HOW BIG WERE THE FIRST PLANETESIMALS? DOES SIZE MATTER? S. J. Weidenschilling, Planetary Science Institute, 1700 E. Ft. Lowell Road, Suite 106, Tucson, Arizona 85719-2395 USA; sjw@psi.edu

Introduction: The terrestrial planets formed by collisional accretion of small planetesimals [1,2]. Stochastic coagulation and runaway growth yield an "oligarchy" of embryos with similar sub-planetary masses [3] that then collide to yield planets [4-5]. A common assumption is km-sized initial planetesimals, based on the scale of gravitational instability in a dust layer in a quiescent solar nebula [6-7]. This mechanism is untenable due to shear-induced turbulence [8]. Alternative mechanisms [9-11] depend on poorly constrained properties of particles (sticking efficiency, impact strength) and/or the nebula (turbulent velocity, eddy timescale), and do not predict planetesimal sizes from first principles. Here we investigate by numerical modeling effects of initial planetesimal size on outcomes of accretion.

Collisional Outcomes: Collision between planetesimals yield net growth or destruction, depending on size, strength, and impact velocity. Impact strength Q^* is defined as specific energy to remove half of the target's mass. This involves fracturing the target and partitioning kinetic energy to fragments that escape their mutual gravity. Small bodies are dominated by material strength; large ones by self-gravity. Scaling laws yield Q^* with a minimum at roughly km size [12]. We assume 1% of impact energy is partitioned into fragment kinetic energy.

Collisional Modeling: We use the PSI multi-zone accretion code [13]. The swarm has surface density $\propto 1/R$. Initial swarm mass is 7 $M_\oplus$ between 0.5 and 4 AU (most mass at $R > 1$ AU is depleted after Jupiter forms). Velocities are stirred by mutual perturbations and damped by collisions and gas drag. Gas decays on a timescale 2 My, but outcomes are insensitive to gas density. Fragments < 125 m are lost. Simulations run to model times of 5 My, but in most cases runaway growth ends in < 1 My and later evolution is slow.

Mass Budget of the Planetesimal Swarm: Typically, runaway growth yields a bimodal population, with about half the initial swarm mass in embryos ~ 10^{26} g. The remaining mass is in bodies with typical sizes a few times the starting size d_0. Their fate is to collide with each other or with the embryos. Collisions with embryos result in accretion. However, perturbations by embryos typically produce velocities for which mutual collisions of the small bodies are destructive. Fragments with $d < 1/8$ km have lifetimes against gas drag $\lesssim 10^4$ y, and are unlikely to be captured by the embryos. A smaller minimum fragment size threshold only results in additional losses from erosion. For d_0 = 1 km, the loss of small bodies by collisional grinding is nearly total; about half of the swarm's starting mass is lost. If the first planetesimals were km-sized or smaller, the surface density of the solar nebula in the terrestrial planet region had to be about twice the value associated with "minimum mass" models. For d_0 = 10 km, only about 5% is lost. This difference is partly due to gravitational binding energy, but mostly due to fewer collisions between ~ 10-km bodies; their collision rate varies as d^{-2}. Most of them last long enough to be accreted by embryos.

Timescale for Runaway Growth: An embryo grows most rapidly when small body approach velocities are dominated by Keplerian shear rather than random motions. Shear dominates when the embryo's mass is ~ 10^4 times the mean mass of the background population [14], regardless of their absolute sizes. Multiple stochastic coagulation events must occur to produce a body with the critical mass ratio. The time to initiate runaway is proportional to the collision timescale, i.e., planetesimal size. Once runaway begins, the timescale for embryo growth does not depend on planetesimal size. In the asteroid region, runaway growth goes to completion in < 1 My if d_0 = < 10 km, but takes > 1 My for d_0 = 50 km. If planetesimals were heated by ^{26}Al, their temperatures depended on both size and time of formation. If they formed soon after CAIs, those with d_0 > 10 km would melt [15]. Smaller bodies could escape significant thermal metamorphism, but would be ground down by collisions after embryos grew. Thus, the surviving fraction of primitive material would be small, regardless of planetesimal size.

Asteroidal Size Distribution: Although most evidence for the original size of planetesimals has been destroyed, some evidence may be preserved in the asteroid belt. The present belt has an excess of asteroids ~ 100 km. Collisional modeling of the last 4 Gy suggests that this feature is a "fossil" remnant of a primitive size distribution [16]. This is not the size distribution of the first planetesimals, but the product of a few My of accretion before the belt was stirred and depleted by the formation and/or migration of Jupiter [17]. Modeling the accretionary stage shows that the resulting size distribution depends on the initial planetesimal size. For d_0 = 1 km, a hump develops at ~ 10-20 km (Fig. 1). For d_0 = 10 km, a hump forms at ~ 100 km after a few My; there is a slight deficit of bodies < 10 km, which are fragments of disrupted larger bodies (Fig. 2). For d_0 = 50 km (Fig. 3) the hump is at ~ 200 km, with a deficit of smaller bodies, as few bodies > 50 km are disrupted. The lack of smaller projectiles inhibits the later collisional evolution of the belt.

Summary and Conclusions: Km-sized initial planetesimals result in significant mass loss from the terrestrial planet region and yield a poor fit to the size distribution inferred for the early asteroid belt. Sizes ≥ 50 km do not yield enough smaller fragments for collisional evolution of the asteroid belt after its depletion. If planetesimals formed with a single characteristic size, the best fit is for d_0 ~ 10 km. These models assume planetesimals formed instantaneously; it is not clear if other outcomes may result if formation occurred over an extended interval.

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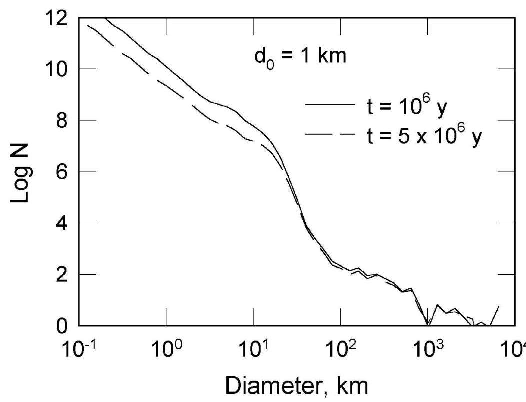

Fig. 1

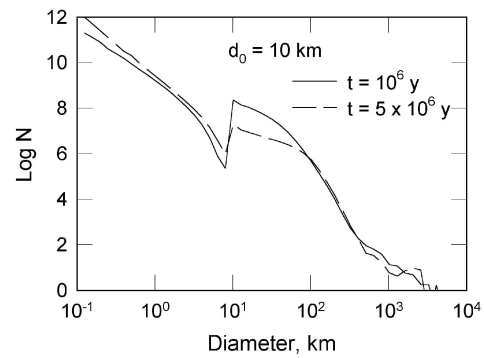

Fig. 2

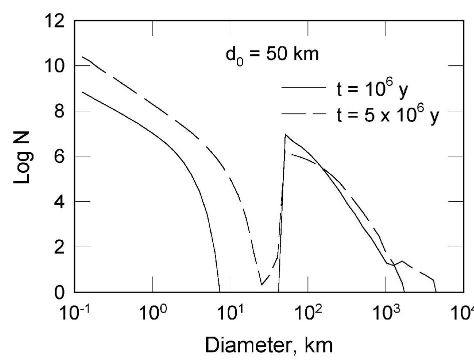

Fig. 3

Size distributions of bodies produced in the asteroid region by simulations of accretion with fragmentation (compare with Fig. 4 of [16]). Incremental numbers of bodies in logarithmic mass bins are shown for populations between 2 and 3.5 AU, at model times 1 and 5 My. **Fig. 1:** Initial size 1 km produces a hump at ~ 20 km; smaller bodies are depleted by fragmentation. **Fig. 2:** Initial size 10 km yields a hump at ~ 100 km after a few My. **Fig. 3:** Initial size 50 km has a deficit of smaller bodies (fragments), even after 5 My.