

Can Terrestrial Planets Form in Hot-Jupiter Systems?

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Abstract. Models of terrestrial planet formation in the presence of a migrating giant planet have challenged the notion that hot-Jupiter systems lack terrestrial planets. We briefly review this issue and suggest that hot-Jupiter systems should be prime targets for future observational missions designed to detect Earth-sized and potentially habitable worlds.

1. Introduction.

Since the discovery of the first extrasolar planets (Wolszczan & Frail 1992; Mayor & Queloz 1995), astronomical techniques and observational baselines have advanced to the point where over 200 extrasolar planetary systems have been identified (Butler et al. 2006). Most detected exoplanets are in the giant planet mass range and it is now clear that our solar system is but one variant within a great diversity of planetary system architectures. One of the most surprising discoveries has been of a population of giant planets, the so-called *hot-Jupiters*, found orbiting in a region of extreme insolation very close ($r < 0.1$ AU) to their central stars and well within the radius of the original nebular snowline ($r \approx 3 - 5$ AU) where giant planets are thought to form (Pollack et al. 1996). Hot-Jupiters are not uncommon: they amount to about a quarter of exoplanet discoveries, and are thought to provide evidence that protoplanets can migrate over large radial distances via tidal interactions with the protoplanetary disk (e.g. Lin & Papaloizou 1986; Lin et al. 1996; Ward 1997; Nelson et al. 2000). Since the disk gas is observed to disperse within the first few Myr of the system's existence (Haisch et al. 2001), giant planets must form and migrate through the inner system within this period, which is considerably less than the $\sim 10-100$ Myr thought to be required to complete terrestrial planet formation (Chambers 2001; Kleine et al. 2002; Halliday 2004; O'Brien et al. 2006).

Test particle studies have shown that terrestrial planets external to a hot-Jupiter would have stable orbits (Jones et al. 2005), and Raymond et al. (2005) have shown that they should be able to form, in the presence of a giant planet already at ~ 0.1 AU, from any available pre-planetary material with a period ratio roughly > 3 . However, until recently it has been a common assumption that terrestrial planets could not have formed in hot-Jupiter systems due to the disruptive effect of the giant planet's migration which is deemed to have cleared the inner system of planet-forming material (e.g. Armitage 2003), prompting claims that the observed abundance of hot-Jupiters could be used to constrain the general abundance of habitable planets (Ward & Brownlee 2000), and even their galactic location (Lineweaver 2001).

This picture has been challenged by the work of two groups who have modeled terrestrial planet formation concurrently with, and following, an episode of giant planet migration (Fogg & Nelson 2005, 2006, 2007a,b; Raymond et al. 2006; Mandell et al. 2007). Their findings suggest that inner system solids disks are *not* destroyed by the intrusion of a migrating giant planet and that terrestrial planet formation can resume in the aftermath and run to completion.

In this paper, we briefly describe our model of terrestrial planet formation and show some typical results.

2. The Model

We picture our model systems to be composed of an inner system solids disk, at its oligarchic growth stage (Kokubo & Ida 1998), extending between 0.4 – 4.0 AU, with its initial parameters being those of a classic minimum mass solar nebula (MMSN) model (Hayashi 1981), scaled up in mass by a factor of 3. This disk is embedded in the nebular gas which depletes over time by accreting onto the central star. We generate a number of different scenarios by allowing planetary growth to proceed in the inner disk for between 0.1 – 1.5 Myr before placing a $0.5 M_{\text{Jup}}$ giant planet at 5.0 AU and allowing it to migrate inward. We end the migration episode when the giant planet reaches 0.1 AU. Since our giant is massive enough to open up a gap in the gas disk, we are specifically assuming the operation of type II migration, where the planet is locked into the viscous evolution of the gas and migrates inward in step with its radial motion (e.g. Lin & Papaloizou 1986; Lin et al. 1996; Ward 1997; Nelson et al. 2000).

We use a modified version of the *Mercury 6* hybrid-symplectic integrator to perform our calculations (Chambers 1999), and run it as an $N + N'$ simulation, where we start with N protoplanets embedded in a swarm of N' “super-planetesimals”. These latter objects are tracer particles with masses a tenth of the initial masses of protoplanets that act as an idealized ensemble of a much larger number of real planetesimals and are capable of exerting realistic dynamical friction on larger bodies (e.g. Thommes et al. 2003). The central star, giant planet, and protoplanets interact gravitationally and can accrete and merge inelastically with all other bodies. Super-planetesimals however are non-self-interacting but subject to gas drag equivalent to that experienced by a single 10 km radius planetesimal. Details of these aspects of our model are given in Fogg & Nelson (2005).

We calculate the evolution of the nebular gas using a 1-D viscous disk model, with an alpha viscosity of $\alpha = 2 \times 10^{-3}$, that solves numerically a modified viscous gas disk diffusion equation that includes the tidal torques exerted by an embedded giant planet (Lin & Papaloizou 1986; Takeuchi et al. 1996) and have described its implementation in Fogg & Nelson (2007a). The gas responds over time by draining via viscous accretion onto the central star; opening up an annular gap centered on the giant planet’s orbit; and forming a partial inner cavity due to dissipation of propagating spiral waves excited by the giant planet. The back reaction of these effects on the giant planet is resolved as torques which self-consistently drive type II migration.

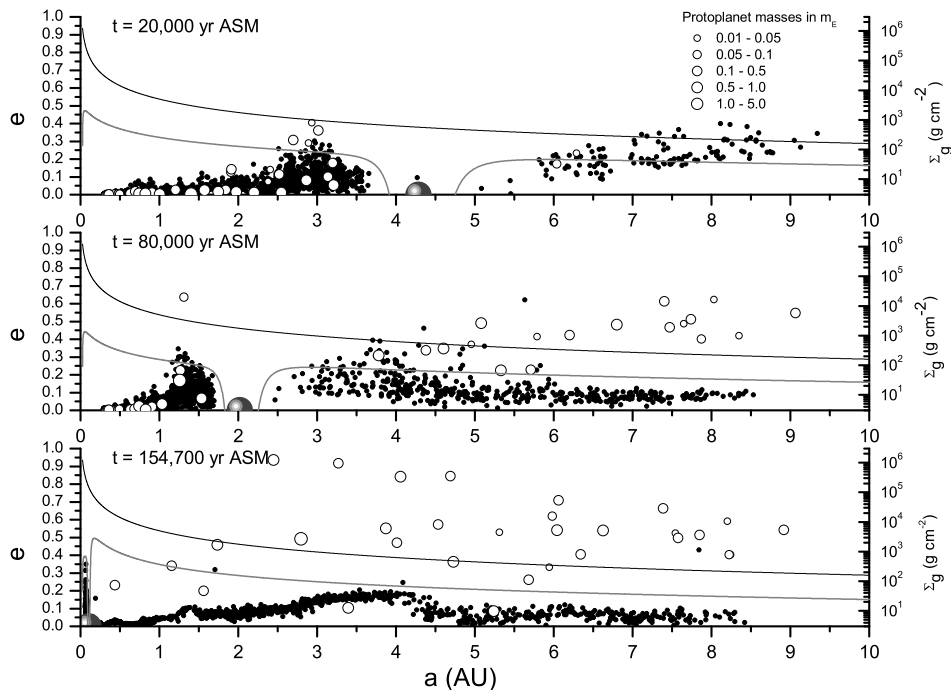


Figure 1. Details of a migration scenario through a 1 Myr old inner disk. The three panels, from the top down, show the system at 20 000, 80 000 and 154 700 years after the start of giant planet migration (ASM). Eccentricity of objects is plotted vs. semi-major axis and is read from the left hand axes. Black dots are super-planetesimals, grey or white circles are protoplanets, and the large highlighted circle is the giant planet. Gas surface density is read from the right hand axes, with the upper black curve being the initial profile for a $3\times$ MMSN and the lower grey curve being the current evolved profile.

3. An Example Scenario.

We illustrate the behavior of one of our scenarios in Fig. 1, where the system has been previously evolved for 1 Myr before the appearance of the giant planet and the start of its migration. Three time slices from within the migration episode are shown in the three panels: the lowest panel showing the point at which the giant planet halts at 0.1 AU, 154 000 years after the start of migration.

The results show that the passage of the giant does not sweep the inner system clear of planet-forming material. Instead, the giant planet shepherds the solids disk inward, compacting it and exciting the orbits of objects captured at mean-motion resonances. Much of this excited material eventually experiences a close encounter with the giant planet and is expelled into an exterior orbit, augmenting a new disk of solid material that progressively builds up in orbits external to the final position of the hot-Jupiter. In this particular case, 86% of the solids disk survives, with 82% of it residing in the external scattered disk.

Mass loss is modest and mostly occurs via accretion onto the giant planet. The effect of the giant's passage is therefore not the elimination of the inner system disk, but instead a modest dilution and strong excitation of solid material and a radial mixing that drives volatile-rich material inward. This outcome is robust to considerable variation of model parameters, such as the mass of the giant and the timing of its formation and migration. The results of further simulation of accretion in this scattered disk show that the initially eccentric orbits of protoplanets are rapidly damped and circularized via dynamical friction exerted by smaller bodies and possibly via tidal drag exerted by the remaining gas (Fogg & Nelson 2007b). Planetary growth resumes and over the following $\sim 10 - 100$ Myr gives rise to a set of water-rich terrestrial planets in stable orbits external to the hot-Jupiter (see also Raymond et al. 2006; Mandell et al. 2007).

4. Conclusions.

Our models predict that terrestrial planets might be routinely expected in hot-Jupiter systems, including within their habitable zones, and may be detectable by forthcoming missions such as Kepler, Darwin, SIM PlanetQuest and TPF.

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