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Collision Probabilities in the Presence of Nebular Gas Drag

David. M. Kary and Jack. J. Lissauer, SUNY @ Stony Brook

The dynamics of the planetesimal swarm was likely to have been strongly affected by gas drag in the solar nebula. Significant amounts of gas were certainly present during the formation of Jupiter and Saturn, and may have been important in the formation of other planets (Nakagawa, Hayashi, and Nakazawa 1983, *Icarus* 59, 552). Work by Weidenschilling and Davis (1985, *Icarus* 62, 16) has shown that the combination of gas drag and perturbations due to mean motion resonances with a protoplanet is likely to have had important consequences for the evolution of planetesimal orbits. They pointed out that while gas drag tends to cause planetesimals to spiral in towards the Sun, resonant perturbations tend to force the planetesimals away from the protoplanet. For planetesimals starting outside the protoplanet orbit, these two forces oppose each other, and at some point there will be a balance between them. At these resonance locations the planetesimal eccentricities are strongly excited, which would lead to high velocity collisions that would grind down the planetesimals until they are much more strongly affected by the gas drag. This would cause a more rapid inward migration of the planetesimals and thereby make gas drag a more significant factor in planetary growth. This process would have been especially important in runaway accretion scenarios, in which large protoplanets would be expected to accrete much of their mass from significantly smaller planetesimals, often in the presence of nebular gas drag.

We are developing a model to determine what fraction of the planetesimals would have hit a protoplanet on their sunward journey as opposed to having a close approach and passing into an inferior orbit. The model involves direct numerical integration of restricted-three-body orbits using a predictor-corrector integrator. A simple gas drag law with a v^2 dependence has also been included in the equations of motion. Runs of 100 to 500 particles have already been performed, while some future runs may require several times this number in order to get good impact statistics. All planetesimals start in superior orbits with semi-major axes 5 to 10 R_H from the protoplanet, where R_H is the protoplanet's Hill Sphere radius. The orbit is followed until the planetesimal has passed into an inferior orbit at least 10 R_H from the protoplanet. This process typically requires 10^4 to 10^5 orbits.

The simulations performed thus far have used a protoplanet of mass $10^{-6}M_{\odot}$ and drag parameters corresponding to planetesimals with radii from 30m to 3km moving through a nebula with a density of $10^{-9}g/cm^3$. Planetesimals with the larger radii ($> 1km$) are found to be held in superior orbits by the perturbations from the planet at mean-motion resonances. The particles held at these resonances are excited to relatively high eccentricities. The smaller the planetesimals, the stronger the gas drag force and therefore the closer they get to the protoplanet. At small enough planetesimal radii, the gas drag force is strong enough to overcome mean-motion resonant perturbations, and all of the planetesimals pass the protoplanet. For 300m planetesimals, the probability of

impacting a protoplanet with the Earth's density and location is only $\frac{1}{3}$. The probability of hitting an icy core at the location of Jupiter is $\frac{1}{6}$, while at Neptune's location it is $\frac{1}{11}$. For still smaller planetesimals, the fraction of bodies impacting the planet decreases slowly, so that for $30m$ planetesimals the accretion probability is $\sim \frac{2}{3}$ that for $300m$ bodies.

In future work we will determine the dependence of the accretion probability on the mass of the protoplanet. The effects of a protoplanet in an eccentric orbit will also be investigated.

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