protoplanets and planetesimals. The more rapid growth of planetesimals closer to the Sun could have caused bodies larger than 20 km in size to be melted by ^{26}Al [6], whereas planetesimals in the belt that accreted 2-4 Myr after ^{26}Al had largely decayed, failed to melt, and later supplied us with chondrites. Thus this model implies that some parent bodies of iron meteorites were disrupted at 1-2 AU very early in solar system history.

Although the model of Bottke et al [5] demonstrates the plausibility of the out-scattering of melted planetesimals or their fragments into the inner asteroid belt, it does not include the gravitational effects due to (growing) giant planets. The accretion and scattering of planetesimals through interactions with planetary embryos has occurred while the cores of giant planets were growing. These objects have played an important role in the dynamical evolution of the bodies in the protoplanetary disk and the interactions between planetesimals and planetary embryos. We have developed a more complete model for the origin of the parent bodies of iron meteorites in which the interactions of planetesimals and planetary embryos as well as their out-scattering from the terrestrial planet region to the inner asteroid belt are simulated during the growth of giant planet(s) in the orbit(s) of Jupiter (and Saturn). In this talk, we present our model and discuss the implications of the results for the origin of iron meteorites parent bodies, efficiency of their out-scattering from the terrestrial region into the inner asteroid belt, and constraining the time of giant planet formation.

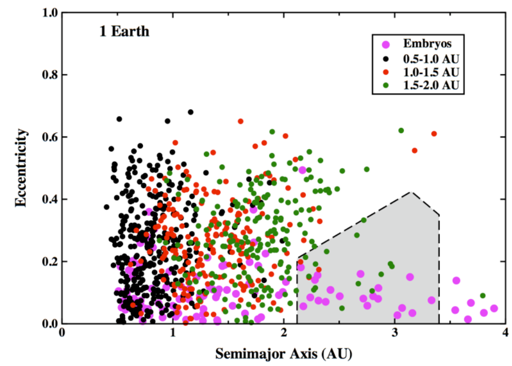
Numerical Simulations: Our model consists of a growing planet in the orbit of Jupiter and a protoplanetary disk of several hundred Moon- to Mars-sized objects (planetary embryos) and 1200 planetesimals. The planetary embryos were randomly distributed between 0.5 AU and 4 AU with mutual separations of 3-6 Hill radii. The masses of these objects were chosen to increase with their semimajor axes (a) and the number of their mutual Hill radii (Δ) as $a^{3/4}\Delta^{3/2}$. The total mass of the protoplanetary disk was approximately 4 M_E, and its surface density, normalized to 8.2 g cm^{-2} at 1 AU, was considered to be proportional to $r^{-3/2}$ [7,8]. Following Bottke et al [5], the planetesimals were considered to be massless particles. Since we are interested in the out-scattering of these objects from the region interior to 2 AU, we only focused on that region and randomly distributed planetesimals between 0.5 AU and 2 AU. We assigned a randomly chosen eccentricity between 0 and 0.05 to each planetesimal and planetary embryo, and assumed that the initial orbital inclinations of these objects were 0.1 deg. As in Bottke et al [5], we integrated the system for 10 Myr. In order to examine the effect of the perturbing planet, we integrated the system for different values of the mass of this object ranging from 0.1 to 300 M_E.

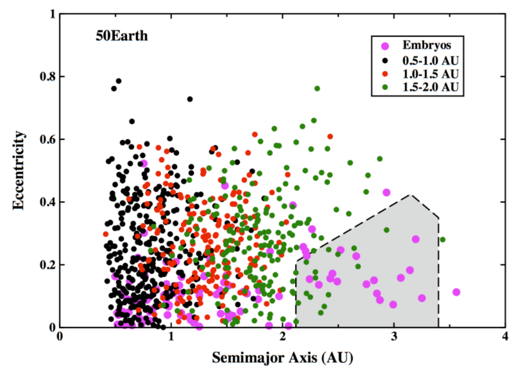
Results: The top figure shows the eccentricities and semimajor axes of planetesimals at 10 Myr for the simulation with a planet mass of 1 M_E. An inspection of the state of the surviving planetary embryos (pink circles) indicates that for small values of the mass of the planet (0.5-1 M_E), the perturbing effect of this object is negligible. This result is consistent with the results of Bottke et al [5]. In these systems, the dynamics of planetesimals and their scattering to outer regions is primarily governed by their interactions with the planetary embryos.

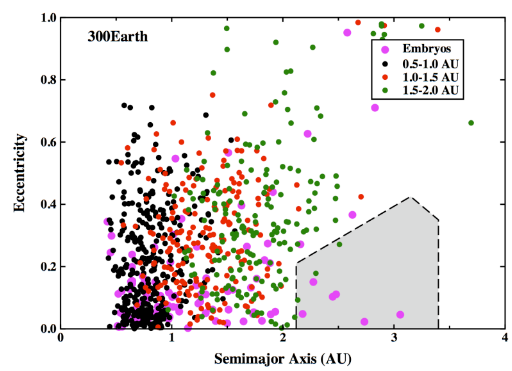
By contrast, when the perturbing planet has a mass of 10-50 M_E (middle figure), its effects become apparent. The planet in these systems excites the orbits of planetary embryos, in particular those in the region of 3-4 AU, causing many of these objects to attain high eccentricities and/or be ejected from the system. This results in high excitation of the orbits of the embryos at closer distances (2-3 AU) which in turn causes many planetesimals in those regions to be also dynamically excited. The perturbing effect of the planet is even more pronounced when its mass reaches 100-300 M_E (bottom figure). As expected, in these systems, the perturbation of the planet is so strong that the orbits of many planetesimals and planetary embryos in the range of 2-4 AU become unstable. These planetary embryos extend the destabilizing effect of the planet to the inner part of the protoplanetary disk at 1-2 AU causing many of the local planetesimals to become unstable and leave the system and only a few reach the inner asteroid belt.

Implications of the Results: One important implication of the results of our simulations is for the region from where the parent bodies of iron meteorites might have been originated. Our simulations indicate that majority of the out-scattered planetesimals were from the region of 1.5-2 AU, although a small number of planetesimals from 1-1.5 AU also contributed.

Perhaps the most important implication of our results is for the time of giant planet formation. Our simulations indicate that the gravitational effect of the perturbing planet was readily apparent after 5 Myr and for the planet mass of ~50 M_E. This effect was most prominent when the mass of the planet reached 100-300 M_E. Simulations also show that in these systems only ~20% of the embryos that formed in the asteroid belt survived and the remainder was scattered across the solar system by the planet. Since embryos play a key role in the transfer of planetesimals from the inner solar system into the asteroid belt, this process can only operate efficiently before the giant planet reaches the critical mass of 50 M_E. Results of our simulations suggest that the period during which a significant number of planetesimals can be transferred from the inner solar system into the asteroid belt has to be within the first 5 Myr. In other words, any giant planet formation mechanism through which the planet reaches 50 M_E before the first 5 Myr (e.g., the disk instability scenario [9]) would be inconsistent with the time of the formation and scattering of the parent bodies of iron meteorites.







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