



Migration and Evolution of Extrasolar Planets

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Abstract. Giant planets in circumstellar disks can migrate inward from their initial (formation) positions at several AUs. Inward radial migration of the planet is caused by torques between the planet and the disk; outward radial migration of the planet is caused by torques between the planet and the spinning star, and by torques due to Roche lobe overflow and consequent mass loss from the planet. We present self-consistent numerical considerations of the problem of migrating giant planets by summing torques on planets for various physical parameters of the disk and of planets. We find that Jupiter-mass planets can stably arrive and survive at small heliocentric distances, thus reproducing observed properties of some of the recently discovered extra-solar planets. The range of fates of massive planets is broad, and some perish by losing all their mass onto the central star during Roche lobe overflow, while others survive for the lifetime of the central star. Surviving planets cluster into two groups when examined in terms of final mass and final heliocentric distance: those which have lost mass and those which have not. Some of the observed extrasolar planets fall into each of these two exclusive classes. We also find that there is an inner boundary for planets' final heliocentric distances, caused by tidal torques with the central star. Planets in small orbits are shown to be stable against atmospheric loss.

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1 Introduction

The recent discoveries (Mayor & Queloz 1995; Marcy & Butler 1996; Butler & Marcy 1996; Butler et al. 1997; Cochran et al. 1997; Noyes et al. 1997) of extrasolar planets have revitalized discussions on the theory of planetary system formation and evolution. We have studied how giant planets can end up at small heliocentric distances with Jovian masses. Jupiter-mass plan-

ets can migrate inward from their formation locations (see, for example, Goldreich & Tremaine 1980; Ward & Hourigan 1989; Lin & Papaloizou 1986; Lin & Papaloizou 1993; Lin, Bodenheimer, & Richardson 1996; Trilling et al. 1998; Murray et al. 1998). We have considered under what physical conditions planets may migrate inward, as well as how, where, why, and when a planet will stop its inward migration. A brief summary of our model is included here, followed by discussion of results and planetary atmospheric stability.

2 Brief Summary of the Model

Our general model is to sum up the torques on a planet and find its radial motion in the circumstellar disk. A more complete discussion of our model and results is given in Trilling et al. (1998). To summarize, we compute, in a self-consistent one dimensional model, torques on a planet due to disk interactions (inward for the parameters which we adopt); torques on a planet due to interactions with the rapidly-spinning star (outward); and torques on the planet due to mass loss onto the star (outward for the conservative mass transfer case).

A giant planet orbiting in a circumstellar disk opens a gap in the disk and sends spiral density waves traveling away from the planet. Interactions of these density waves at the planet's Lindblad resonances cause exchange of angular momentum between the planet and the disk; this angular momentum exchange results in a change of orbital distance of the planet. This we refer to as the planet-disk interactions; for the parameters we adopt, this migration is always inward. The tidal planet-star interaction is directly analogous to the tides in the Earth-Moon system: tidal bulges are raised on the central body by the orbiting body. When the tidal bulges lead the line of centers between the two bodies, the central body is slowed and the orbiting body feels a torque which causes it to move away from the cen-

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tral body. The last torque we consider is the process of Roche lobe overflow from the planet onto the central star. This occurs when the planet's radius is larger than the Roche radius. Some mass is transferred onto the central star, and the planet moves outward, to conserve angular momentum. This is the mass loss torque. We compute the magnitude of each of these torques at every time step, as well as computing the planet's radius, making these calculations self-consistent and representative of physical planets, not just point masses. These calculations of these torques are described in more detail in Trilling *et al.* (1998).

Massive planets migrate smoothly as a result of the net torques on the body. We find three broad classes for massive planets: (I) planets which migrate inward very quickly and disappear due to mass loss from Roche lobe overflow; (II) planets which migrate inward, lose some but not all of their mass, and stably survive at small heliocentric distances; and (III) planets which do not lose any mass during migration. Some planets in class III move radially only a small distance from their formation locations. In the context of this picture, massive close companions can result from a variety of initial conditions, and form a population which overlaps with and includes the detected close companion population. Our distribution of final masses and heliocentric distances predicts that massive planets can be present at any heliocentric distance between their formation locations and extremely small orbits.

3 Results and Discussion

The general result of our model is that planets migrate inward from their formation locations, sometimes quite rapidly, and that many planets which form do not survive, having lost all their mass onto their central stars. Figure 1 shows the results of migration models for planets in our nominal disk, with heliocentric distance shown as a function of time. The nominal disk has a disk lifetime of 10^7 years, based on observational evidence (Zuckerman *et al.* 1995); we also use the α viscosity prescription of Shakura & Sunyaev 1973) with an α value of 5×10^{-3} ; Q_* of 1.5×10^5 , where Q_* is the tidal dissipation factor for the star (after Lin *et al.* 1996); disk mass of $1.1 \times 10^{-2} M_\odot$, from observation (Béckwith & Sargent 1993); and a stellar despin timescale of 10^8 years (Skumanich 1972). These values are varied from nominal for our various disks. Migration timescales are a few times 10^6 years. For planets in class III, the dominant effect is that the planets clear a large gap in the disk on a timescale shorter than the migration timescale, so that the inward disk torque is very small, and the planets do not move very far. In general, larger planets are generally not found at small heliocentric distances, although deviations from the nominal disk do allow for this to happen. Planets' inward motions are slowed by

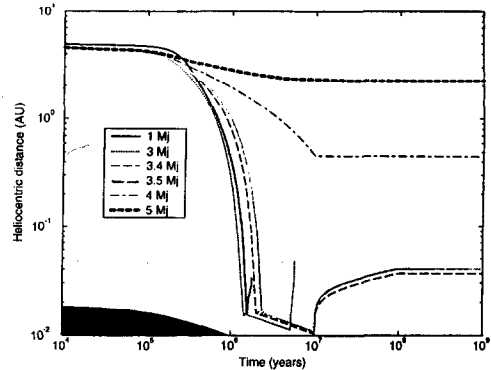


Fig. 1. Heliocentric distance versus time, for various initial masses, in the nominal disk. Evident here are all three classes: class I, which lose all their mass ($\leq 3.36 M_J$); class II, with initial masses $3.36 M_J < M_p < 3.41 M_J$; and class III, with initial masses $\geq 3.41 M_J$. See text for discussion of these three classes. The outward motion of the surviving planets between 10^7 and 10^8 years is because the (outward) tidal torque is the only torque acting on the planets during this time. The shaded region in the lower left represents the radial extent of the central star.

outward tidal torques, seen as the region at small heliocentric distances with significantly shallower, but still negative, slopes. Planets' inward motions are reversed if the planetary radius exceeds the Roche radius and mass loss begins.

The aggregate results of our orbital migration model are shown in comparison to the observed extrasolar planets in Figure 2. This is not meant to be a complete parameter study, but rather focuses in particular on cases interesting to extrasolar planets and to Jupiter. There are no class I planets in this figure, since they all lose all their mass onto the star and do not survive. Class II planets (open circles) are shown, and are similar to 51 Peg b and ν And b. The remaining model planets are in class III, planets which do not lose any mass during their evolution; τ Boo b, 55 Cnc b, ρ CrB b, 47 UMa b, and Jupiter fall within the population of this class. These planets may not have migrated far, and Jupiter has probably moved radially < 1 AU from its formation location. Not shown are the extrasolar planets with high eccentricities (16 Cyg Bb, 70 Vir b), as our model does not produce planets in highly eccentric orbits. In these systems, it is likely that some post-migration dynamical processing has taken place (e.g., Cochran *et al.* 1997; Lin & Ida 1997).

The solid line in Figure 2 represents an inner boundary for close planetary companions. The slope of this line is governed by the tidal torque between the planet and the central star: this torque has an outward sense, and a magnitude proportional to the mass of the planet (yielding the positive slope in mass-distance space). This slope corresponds to a Q_* of 1.5×10^5 , where Q_* is the tidal dissipation factor for the star. There are three parallel trends with this slight positive slope, corresponding

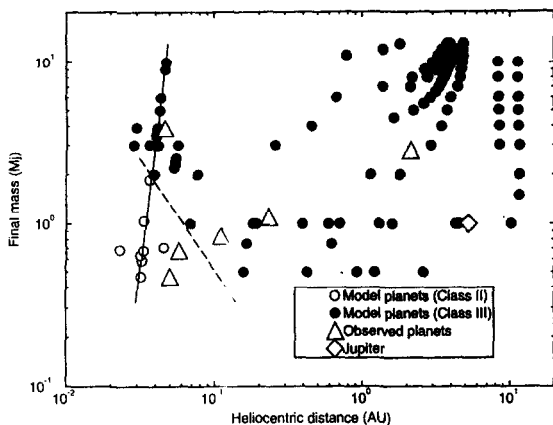


Fig. 2. Final mass versus heliocentric distance, for model runs plus observed extrasolar planets. This figure includes results from many model runs with different physical parameters varied, but is not meant to be an evenly gridded or complete parameter study. Initial masses are integers between 1 and $13 M_J$, and also 0.5 and $0.75 M_J$ for several sets of parameters. Open circles show planets which lose some mass during their migration, but survive (class II). Filled circles indicate models in which the planet does not lose any mass during its evolution and migration (class III). Triangles show observed extrasolar planets. We find a wide range of final heliocentric distances and masses for migrating planets. The preponderance of models which have final masses of $1 M_J$ reflects an excess of model runs with this initial mass, in order to study Jupiter's evolution. The curving trends of planets at $> 5 M_J$ and > 1 AU represent planets which are massive enough to clear their disks before they can migrate inward very far. More massive planets clear their disks more quickly, so that the most massive planet in our models, $13 M_J$, has a final heliocentric distance which is only a few percent different than its starting position. In general, more massive planets do not move as far, although we have several examples of large ($> 5 M_J$) planets at small heliocentric distances, due to migrations in disks with varying disk masses or viscosities. The solid line represents an inner tidal limit. The dashed line represents the boundary between surviving planets which have lost mass and those which have not. Observed planets included are the following: 51 Peg b, ν And b, 55 Cnc b, ρ CrB b, 47 UMa b, and τ Boo b. Jupiter is the diamond at 5.2 AU and $1 M_J$. Importantly, two (51 Peg b, ν And b) of the observed extrasolar planets are found within the region of planets which have lost mass during their evolution. See text for discussion.

to the three different Q_* values used in our study (Q_* greater than and less than nominal by factors of ten). Systems in which the tidal torque is active long after the other torques, and which have Q_* within the range considered in this work, should not have planets inward of this inner limit, and this late tidal outward evolution has the effect of erasing any locational signatures of previous evolutionary stages. There is also a very late inward migration, typically much longer timescales than the age of a main-sequence star (Rasio *et al.* 1996), which we do not consider.

The dashed line in Figure 2 delineates a cutoff between class II and class III planets. There are no class II planets, in $M_f - a_f$ space, above and to the right of this line; and there are no class III planets below and to the left of this line. This segregation is found over a wide range of disk parameters. Therefore, we suggest that observed planets within this region likely are class II planets, having lost some but not all of their mass. This region includes 51 Peg b and ν And b. Therefore, we believe that our model is important in understanding the evolution of extra-solar planets, since two planets fall within the region where mass loss almost certainly is important.

We also show in Figure 2 that planets can be found at a range of heliocentric distances and masses. Because of planetary migration, there is no such thing as a "sacred" region for giant planets, that is, a span of heliocentric distances which represents the only possible location for giant planets. Instead, giant planets can be found at any distance from their formation distance in to several stellar radii (inward of that the planets are unstable to mass loss and cannot survive). The discovery of giant planets at a range of distances, and the subsequent modeling which has shown how this is possible, have changed the paradigm of the early solar system from a relatively quiescent model to a dynamic one in which large ranges of heliocentric distances are covered by giant planets. Similarly, masses between 1 and 5 Jupiter masses are all likely, if planets of all these masses can be created. The population of giant planets is likely much more diverse than was expected before the first announcement of extrasolar giant planets.

4 Stability of Close Planet Atmospheres

The presence of planets extremely close to their central stars raises the question of atmospheric stability against the solar wind. Guillot *et al.* (1996) studied this problem initially, showing that atmospheric mass loss from 51 Peg b is small; here, we re-examine atmospheric stability in greater detail. Atmospheric mass loss may take place either through classical Jeans evaporation or through nonthermal production of ions by absorption of UV flux from the central star. Guillot *et al.* showed that classical Jeans escape is negligible

for planets at 0.05 AU. In our model, however, planets can migrate inward of this distance, thereby increasing the heating from the central star. Furthermore, we now explicitly include planetary evolution (e.g., change in planetary radius) in the Jeans escape calculations. However, even considering migration and the details of planet evolution, Jeans escape is still small, and therefore is a negligible mass loss process.

Non-thermal production of ions and consequent mass loss presents a more complex issue. Guillot *et al.* scaled the current UV flux at Jupiter to a heliocentric distance of 0.05 AU, and found that mass loss was less than 1% of the planet's total mass over the lifetime of the planet. However, the young sun had a UV flux which was 3 to 4 orders of magnitude more intense than the current solar UV flux (Canuto *et al.* 1982). We incorporate this increased UV flux into our migration model and find that non-thermal mass loss could become important, by the simple scaling argument, with more than 10% of the planet's mass lost through hot ion production and escape. However, as shown by Hunten & Watson (1982), the actual rate of escape is limited by heat exchange into the region where mass loss is taking place. By applying the heat balance arguments of Hunten & Watson, we find that for all reasonable cases of planetary migration and evolution, the mass lost is always less than 0.1% of the planet's mass. Therefore, non-thermal escape of a close planet's atmosphere is, as stated in Guillot *et al.*, almost certainly negligible, though for the reasons stated here.

5 Conclusions

Planets in circumstellar disks are subject to various torques which can cause the planets to migrate inward. We present results from a self-consistent quantitative model which describes evolution and migration of giant planets. Some planets migrate very rapidly and disappear due to mass loss in less time than the disk lifetime. Other planets or planets under other disk conditions can be left in various orbits, from very close to the star to very close to where they started, and with masses equal to or less than their initial masses. There is a wide range of possible fates (heliocentric distance and final mass) for migrating Jupiters. A migrating planet may survive, possibly without moving radially very far. Other migrating planets lose all their mass due to Roche lobe overflow. There exists a region of $M_f - a_f$ space

populated *only* by planets which have lost mass and including 51 Peg b and ν And b. All observed extrasolar close companions fall within the population of surviving planets in our model, suggesting that this mechanism may explain the presence of planets very close to their stars. We also find an inner boundary created by late outward tidal torques on the planet. Close companion planets are stable against atmospheric mass loss despite their extreme proximity to their central stars.

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