COLLISIONAL EVOLUTION OF A MASSIVE PLANETESIMAL DISK DURING SLOW MIGRATION OF THE OUTER PLANETS.

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Many features of our solar system can be explained by invoking slow migration of the giant outer planets, followed by a chaotic phase of orbital evolution [1-3]. In this “Nice Model” the gas giants Jupiter and Saturn and the ice giants Uranus and Neptune formed within a relatively narrow range of heliocentric distance ~ 5 - 15 AU. The planets then migrated due to gravitational scattering of planetesimals which were originally present in a massive (30 - 50 $M_\oplus$) external disk in the region ~ 15 - 30 AU. These bodies were scattered inward by the three outer planets until they became Jupiter-crossing and were ejected on hyperbolic orbits. Conservation of angular momentum caused Jupiter to migrate slightly inward, with the other planets moving outward over larger distances. At some stage, Saturn crossed the 1:2 mean motion resonance with Jupiter; this destabilized the system, increasing eccentricities and allowing orbits to intersect. The ice giants were scattered outward, and may have exchanged positions. Dynamical friction exerted by the disk then damped eccentricities and inclinations to values consistent with current values. This model can account for the eccentricities and inclinations of the giant planets [1], and capture of Jovian Trojans [2].

Gomes et al. [3] also suggest that the 1:2 Jupiter-Saturn resonance destabilized orbits in the asteroid region, causing the Late Heavy Bombardment (LHB) of the inner solar system. It is generally accepted that the LHB occurred around 3.8 to 4.0 Gy ago; if it was indeed caused by chaos in the outer solar system, this constrains the time of the Jupiter/Saturn resonance and the rate of planetary migration. According to [3], the timing of the resonance crossing is determined primarily by the initial separation of the orbits of Jupiter and Saturn, and the distance between the inner edge of the disk and the outermost ice giant. Delays of up to ~ 1 Gy could be easily be produced by appropriate choices of starting orbits. However, it is necessary for the planetesimals to survive for the duration of planetary migration. The simulations described by [1] were N-body integrations of the orbits of the planets and ~ 1000 - 5000 equal-mass test particles that comprised the mass of the planetesimal disk. These particles interacted gravitationally with the planets, but did not interact with each other by gravity or physical collisions. Actually, the planetesimals would be subject to collisional evolution, and could undergo accretion and/or comminution during the long quiescent interval before the resonance crossing. Modeling this collisional evolution may place constraints on the disk mass and size distribution of the planetesimals.

I use a variant of the PSI multi-zone planetesimal evolution code to study the evolution of a massive external disk. Details of the code are described in [4]. The code computes collision rates and impact velocities in a series of interacting zones of semimajor axis. The size distribution is treated as a series of logarithmic diameter bins, allowing a wide range of sizes to be modeled. Gravitational interactions between planetesimals include viscous stirring and dynamical friction. The giant planets are treated as discrete bodies. For the present study, the giant planets were assumed to have their present masses. Their orbits were held fixed at semimajor axes 5.5, 8.5, 11.5 and 14.5 AU (Uranus in the outermost orbital position), and eccentricities kept constant at 0.01. The planetesimal disk had surface density varying as 1/R, with a total mass of 38 $M_\oplus$ between 15 and 30 AU. The initial size distribution of planetesimals was assumed to be a power law with the collisional equilibrium (incremental mass) index of 11/6, from a minimum size of 0.125 km up to a limiting size D_{max}. Collisional outcomes were modeled including size-dependent material strength and gravitational binding energy [5]. Material parameters were chosen to favor accretion, with relatively high strength of 1.5×10^6 erg/g, and 1% of impact energy converted to kinetic energy of fragments.

The disk is stirred mainly by planetary perturbations according to the model of [6]. For non-crossing orbits eccentricities are excited more effectively than inclinations, and stirring by a dominant body produces relative velocities that depend only weakly on planetesimal size. This yields a fairly distinct size threshold such that bodies larger than a critical size can accrete, while smaller ones are destroyed by collisions. This stirring also tends to inhibit runaway growth throughout the disk. In these simulations, fragments smaller than 0.125 km are not retained, and are assumed lost from the system. Smaller bodies have such short collisional lifetimes that they would be ground into dust and expelled by radiation pressure. Also, including smaller bodies would increase the number of projectiles, leading to more erosion of the larger target bodies.

Initially the planetesimals do not cross the orbits of the giant planets; this remains the case for most of the disk except for zones near the inner edge. Collision rates and impact velocities are highest in the inner disk, leading to fragmentation and depletion of the population of potential planet-crossers. The choice of parameters results in a size threshold for collisional destruction of about 100 km in the inner disk. Figure 1 shows the outcome for D_{max} = 10 km; the disk is almost totally depleted of mass inside ~ 20 AU on a timescale ~ 10^7 y. Figure 2 shows evolution of the disk surface density for D_{max} = 100 km. There is an initial "shepherding" effect as the outermost planet stirs the inner disk, pushing planetesimals outward to form a local maximum in the surface density near 18 AU. About 50% of the mass originally inside 20 AU is depleted within 10^7 y, but the rest survives for 5×10^8 y. If D_{max} = 500 km, about 70% of the mass inside 20 AU survives for more than 10^8 y. Most of the loss consists of the fraction of the mass distribution that was in bodies smaller than ~ 100 km at the start of the simulation.

In summary, if the outer planets were subject to migration due to scattering of planetesimals in a massive outer disk, the scattered bodies must have had collisional lifetimes at least comparable to the duration of planetary migration. If this phase lasted longer than ~ 10^8 y, only bodies larger than about 100 km (for a conservative choice of parameters) were effective contributors to the migration. These bodies had to form before the giant planets approached their final masses. The accretion of such bodies by runaway growth during the few My lifetime of the solar nebula is plausible; the existence of Pluto, Triton, and large KBOs is evidence that such growth occurred. However, it should be noted that runaway growth is self-limiting, ceasing when the mass in the large embryos is comparable to that in the background population of small planetesimals. Thus, if migration implies that the giant planets experienced dynamical interaction with a disk of ~ 30-50 $M_\oplus$ [1], the outer solar nebula needed to produce a mass of condensed solids that was roughly twice this value.

References: [1] K. Tsiganis et al. Nature 435, 459 (2005). [2] A. Morbidelli et al. Nature 435, 462 (2005). [3] R. Gomes et al. Nature 435, 466 (2005). [4] S. Weidenschilling et al. Icarus (1997). [5] D. Durda et al. Icarus 135,431 (1998). [6] S. Weidenschilling, Icarus 80, 179 (1989).

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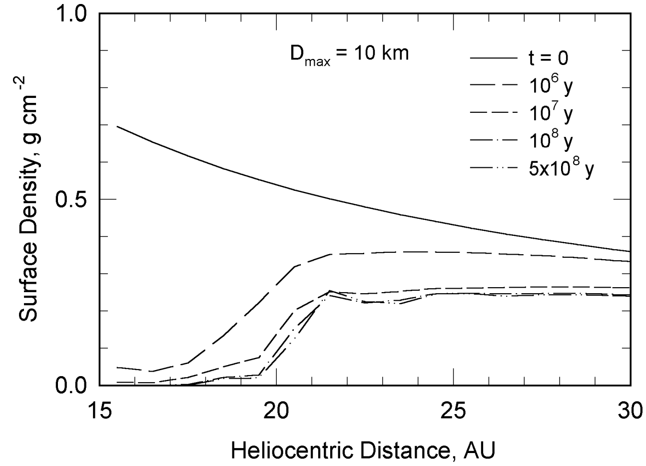

Figure 1. Evolution of the surface density of a disk of planetesimals with initial maximum diameter 10 km, perturbed by a Uranus-mass planet at 14.5 AU. The inner edge of the disk is initially at 15 AU. The region of the disk inside 20 AU is almost completely depleted within 10^7 y.

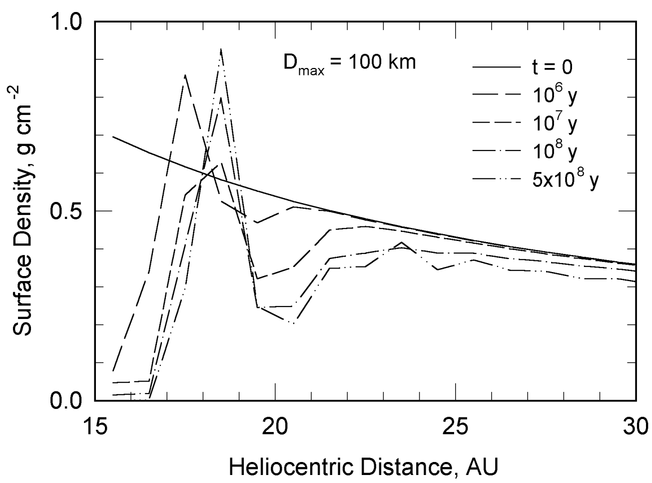

Figure 2. Same as Fig. 1, but with maximum diameter 100 km. Shepherding with collisional damping pushes the larger surviving planetesimals outward to form a peak near 18 AU. About half the mass inside 20 AU is depleted, but the largest bodies survive for more than 10^8 y.