The Astrophysics of Planetary Systems: Formation, Structure, and Dynamical Evolution
Proceedings IAU Symposium No. 276, 2010
A. Sozzetti, M. G. Lattanzi & A. P. Boss, eds.

doi:10.1017/S1743921311020989

Evolution of planetary systems in dissipating gas disks

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Abstract. In a recently published paper Matsumura *et al.* (2010) (hereafter M10), we have studied the evolution of three-planet systems in dissipating gas disks by using a hybrid N-body and one-dimensional gas disk evolution code. In this article, we highlight some results which are only briefly mentioned in M10.

Keywords. methods: n-body simulations, planetary systems: protoplanetary disks, planetary systems: formation

For the details of initial conditions and the code we use, please refer to M10.

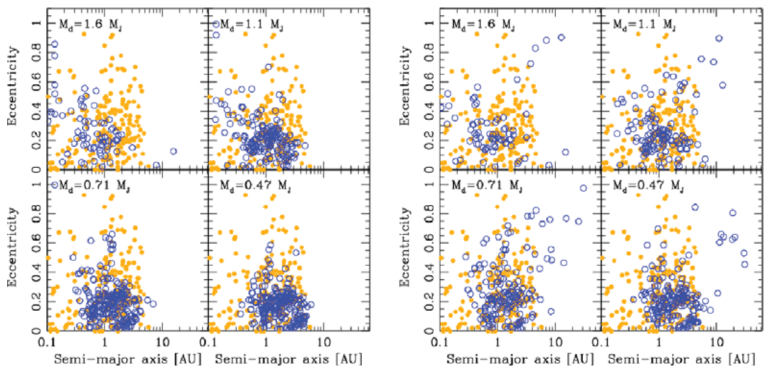

Figure 1. Distribution of observed planets (orange circles) compared with that of our simulations (blue circles) at τ_{GD} (left) and at 100 Myr (right). Evolutions of 100 three-planet systems in various initial disk masses are shown.

In Fig. 1, we compare the distribution of observed planets with that of our simulations at the disk's dissipation time τ_{GD} and at the end of the simulations 100 Myr. We find that the semimajor axis (a) distributions at τ_{GD} and 100 Myr are similar to each other. This supports the expectation that the a distribution of exoplanets is largely determined by planet–disk interactions. Additionally, more massive disks lead to more efficient migration. In contrast to the a distributions, we find that the eccentricity (e) distributions are very different at τ_{GD} and 100 Myr — most planets have $e < 0.2$ at τ_{GD} while the eccentricity distribution is more diverse at 100 Myr, similar to the observed planets. Thus, eccentricity distribution appears to be largely determined by planet–planet interactions after the disk's dissipation. From these results, we can verify the initial conditions used by previous N-body studies without gas disks. Chatterjee *et al.* (2008) and Ford & Rasio (2008) assumed that planets are initially beyond the ice line, on nearly circular orbits.

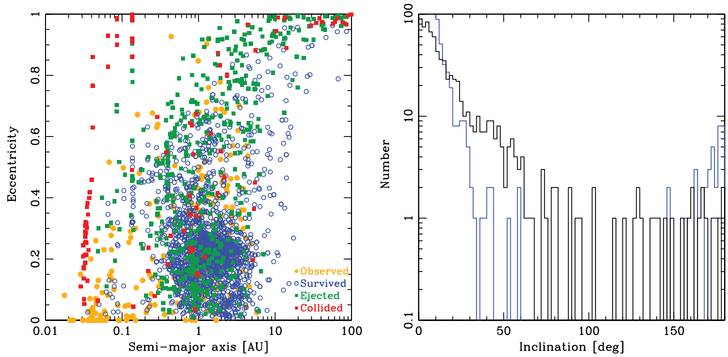

Figure 2. Left: $a - e$ scatter plot of 2000 simulations. Right: corresponding inclination distribution of survived planets (blue) and removed planets (black).

Our results indicate that their initial eccentricity assumption is reasonable, but the semi-major axis distribution may be too conservative. Jurić & Tremaine (2008) studied various initial conditions and found that initially dynamically active systems with a wide range of eccentricity can successfully reproduce the observed eccentricity distribution for $e > 0.2$. We cannot directly compare our results with those of Jurić & Tremaine (2008), because we focus on three-planet systems while they considered up to fifty-planet systems. Having this difference in mind, our results indicate that it is difficult to have dynamically active systems with a wide range of eccentricities at the end of disk dissipation.

In the left panel of Fig. 2, we show the $a - e$ scatter plot for all the simulations at 100 Myr. Also plotted are the final-recorded orbits for planets which are either ejected from the systems, or came too close to the central star (within 0.02 AU, marked with "collided" in the plot). Our simulated results agree well with the observed properties. In the right panel of Fig. 2, we plot the corresponding inclination distribution for survived (blue) and removed (black) planets. Note that most of our planets are on prograde orbits. In fact, only about $\sim 2\%$ of planets are on retrograde orbits. N-body simulations without gas disks done by C08 lead to a similar fraction of retrograde planets (contribution of Chatterjee *et al.* in this volume). These values are much smaller than what is expected from the observations of close-in planets (e.g., Triaud *et al.* 2010). Nagasawa *et al.* (2008) studied evolution of three Jupiter-mass planets with tidal dissipation and without a gas disk, and showed that planet–planet scatterings could also initiate Kozai migration (e.g., Fabrycky & Tremaine 2007; Naoz *et al.* 2010). Their results show a much flatter distribution of orbital inclinations, with more retrograde planets. If planet–star tidal interactions had been included in our simulations, at least some of our "ejected" or "collided" planets could have survived, creating more retrograde planets.

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