GRAVITATIONAL DIFFUSION AND MIXING DURING ACCRETION OF THE ASTEROIDS.

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Introduction: The asteroid belt shows radial zoning in composition, with abundances of different taxonomic types varying on length scales ~ 1 AU [1,2]. On much smaller scales, many meteorites show compositional inhomogeneities, consisting of one dominant class with xenoliths of another type [3,4]. Extreme examples include Kaidun [5] and Almahata Sitta [6], each of which contains multiple disparate lithologies. At least some of these large- and small-scale heterogeneities occurred after the excitation and depletion of the main belt in the early solar system, during ~ 4 Gy of high-velocity collisional evolution. However, there must have been some migration during the earlier stage before Jupiter's formation, when impact velocities were low and accretion was dominant. Accretion of the asteroids was accompanied by mixing of material that originated over a range of heliocentric distances. I have begun to model this process, in order to constrain the properties of the solar nebula and the earliest evolution of the main belt.

Numerical Modeling: Accretion of asteroids and protoplanetary embryos is modeled using a code similar to that of [7]. Small planetesimals are represented by a statistical continuum. Large Moon- to Mars-sized embryos are treated as discrete bodies. Their orbits are integrated explicitly, using a symplectic algorithm [8]. Collisional damping and gas drag are modeled as perturbations to their orbits. A simulation begins with planetesimals of initial size 0.1 km, as this yields the best fit to the asteroidal size distribution [7]. The swarm is modeled from R = 1.5 to 4 AU, with surface density varying as 1/R. The continuum is modeled by a series of zones with width 0.1 AU. The small initial size yields rapid runaway growth and embryo formation on timescales < 10^5 yr. At 5×10^4 yr, a population of 100 asteroid-sized (d=200 km) test bodies is added, uniformly distributed in semimajor axis. Their orbits are integrated as they are scattered by encounters with the embryos, and collide with smaller continuum bodies. The code tracks their orbital elements, the amount of mass accreted from each zone, and the mass-weighted impact velocity of the accreted material.

Results: The principal parameter affecting the outcome is the initial surface density of the swarm. Higher surface density leads to formation of larger numbers of embryos with larger masses. In general, a significant fraction of the starting mass of the swarm is ground down by collisions into fragments smaller than ~ 10 m, which is lost from the simulation. Results are shown here for the nominal case, with a starting mass of 3 $M_\oplus$ between 1.5 and 4 AU. At t=4×10^5 yr after planetesimal formation, less than half of this mass remains, comprising 77 embryos with diameters ~ 1000 - 6000 km, and total mass 1.1 $M_\oplus$, plus 0.2 $M_\oplus$ in the continuum of asteroid-sized bodies. Figure 1 shows eccentricities and semimajor axes of embryos and test bodies. The latter have typical eccentricities of a few per cent. Gravitational scattering by embryos has caused their orbits to diffuse; the variation from their starting semimajor axes is shown in Fig. 2. The mean diffusion distance at this time is 0.176 AU, with the largest migration ~ 0.5 AU in both inward and outward directions. Figure 3 shows the history of mass accretion for the test body with the largest inward displacement. Starting at 3.14 AU, it has migrated to 2.63 AU, and has accreted mass originating over the range 2.4 - 3.3 AU. The total mass gained is ~ 2% of the initial value. While this fraction is small, the net mass gain would be concentrated in a relatively thin layer of regolith. Figure 4 shows the impact velocities of the mass accreted from the various radial zones; typical velocities are a few hundred m/s, including the effects of the gravity of the test body (escape velocity ~ 100 m/s).

Implications and Future Work: The results of this case show that a modest fraction of asteroidal bodies could migrate over distances of a significant fraction of an AU on timescales of several 10^5 yr during the early accretional evolution of the asteroid belt. Simulations are continuing for this case and others with higher initial mass for the swarm. Preliminary indications are that larger surface density leads to more massive embryos and greater scattering distances with more mixing in the belt. The observed radial zoning may set an upper limit to the primordial mass in this region of the solar nebula. Additional stirring and migration would occur after Jupiter's formation, with resonant excitation of embryos and migration due to gas drag [8]. These effects will be modeled in future studies.

References: [1] Gradie J. & Tedesco E. F. (1982) Science 216, 1405. [2] Gradie J. et al. (1989) in Asteroids II, R. Binzel et al., Eds., U of AZ Press, p. 316. [3] Wilkening L. (1977) in Comets, Asteroids, Meteorites, A. Delsemme, Ed., U Toledo Press, p. 389. [4] Scott E. R. D. (2002) in Asteroids III, W. F. Bottke et al., Eds., U of AZ Press, p. 697. [5] Zolensky M. & Ivanov A. (2003) Chemie der Erde 63, 185. [6] Bischoff A. et al. (2010) MAPS 45, 1638. [7] Weidenschilling S. J. (2011) Icarus 214, 671. [8] Hood L. & Weidenschilling S. J. (2012) MAPS, in press.

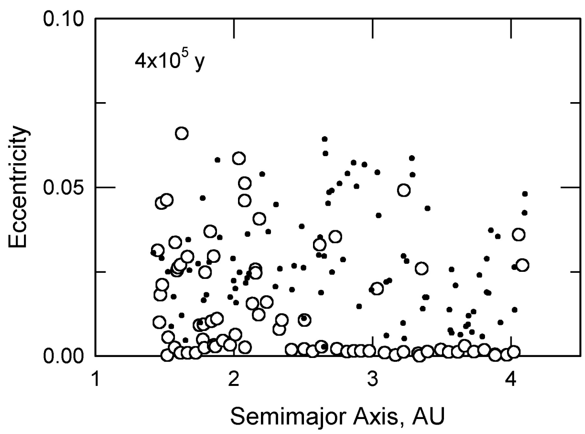

Figure 1. Eccentricities of embryos (open circles) and asteroid-sized test bodies (dots) 4×10^5 yr after the start of planetesimal accretion. At this time there are 77 embryos with diameters ~ 1200 - 6000 km, and 94 surviving test bodies (4 have collided with embryos).

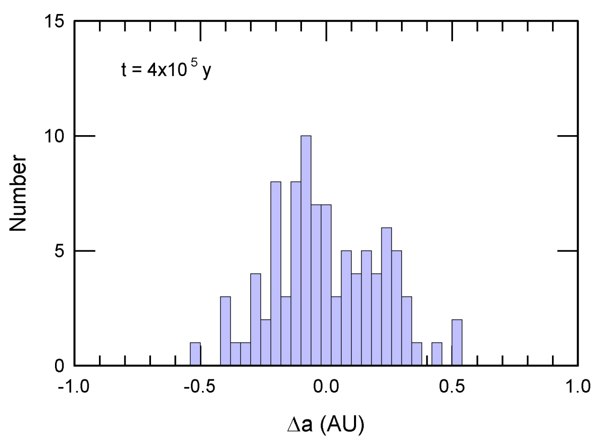

Figure 2. Histogram of displacement in semimajor axis from the starting values of the surviving test bodies. The mean displacement is 0.176 AU, with outliers displaced ~ ±0.5 AU.

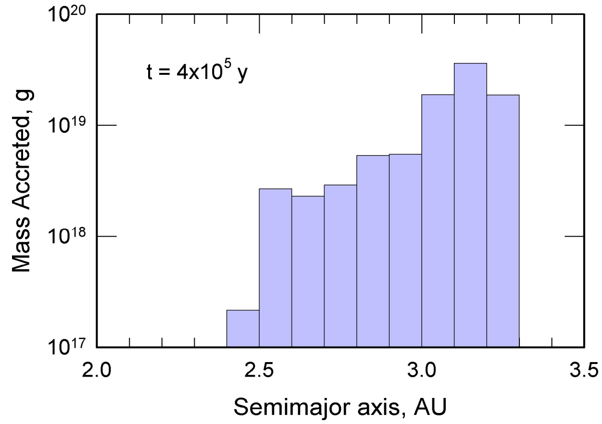

Figure 3. Mass accreted from various heliocentric distances by the test body that has migrated inward by ~ 0.5 AU. The accreted mass is derived from a range from 2.4 to 3.3 AU. The total mass accreted is a few per cent of the starting mass of the test body.

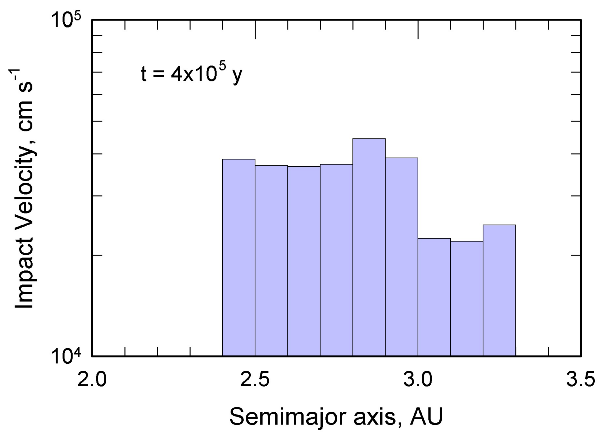

Figure 4. Distribution of impact velocities of the mass accreted from the various zones shown in Fig. 3. Typical impact velocities are ~ 400 m/s.