WERE ASTEROIDS BORN BIG? AN ALTERNATIVE SCENARIO. S. J. Weidenschilling. Planetary Science Institute, 1700 E Ft Lowell Rd, Ste 106, Tucson AZ 85719-2395 USA; sjw@psi.edu

Introduction: Although most evidence for the size(s) of initial planetesimals has been destroyed, some evidence may be preserved in the asteroid belt. The size frequency distribution (SFD) in the present belt has an excess at diameter ~ 100 km relative to an equilibrium power law. Collisional evolution modeling suggests that this feature is a "fossil" remnant of the population already present ~ 4 Gy ago [1]. This was not the SFD of the first planetesimals, but the product of a few My of accretion before the belt was stirred and depleted by Jupiter's formation [2]. Modeling the accretionary stage [3] shows that the resulting SFD depends on the initial planetesimal diameter. Canonical km-sized planetesimals yield an excess at ~ 10 km, but a deficit at ~ 100 km, and so can be ruled out. An initial size ~ 10 km yields a somewhat better fit. Recently [4] examined this problem in more detail. In addition to the 100 km excess, a relative deficit of ~ 30 km objects is needed to preserve Vesta's crust. Also, runaway accretion must produce embryos of at least a few × 10^3 km to provide dynamical stirring. Accretional simulations by [4] were unable to meet all these constraints starting with a single planetesimal size. They concluded that the initial SFD closely resembled that presently observed, i.e., the planetesimal formation process produced bodies in a range from ~ 100 to > 1000 km directly from sub-m particles, without passing through intermediate values. They favored collective effects due to turbulence in the solar nebula [5,6]. While such a scenario cannot be excluded, turbulent concentration models do not yet predict the SFD of bodies produced, and the source of turbulence is problematic. It seems premature to abandon more conventional accretion scenarios without a fuller examination of the parameter space.

Accretional Modeling: I use a multi-zone code [7] to model the accretion of bodies in the asteroid region for a variety of starting populations, including monodisperse swarms and power laws extending over various sizes. Simulations are performed for 25 zones of heliocentric distance R from 1.5 to 4 AU. The surface density of the swarm varies as 1/R; nominal parameters give 4.8 $M_\oplus$ of solids with the complement of gas. Fragmentation is allowed, with fragments retained in size bins as small as 15 m. At these sizes, radial velocities due to gas drag are significant, and are included in calculating collision rates. Smaller fragments can be lost from the system or recycled into new planetesimals. Simulations are run to model times of 3 My.

Results: For any single initial size, d_0 simulations fail to meet one or more of the criteria for the early asteroid population. As mentioned above, km-sized bodies yield an excess at ~ 10 km and a deficit at ~ 100 km. d_0 = 10 km yields a bump at ~ 100 km, but too many ~ 30 km bodies to allow survival of Vesta's crust. Larger d_0, e.g., 50 km, have runaway growth too slow to produce the needed large embryos in a few My, and do not yield enough fragments to account for the observed population of smaller asteroids. The best fit with d_0 > 1 km is an initial power law with a lower limit > 30 km and an upper limit > 100 km, consistent with [4]. However, these initial conditions do not exhaust the possibilities. If planetesimals formed by coagulation in collisions driven by size-dependent drift due to drag of nebular gas, their growth rates decline as drift velocities decrease with increasing size. This process tends to produce bodies with a characteristic size ~ 100 m [8] before growth by gravitational accretion. This scenario suggests a starting condition with d_0 = 0.1 km. Figure 1 shows the SFD resulting from this initial size. Surprisingly, it meets all the requirements for the early asteroid population, with a "bump" at ~ 100 km, a deficit at ~ 10 - 50 km, and adequate embryos > 1000 km. The requisite properties are established on a timescale < 10^5 y from the start of accretion. The form of the SFD is not sensitive to the assumed asteroid density or the nebular surface density. It does not depend on the impact strength; the variations in slope are not oscillations produced by differential fragmentation [9], but appear even in simulations without fragmentation.

Several processes appear to contribute to this result. The small initial size produces very low relative velocities at the start of accretion. These allow runaway growth to start when the first bodies attain sizes ~ 1 km. These bodies then grow rapidly to sizes ~ 100 km, leaving a relative deficit of bodies at intermediate sizes of tens of km. Gravitational stirring then raises the relative velocities of the smaller bodies, while damping by collisions and gas drag gives them a fairly flat velocity distribution. Dynamical friction produces a "shoulder" in the velocity distribution at sizes ~ 100 km (Fig. 2). The flat velocity distribution halts runaway growth at smaller sizes. Larger bodies have lower velocities and continue runaway growth to produce embryos. Further growth of the smaller bodies is essentially halted by the higher velocities; they tend to be accreted by the embryos or ground down to small fragments by mutual collisions. The deficit of bodies at tens of km and the excess at ~ 100 km are "fossils" of the very early period of runaway growth at small sizes. This outcome occurs for simulations with initial sizes ≲ 0.2 km, whether the planetesimals are produced instantaneously or added over an interval of a few times 10^4 y. The nebula's turbulence level has to be low in order to produce the planetesimals in the first place, if they formed by collisional coagulation [10]. Planetesimal formation could have been triggered by a sudden decay of turbulence, possibly temporary. Once formed, bodies ≥ 0.1 km are not strongly affected by aerodynamic effects of turbulence, but can be stirred by gravitational perturbations due to resulting fluctuations in the gas density [11]. Following [4], I introduce a stirring rate γ for eccentricities and inclinations that is independent of size. The asteroidal SFD is still produced by simulations with $\gamma <$ a few $\times 10^{-3}$.

Thermal Consequences: The short accretion timescale with the presence of ^{26}Al would melt typical bodies ≥ 100 km. However, about half of the starting mass is left in bodies < 10 km. These are ground down or accreted by the larger bodies on timescales > 10^6 y. Thus, there is an ample reservoir of unmelted primitive material, which could produce layered structure in asteroids, with less thermally processed material near the surface.

Conclusions: An asteroidal SFD consistent with observations can be produced by accretion from small bodies, if initial planetesimals have sizes ~ 0.1 km. These must form in a fairly quiescent nebula, presumably after decay of an earlier turbulent stage. Formation of planetesimals by collisional coagulation induced by gas drag remains a plausible mechanism.

References: [1] Bottke W. et al., Icarus 175, 111-140 (2005). [2] Chambers J. & Wetherill G. W., MAPS 36, 381-399 (2001). [3] Weidenschilling S. J., LPSC XL, 1760 (2009). [4] Morbidelli A. et al., Icarus 204, 558-573 (2009). [5] Johansen A. et al., Nature 448, 1022-1025 (2007). [6] Cuzzi J. N. et al., ApJ 687, 1432-1447 (2008). [7] Weidenschilling S. J. et al., Icarus 128, 429-455 (1997). [8] Weidenschilling S. J., Icarus 127, 290-306 (1997). [9] Campo Bagatin A. et al., Planet. Space Sci. 42, 1079-1092 (1994). [10] Cuzzi J. N. & Weidenschilling S. J. , in Meteorites and the Early Solar System (Ed. D. Lauretta & H. McSween), U Arizona press, Tucson, 353-381 (2006). [11] Ida S. et al., ApJ 686, 1292-1301 (2008).

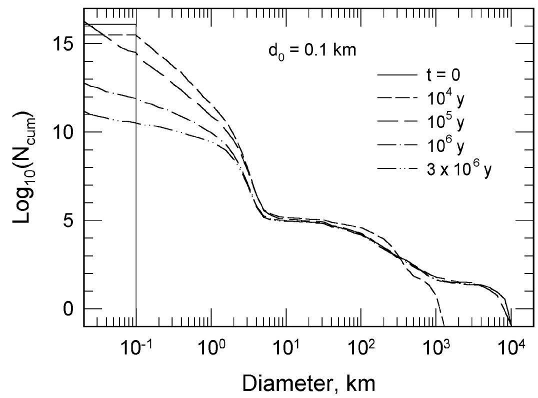

Figure 1. Cumulative size distribution for bodies between 2 and 3.5 AU. At *t=0*, all mass is in bodies with diameter 0.1 km. Runaway growth produces a "bump" at ~ 100 km and large embryos up to 10^4 km in 10^5 y. About half of the total mass is left in bodies smaller than a few km. Most of the later evolution to 3 My is depletion of the small bodies by collisional grinding and accretion onto the embryos.

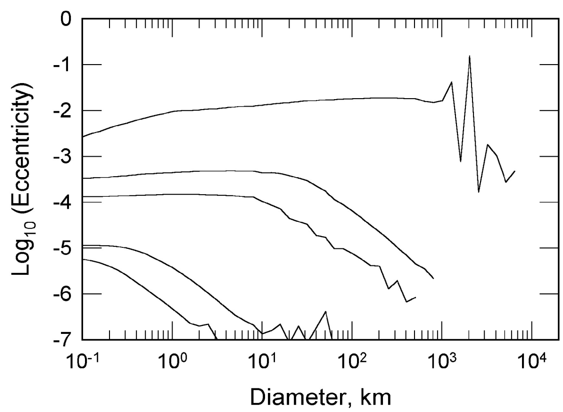

Figure 2. Mean eccentricity vs. size; curves show increasing values at times 1000, 3000, 5000, 10^4 and 10^5 y. For clarity, only zones between 2.5 and 3 AU are shown. The variations at sizes larger than 10^3 km are due to the stochastic scattering of individual bodies.