**PERTURBED PLANET FORMATION: ACCOUNTING FOR MASSIVE COMPANIONS IN SIMULATIONS OF PLANETESIMAL GROWTH.** Steve Kortenkamp, S.J. Weidenschilling, *Planetary Science Institute, 1700 East Ft. Lowell, Suite 106, Tucson, AZ, 85719-2395 (kortenka@psi.edu)*, Francesco Marzari, *Physics Dept., University of Padova, Italy*.

The standard model of planet formation was initially developed to help explain how planets could have formed around our isolated sun. This model typically begins with a protoplanetary disk of gas and dust orbiting a young protostar. Growth of terrestrial planets in such a disk is usually treated in three stages: [stage I] accretion of dust particles into $10^{12}$ to $10^{18}$ gram (kilometer-size) planetesimals in $\sim 10^4$ years, [stage II] gravitational accumulation of planetesimals through a process known as "runaway growth," which produces $10^{26}$ to $10^{27}$ g (Mercury- to Mars-size) planetary embryos in $\sim 10^5$ years, and [stage III] giant impacts between embryos, resulting in full-size $10^{27}$ to $10^{28}$ g terrestrial planets in $\sim 10^7$-$10^8$ years.

Farther out in the protoplanetary disk, where temperatures are lower, the density of solids is enhanced with condensed ices and the embryos may be capable of reaching about 10 Earth-masses ($M_\oplus$) in $\sim 10^6$ years. Upon reaching this mass the bodies may begin accumulating $\sim 10^2$ $M_\oplus$ of disk gas to form giant planets like Jupiter and Saturn in $\sim 10^7$ years. This is the "core-accretion" mechanism of giant planet formation [1]. An alternative to core-accretion is the "disk instability" mechanism of giant planet formation [2]. Disk instability bypasses the three stage process of core-formation, allowing giant planets to form rapidly ($\sim 10^3$ years) via gravitational collapse of large clumps in a protoplanetary disk. With such an origin, gas giant planets would predate the formation of terrestrial planets.

The uncertainty about whether giant planets pre-date or post-date formation of terrestrial planets complicates the three-stage standard model of terrestrial planet formation because it may not be easily adaptable to systems perturbed by pre-existing giant planets. A similar problem occurs when considering the case for planet formation in multiple-star systems. As examples of the perturbed environments that planets are known to have formed in consider the two systems Gliese 86 [3] and Gamma Cephei [4]. Each of these systems hosts a giant planet — Gliese 86 is orbited by one on a tight 16 day orbit while $\gamma$ Ceph has a more distant one on an orbit at 2.1 AU. Each of these systems also contains another more massive companion orbiting at just 20 AU — at Gliese 86 it is a 40-70 Jupiter-mass brown dwarf while at $\gamma$ Ceph it is a 0.4 solar-mass M dwarf star.

Our goal is to study planet formation in perturbed systems where planetesimal growth occurs under the influence of massive companions, either pre-existing giant planets (e.g., Jupiter and Saturn in our own solar system) or additional stars (e.g., Gamma Cephei). Figure 1 shows an idealized illustration of the difference between planetesimal distributions in unperturbed and perturbed systems. In the unperturbed system on the left all orbits have identical eccentricity (0.2) and inclination (10°), but randomly oriented longitudes of pericenter and ascending node. This leads to a symmetrical toroidal shaped distribution with inner boundary defined by a circle with radius equal to the pericenter distance and outer boundary defined by a circle with radius equal to the apocenter distance. In the unperturbed edge-on cross-sectional view the planetesimal distribution is symmetrical with respect to the disk midplane and the limits in latitude are defined by the inclination of the orbits.

The situation in the perturbed system on the right is dramatically different. Here there are additional components of the orbital elements arising from the forced perturbations of the companion star. The proper elements are identical to those used in the left panels, but now we have added a forced eccentricity (0.4), forced inclination (3°), and forced longitudes of pericenter ($\tilde{\omega}_f$) and ascending node ($\Omega_f$). The resulting toroidal distribution is no longer symmetrical, now having inner and outer boundaries defined by ellipses that are dependent on the proper and forced orbital elements. The edge-on cross-sectional view in the perturbed system is more complicated as well.

Note that the illustration in Figure 1 represents only a single semi-major axis and a single size planetesimal. A further complication is that planetesimals with different semi-major axes and/or different sizes will have different forced elements, with the size dependence caused by the damping effect of nebular gas drag. Evolution of the entire ensemble of planetesimals must then be modeled, and this is traditionally done with either direct $N$-body integration or a statistically based "particle-in-a-box" technique.

Full-scale $N$-body simulations of accretion in a perturbed protoplanetary disk would need to include not only the massive companions, but also mutual gravitational perturbations of the planetesimals, gas drag from the circumprimary disk, and fragmentation as well as accretion. Some $\sim 10^{14}$ km-sized planetsimals would be required to form a single Earth-mass planet over time scales spanning about $10^7$ years. Currently direct $N$-body integrations of this type are limited to $\sim 10^3$ bodies. The limitation on the number of bodies means that direct integrations must start with large bodies, presupposing that they could form in the first place. Collisional fragmentation is not feasible either, as this would multiply the number of bodies beyond any reasonable limit. The limited size range means that phenomena that affect small bodies, such as gas drag and dynamical friction (the tendency toward equipartition of kinetic energies among bodies of different masses) cannot be included in a realistic manner.

We have chosen to pursue the statistical approach by utilizing the multizone accretion code developed at the Planetary Science Institute [5]. This code can treat a much wider range of particle sizes than is possible with $N$-body codes, allowing realistic modeling of systems evolving with fragmentation/erosion. Processes that affect small bodies, such as gas drag and collisional damping, can be modeled realistically. The code divides a swarm of planetesimals into a series of zones in semi-major axis (thus the name "multizone"). Within each zone, the size distribution is represented by a statistical continuum of bodies at small sizes, while above a selected threshold size they are treated individually. Each continuum bin has mean values of eccentricity and inclination, with an assumed range about that mean. Discrete large bodies have individual masses, semi-major axes, eccentricities, and inclinations.

Perturbations from massive companions are incorporated into the code using analytical secular perturbation theory [6]. Algorithms were developed to follow the evolution of forced orbital elements in each semi-major axis zone and for planetesimals in each size bin (if size dependent effects such as gas drag are used). These new secular perturbation algorithms can account for multiple companions acting on each other as well as the planetesimal swarm. While the forced orbital elements are determined by these new algorithms the proper elements are modeled as in the original code, using statistical techniques to account for gravitational stirring, dynamical friction, gas drag, collisions, and ejection of fragments. The overlap of planetesimal orbits as well as the velocity and rate of collisions are determined using the total osculating orbital elements by combining the forced and proper components.

The original version of the multizone code assumes uniform distribution of angular elements (longitudes of pericenter and node). The new version allows for alignment of orbits arising from the forced angular elements. Orbital alignments affect collision rates and impact velocities, may determine rates of growth of terrestrial planets, or indeed whether than can form at all in the presence of massive companions. Our goal is to use the new code to provide more realistic constraints on accretion in such systems.

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[1] Pollack *et al., Icarus* **124**, 62–85, 1996; [2] Boss, *Science* **276**, 1836–1839, 1997; Mayer *et al., Science* **298**, 1756–1759, 2002; [3] Els *et al., A&A Letters* **370**, 1–4, 2001; Eggenberger *et al.,* In *Scientific Frontiers in Research on Extrasolar Planets* (Deming D., Seager S., Eds.), ASP Conf. Series, 2003; [4] Cochran *et al.,* 34th DPS Meeting, Abstract #42.02, 2002; Hatzes *et al., Ap.J.* **599**, 1383–1394, 2003; [5] Weidenschilling *et al., Icarus* **128**, 429–455, 1997; [6] Murray & Dermott, Solar System Dynamics, Cambridge Univ. Press, 1999.

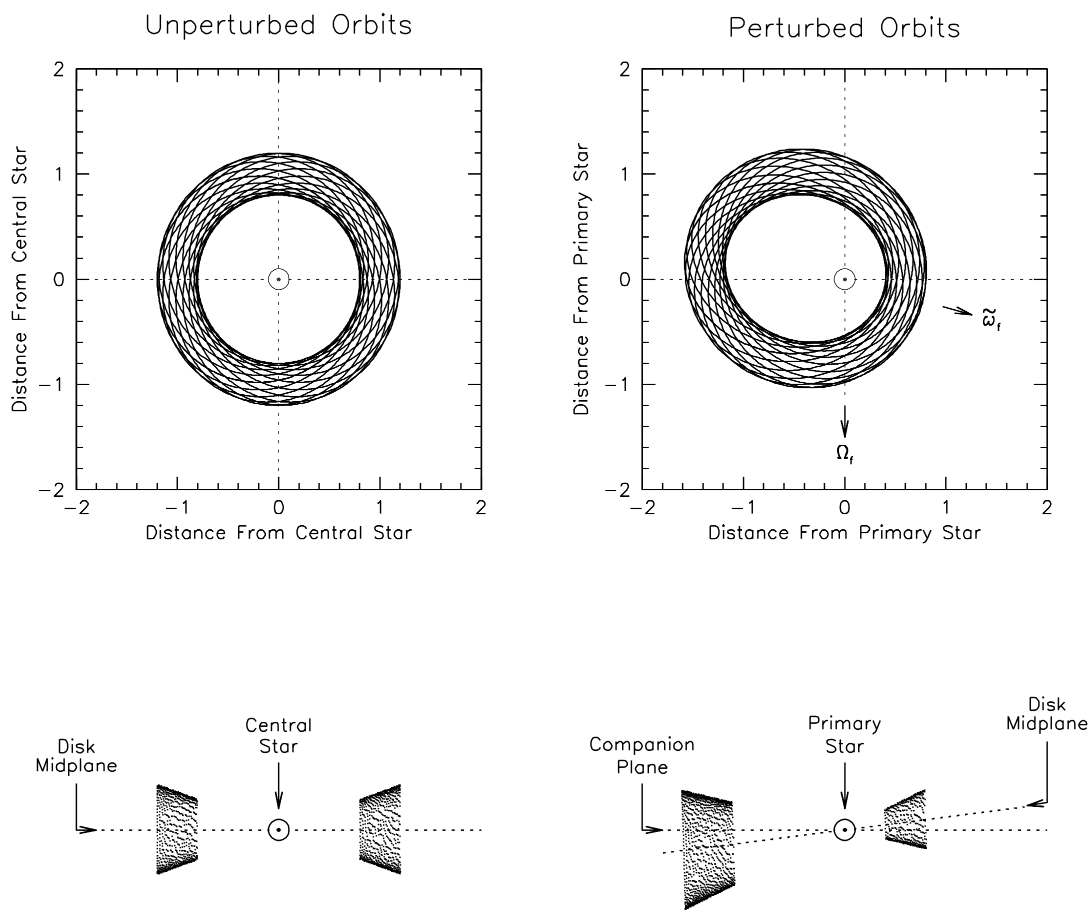


Figure 1: Demonstration of the orbital distribution of planetesimals in an unperturbed system (left panels) and a perturbed system (right panels). All orbits have arbitrary unit value in semi-major axis. The top panels show orbits projected onto the X-Y plane while the bottom panels show a cross-section viewed edge-on from the negative Y direction, where the cross-section is taken perpendicular to the viewing direction. Values of proper and forced eccentricities and inclinations were chosen for illustrative purposes only.