DISPERING THE GASEOUS PROTOPLANETARY DISK AND HALTING TYPE II MIGRATION

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Received 2003 June 28; accepted 2003 August 22; published 2003 September 16

ABSTRACT

More than 30 extrasolar Jupiter-like planets have shorter periods than the planet Mercury. It is generally accepted that they formed farther out, past the “snow line” (∼1 AU), and migrated inward. In order to be driven by tidal torques from the gaseous disk, the disk exterior to the planet had to contain about a planetary mass. The fact that the planets stopped migrating means that their outer disk was removed. We suggest, following the simulation by Kley and Bate et al., that the outer disk was accreted by the planet. This not only halts migration but removes the outer disk. For planets exterior to about 2 AU, the outer disk could have been removed by photoevaporation (Matsuyama et al.). Furthermore, as also shown by Bate et al., this process also provides an upper limit to planetary masses in agreement with the analysis of observed planetary masses by Zucker & Mazeh.

In this scenario, the endgame is a race. The central star is accreting the inner disk and the planet, while the planet is accreting the outer disk. The planet survives if it accretes its outer disk before being accreted by the star. The winner is determined solely by the ratio of the mass of the outer disk to the local surface density of the disk. Some planets certainly lose the race and are eaten by the central star.

Subject headings: planetary systems: formation — planetary systems: protoplanetary disks

1. INTRODUCTION

Planets whose “Roche radii” are comparable to the disk scale height form a gap in the disk. This was first suggested by Lin & Papaloizou (1986) as the mechanism to limit the growth of Jupiter. It was thought that the gap acted as a semipermeable membrane preventing gas from flowing inward. Because the close-in extrasolar planets had migrated inward and then stopped, they must have had an outer disk and then lost it (see Lecar & Sasselov 1999 for some suggestions how). Following on a hint by Artymowicz & Lubow (1996), Kley (1999) employed detailed two-dimensional disk models to show that mass accretes across a gap onto a planet. Recently, Bate et al. (2003) confirmed this result with detailed three-dimensional simulations. Gas did, indeed, stream across the gap, almost as if the gap was not there. Almost all of the gas was accreted onto the planet.

The accretion of the outer disk by the planet solves two problems: stopping the migration and removing the outer disk. A recent study of removal of the disk by photoevaporation showed that photoevaporation is effective only exterior to 2.4 AU (Matsuyama, Johnstone, & Murray 2003). In the minimum mass solar nebula (Hayashi 1981), there are about four Jupiter masses of gas interior to 2.4 AU. In any case, we have to account for the more than 50 extrasolar planets interior to 1 AU. Since the “snow line” starts at 1 AU, there is a possibility that planets outside of 1 AU formed in place or did not migrate much.

An argument in favor of the planet accreting its outer disk is that it provides a natural upper limit to the masses of planets of 10 Jupiter masses. Zucker & Mazeh (2002) found that to be the upper limit to planetary masses and the lower limit to the masses of brown dwarfs. The formation of gas giants by gravitational instability (Boss 2000) provides no natural upper limit to the masses.

We now discuss in more detail the migration process, following Lin & Papaloizou (1986). We wish to illustrate when migration switches from type I (no gap) to type II (gap; Ward 1997). A planet with semimajor axis $a$ migrates at a rate

$$\dot{a} = -1.74a\Omega_p \mu_p \mu_d I,$$

where

$$\Omega = GM_\odot, \quad \mu_p = \frac{M_p}{M_\odot} \quad \mu_d = \frac{2\pi\Sigma a^2}{M_\odot}. \quad (2)$$

The numerical constant is chosen to match Tanaka, Takeuchi, & Ward (2002). For a minimum mass solar nebula (Hayashi 1981), the surface mass density of the disk is $\Sigma = 1700 \text{ g cm}^{-2}$ at 1 AU, and $\Sigma \propto x^{-5/2}$, where $x = a/\text{AU}$. The dimensionless integral, $I$, is given by

$$\int_{\Delta_{\text{in}}}^{\Delta_{\text{out}}} dx \frac{1 + x)^{5/2}}{x^4} - \int_{\Delta_{\text{in}}}^{\Delta_{\text{out}}} dx \frac{1 - x)^{5/2}}{x^4},$$

where for $\Delta \ll 1$, $I$ is insensitive to the upper limits. If there is no gap, $\Delta_{\text{in}} = \Delta_{\text{out}}$ and $I = (5/2)(1/\Delta^2)$, where $\Delta = h/a = c_s/V$, $V$ is the circular orbital velocity, $c_s$ is the sound speed, and $h$ is the scale height. Typically, $c_s/V \approx 0.06x^{1/4}$.

If there is a gap, the planet moves within the gap to equalize the torques from the inner and outer disks. This is accomplished by

$$\Delta_{\text{out}} \approx \Delta(1 + \frac{3}{4}\Delta), \quad \Delta_{\text{in}} \approx \Delta(1 - \frac{3}{4}\Delta). \quad (4)$$

Henceforth, the planet responds to the inward migration of the outer disk, which is driven by viscosity. Once a gap is opened, the further evolution is controlled by viscous accretion and is referred to as type II migration (Ward 1997).

The mass accretion rate is

$$M_{\text{acc}} = 2\pi\Sigma a \dot{a} \equiv 2\pi\Sigma a^2 \frac{\dot{a}}{a} \equiv 2\pi\Sigma a^2 \frac{1}{t_{\text{acc}}}, \quad (5)$$
which by continuity is independent of $x$. If $\Sigma \propto x^{-3/2}$, then $t_{\text{acc}} \propto x^{1/2}$. The time to accrete a Jupiter mass is

$$t_{M_\text{J}} = \frac{M_\text{J}}{M_{\text{acc}}} = \frac{M_\text{J}}{2\pi \Sigma a^2} t_{\text{acc}}.$$  \hspace{1cm} (6)

If the outer disk has, say, a Jupiter mass, in order for a planet to accrete the outer disk before being swept into the star, we require that

$$t_{M_\text{J}} < t_{\text{acc}}$$ \hspace{1cm} (7)

or

$$\frac{M_\text{J}}{2\pi \Sigma a^2} = \frac{M_\text{J}}{2\pi \Sigma_0 a_0^2 x^{1/2}} < 1.$$ \hspace{1cm} (8)

The migration halts when

$$x^{1/2} > \frac{M_\text{J}}{2\pi \Sigma_0 a_0^2}.$$ \hspace{1cm} (9)

For the minimum mass solar nebula, migration would halt at $x = 0.63$ or the orbital period $P = 183$ days. For denser disks, our estimates (with $\Sigma_{\text{min}} = 1700 \text{ g cm}^{-2} \text{ at 1 AU}$) are given in Table 1. For surface densities larger than $4\Sigma_{\text{min}}$, the planet is accreted by the star.

More quantitatively, if the planet is at $a_0$, the ratio $M_\text{J}/2\pi \Sigma_0 a_0^2$ can be written

$$\int_1^x \frac{dx}{x^{1-n}} = \frac{(x^{1-n})}{2-n},$$ \hspace{1cm} (10)

if $\Sigma(x) = \Sigma(1)x^{-n}$ and $x = (a_0/a_\text{J})$. For the planet to accrete its outer disk before the star accretes the planet, that quantity has to be less than 1.0, or $x < x_m$. This is illustrated in Table 2. For comparison, if $a_\text{J} = 5.203 \text{ AU (Jupiter)}$, Saturn is at $x = 1.83$. If $a_\text{J} = 1 \text{ AU}$, photoevaporation is effective at $x > 2.4$.

So far, we have avoided a discussion of the physical source of the viscosity and the value of $\alpha$ (Shakura & Sunyaev 1973), because our result is independent of this physics. But, to make contact with the literature, we note that with our prescription (also used by Bate et al. 2003), $\alpha \propto \alpha_\text{c} x^{1/2}$, we require $\alpha_\text{c} \leq 3 \times 10^{-4}$ in order that the mass accretion be less than $10^{-8} M_\odot \text{ yr}^{-1}$. This is to limit the accretion luminosity to yield the so-called passive disk (Chiang & Goldreich 1997; Sasselov & Lecar 2000). With this value of $\alpha$, we have $t_{\text{acc}} \approx 10^3 x^{1/2}$ yr, which is short, suggesting that $\alpha_\text{c}$ is smaller. However, as pointed out by Kley (1999), $\alpha$ has to be sufficiently large to force accretion across the gap.

We conclude with some speculations about our Jupiter. In the minimum mass solar nebula, with $\Sigma \propto x^{-3/2}$, there is about 2.7 Jupiter masses of gas between Jupiter and Saturn. Clearly, Jupiter (and Saturn) did not accrete it all. However, the investigation of photoevaporation of the outer disk was motivated by the fact that Saturn has only one-third the mass of Jupiter, and in any case, $x^{-3/2}$ yields a divergent mass (proportional to $x^{1/2}$). The surface density profile must steepen. If we keep the minimum mass surface density at Jupiter (143 g cm$^{-2}$) but allow the surface density to decrease outward at a steeper rate, say, $x^{-1/2}$, then there is less than a Jupiter mass between Jupiter and Saturn. If we allow Jupiter to start accreting when its mass was $0.1M_\odot$, as suggested by Bate et al. (2003), then the outer disk is in Jupiter.

We are grateful to the anonymous referee for helpful suggestions.

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