ACCRETION OF THE OUTER PLANETS: OLIGARCHY OR MONARCHY? S. J. Weidenschilling[1], F. Marzari[2], D. R. Davis[1], [1]Planetary Science Institute, Tucson AZ 85719, sjw@psi.edu; [2]Dept. of Physics, Univ. Padova, Italy.

A persistent problem with the formation of the outer planets is the timescale of their formation. Jupiter and Saturn must have formed within the lifetime of the solar nebula. One model for their formation is nucleated instability, in which a rock/ice core of ~ 10 $M_\oplus$ must accrete before capture a gaseous envelope from the nebula [1]. Accretion timescales increase with heliocentric distance, exacerbating the problem for Uranus and Neptune. These planets consist largely of rock and ice, but have captured some gas from the nebula, and so may have approached their present masses on timescales ~ 10^7 y or less. The standard model for their formation assumes formation of embryos of mass ~ $M_\oplus$, followed by merger into the present planets [2]. However, simulations of late-stage accretion show that gravitational scattering excites large eccentricities and inclinations; the decrease in collisional cross section effectively stops accretion, and Uranus and Neptune do not form within the age of the solar system [3]. Thommes et al. [4] suggested that Uranus and Neptune accreted between Jupiter and Saturn, and were ejected to the outer solar system by their perturbations after those planets gained mass by gas accretion. Their orbits were then circularized by dynamical friction due to the population of small planetesimals in the outer nebula. While this approach is more promising than in situ accretion, it would cause strong stirring of the smaller population, which may be inconsistent with the dynamically cold component of the Kuiper Belt [5].

Most attempts to model growth of the outer planets assume that the formation of embryos was oligarchic; i.e., accretion of a swarm of small planetesimals produces a series of large bodies with quasi-uniform masses and orbital spacing. As the accretion timescale increases with heliocentric distance, embryos form successively in a "wave" that propagates outward. Due to stirring of the small bodies by multiple embryos in adjacent orbits, their growth slows when their masses are a few times less than the "isolation mass" M_{iso}, the limit set by the Jacobi energy in the restricted 3-body problem [6]. This style of growth has been shown to occur in the region of terrestrial planets [7]. Thommes et al. [8] assumed that this scaling extended to the outer solar system, but showed that an implausibly massive disk would be required to produce Uranus and Neptune.

We suggest an alternative model that produces rapid in situ growth of Uranus and Neptune with less dynamical excitation of the planetesimal swarm. We use a hybrid multi-zone accretion code [9] to model planetary growth in the outer solar system, beyond the "snow line" for water ice condensation. The range 4 - 30 AU is divided into zones of semimajor axis. Within each zone, the population of small bodies is modeled as a continuum, with the size distribution defined by the numbers of bodies in logarithmic mass bins; their mean eccentricities and inclinations are determined by viscous stirring, damping by gas drag, and dynamical friction. Bodies larger than a threshold size are treated discretely, with individual values of mass, semimajor axis, eccentricity, and inclination. They interact with the small bodies by the continuum stirring equations; however, gravitational stirring between the discrete bodies is treated as a series of stochastic encounters, with changes in orbital elements modeled by a 2-body scattering approximation. The hybrid code allows a wider range of masses than N-body simulations [8], while allowing stochastic orbital evolution that does not appear in statistical continuum models [10].

Figures 1-3 show outcome of a simulation in a solar nebula model with gas surface density 2500 R^{-1} g cm^{-2}, where R is the heliocentric distance in AU. The abundance of rock + condensable ices is 0.015 times that of the gas, giving a surface density of solids of 7.5 g cm^{-2} at 5 AU. The initial population consists of planetesimals with diameter 1 km. In the inner part of the swarm, oligarchic growth produces 5 embryos of mass ~ $M_\oplus$ in 3×10^5 y. At 3.3 x 10^5 y, a body of mass ~ 10^{25} g has a close encounter with one of the embryos, and is scattered into an orbit with a ~ 20 AU, e ~ 0.5. As growth in the outer region is much slower, the scattered body encounters a population with median mass ~ 10^{16} g. Dynamical friction quickly decreases its eccentricity, preventing further encounters with the embryos. The scattered body is left in an isolated circular orbit, in the midst of a population of bodies much smaller than itself. Conservation of the Jacobi parameter limits the stirring, and keeps their encounter velocities low. The result is rapid runaway accretion, which proceeds until the growing body approaches M_{iso}. The entire growth takes ~ 10^5 y. In this example, another scattering event triggers a similar runaway near 13 AU at 4.5×10^5 y. By 10^6 y, the two bodies have masses ~ 15 and 8 $M_\oplus$, about 0.5 M_{iso} at their respective distances.

Planetary formation in the outer solar system differs from that in the inner region due to two factors: M_{iso} increases with distance (if the surface density decreases more slowly than R^{-2}),while orbital velocity V_k decreases. A planetesimal experiencing a close encounter with an embryo can have its heliocentric velocity changed by an amount (ΔV) comparable to the embryo's escape velocity. Assuming that the embryo has mass $\sim M_{iso}$, one can show that $\Delta V/V_k$ is ~ 0.1 at 1 AU, but ~1 at 5 AU. Accretion in the terrestrial region is a local phenomenon. Beyond the snow line bodies can be scattered over large distances, thus a "seed" body can be scattered outward, nucleating runaway growth in a pristine region of smaller planetesimals. We call this style of growth "monarchy" in contrast to the oligarchy in the inner solar system.

In order for this mechanism to work, it is necessary that (i) the surface density of the nebular solids beyond the snowline must be large enough (~ 10 g cm^{-2}) to produce oligarchs with masses ~ $M_\oplus$ to scatter seed bodies. (ii) The scattered bodies must be massive enough to dominate the indigenous population at their new locations. Rapid growth occurs if keplerian shear dominates the local random velocity. Assuming the shear velocity is ~ ΩR_H, where R_H is the seed's Hill radius, and the random velocity is the escape velocity of the small bodies, the seed body must be $\gtrsim 10^6$ times the local mean mass; e.g., a lunar-mass seed in a swarm of 10 km planetesimals.

Implications

The seed body's mass is much less than the final planet. Most of the mass is derived from the nebula at the location where it accretes (before any subsequent migration).

Scattering of seed bodies is stochastic. The numbers and orbital radii of outer planets that form in this manner are subject to random variation, as is the outcome of accretion of terrestrial planets. Only a few planets can form in this manner; once a large core grows, it stirs up the eccentricities of the swarm near its orbit. The higher velocities prevent runaway growth of any other seed body scattered into that region. Rapid formation implies that the planets formed hot.

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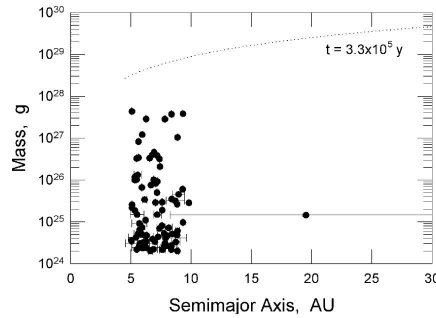

Figure 1. Mass vs. semimajor axis for discrete bodies at 3.3×10^5 y. Bars show perihelia and aphelia. Dotted line shows M_{iso} as function of R. heliocentric distance. Five bodies have formed ~ $M_\oplus$between 5 and 10 AU. A body ~ 10^{25} g has been scattered into an eccentric orbit with a ~ 20 AU.

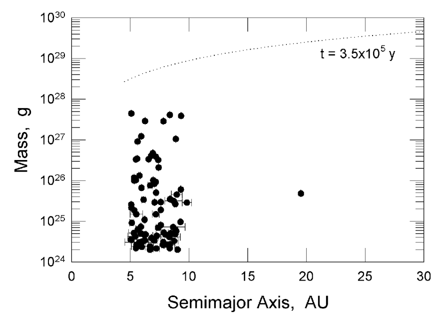

Figure 2. By 3.5×10^5 y, the scattered body has been damped by dynamical friction into an orbit with eccentricity near zero.

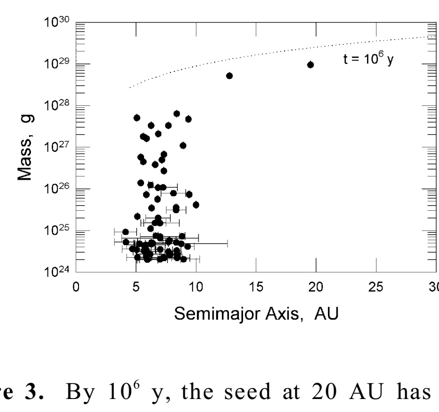

Figure 3. By 10^6 y, the seed at 20 AU has accreted most of the material near its orbit, reaching a mass ~ 15 $M_\oplus$. A second scattered seed has grown in similar fashion to ~ 8 $M_\oplus$ near 13 AU.