MIGRATION OF EXTRASOLAR PLANETS: EFFECTS FROM X-WIND ACCRETION DISKS

Fred C. Adams1,2, Mike J. Cai1,3, and Susana Lizano1,4
1 Michigan Center for Theoretical Physics, Physics Department, University of Michigan, Ann Arbor, MI 48109, USA
2 Astronomy Department, University of Michigan, Ann Arbor, MI 48109, USA
3 Academia Sinica, Institute of Astronomy and Astrophysics, Taiwan
4 Centro de Radioastronomía y Astrofísica, UNAM, 58089 Morelia, Michoacán, Mexico

Received 2009 July 3; accepted 2009 August 10; published 2009 August 24

ABSTRACT
Magnetic fields are dragged in from the interstellar medium during the gravitational collapse that forms star/disk systems. Consideration of mean field magnetohydrodynamics in these disks shows that magnetic effects produce sub-Keplerian rotation curves and truncate the inner disk. This Letter explores the ramifications of these predicted disk properties for the migration of extrasolar planets. Sub-Keplerian flow in gaseous disks drives a new migration mechanism for embedded planets and modifies the gap-opening processes for larger planets. This sub-Keplerian migration mechanism dominates over Type I migration for sufficiently small planets (m_p ≲ 1 M_☉) and/or close orbits (r ≲ 1 AU). Although the inclusion of sub-Keplerian torques shortens the total migration time by only a moderate amount, the mass accreted by migrating planetary cores is significantly reduced. Truncation of the inner disk edge (for typical system parameters) naturally explains final planetary orbits with periods P ~ 4 days. Planets with shorter periods, P ~ 2 days, can be explained by migration during FU-Orionis outbursts, when the mass accretion rate is high and the disk edge moves inward. Finally, the midplane density is greatly increased at the inner truncation point of the disk (the X-point); this enhancement, in conjunction with continuing flow of gas and solids through the region, supports the in situ formation of giant planets.

Key words: MHD – planetary systems: formation – solar system: formation – stars: formation – turbulence

1. INTRODUCTION
The population of observed extrasolar planets exceeds 350, with many objects found in short-period orbits (Udry et al. 2007). Tremendous progress has been made in our theoretical understanding of the migration mechanisms that allow planets to move (usually inward) as they form (Papaloizou & Terquem 2006, hereafter PT06). Parallel advances have been made in our understanding of star formation processes (Reipurth et al. 2007), which produce the circumstellar disks that provide birthplaces for planets. However, these latter developments have not been fully integrated into theories of planet formation/migration. This Letter explores the implications of the predicted disk properties for planet migration.

During the collapse phase of star formation, magnetic fields are dragged inward and retained by the nascent disk. These magnetic fields, along with those generated by the star, can drive powerful outflows (Blandford & Payne 1982; Shu et al. 1994), provide channels for accretion of disk material onto the star (Bouvier et al. 2007), and produce a back-reaction on the structure (Shu et al. 2007, hereafter S07). In particular, circumstellar disks are predicted to display sub-Keplerian rotation curves. We parameterize the rotation speed of the gas through the ansatz \( \Omega_{\text{gas}} = f \Omega K \), where \( \Omega^2 = GM_\odot/r^3 \). Recent magneto-hydrodynamics (MHD) calculations indicate that \( f \approx 0.66 \) for disks around T Tauri stars and \( f \approx 0.39 \) for disks undergoing FU-Orionis (FU-Ori) outbursts (S07). The relative velocity between the gas and orbiting planets is thus a substantial fraction of the Keplerian rotation speed, and \( f \neq 1 \) over much of the disk.

Planetary migration is altered when the circumstellar gas moves at sub-Keplerian speeds. In Keplerian disks, embedded planets drive wakes into the disk, and asymmetric gravitational interactions of these wakes drive planets inward (Goldreich & Tremaine 1979), a process called Type I migration (Ward 1997a, 1997b). In sub-Keplerian disks, embedded planets orbit with Keplerian speeds and experience a headwind from the gaseous disk (which moves slower). This velocity mismatch results in energy loss from the orbit and inward migration. This Letter explores this mechanism (Section 2), including an assessment of the conditions necessary for it to compete with Type I migration. A weaker version of this effect occurs in nearly Keplerian disks, where \( 1 - f = O(H^2/r^2) \sim 1/400 \), where \( H \) is the disk scale height. The headwind produced by this small departure from Keplerian flow affects dust grains as they coagulate into larger bodies, but does not affect planets (Weidenschilling 1977b). The departures from Keplerian speeds due to magnetic effects are larger by two orders of magnitude.

The second feature of magnetic disks is that their inner edge is truncated. Disk material accretes onto the star by moving along magnetic field lines in a “funnel flow.” In one theory, the disk truncation point, the start of the funnel flow, and the origin point for outflows occur at a location known as the X-point (Cai et al. 2008, hereafter C08). This “point” has a finite extent, comparable to the disk scale height. In competing theories, the wind originates from an extended disk region (Pudritz & Norman 1983), but the disk retains an inner truncation point; disk wind models also predict sub-Keplerian flow, which might inhibit wind launching (Shu et al. 2008). Because the disk does not extend to the star, migration is naturally halted at the truncation point \( r \sim 0.05 \) AU, as recognized (Lin et al. 1996) soon after the discovery of extrasolar planets (Mayor & Queloz 1995; Marcy & Butler 1996). This Letter argues that observed ultra-short-period planets \( P \sim 1 - 2 \) day, \( r \sim 0.02 \) AU can be understood through disk truncation at the X-point combined with FU-Ori outbursts (Section 3).

2. SUB-KEPLERIAN MIGRATION
This section presents a migration mechanism driven by sub-Keplerian flow in magnetically controlled disks. To illustrate
the properties of this mechanism, we consider power-law disks, where the surface density and temperature distributions take the form $\Sigma(r) = \Sigma_1 r^{-p}$ and $T(r) = T_1 r^{-q}$. We take $r_1 = 1\text{ AU}$, so the coefficients $\Sigma_1$ and $T_1$ correspond to values at 1 AU. The power-law index for the surface density lies in the range $1/2 < p < 2$ (Cassen & Moosman 1981). For the Minimum Mass Solar Nebula (MMSN), the surface density constant $\Sigma_1 \approx 4500\text{ g cm}^{-2}$ (Kuchner 2004). The power-law index for the temperature profile lies in the range $1/2 < q < 3/4$. Viscous accretion disks (Pringle 1981) and flat reprocessing disks (Adams & Shu 1986) have $q \approx 3/4$; flared reprocessing disks (Chiang & Goldreich 1997) and the early solar nebula (Weidenschilling 1977a) have $q \approx 1/2$.

Planetary orbits are taken to be circular, with orbital angular momentum $J = m_p (G M_* r)^{1/2}$. The disk scale height $H = c_s/\Omega$, where $c_s$ is the sound speed, which is determined by the disk temperature profile. The radial dependence of $H/r$ is thus $H/r = (H/r_1) (r/r_1)^{(q-1)/2}$, where $(H/r_1) \approx 1/20$ (SO7).

2.1. Torques

For circular orbits, the torque $T_X$ exerted on the planet by gas in the sub-Keplerian disk takes the form

$$T_X = C_D \pi R_p^2 \rho_{\text{gas}} v_{\text{rel}}^2,$$

where $r$ is the orbital radius, $v_{\text{rel}}$ is the relative velocity between the gas and planet, $\rho_{\text{gas}}$ is the gas density, and $R_p$ is the planetary radius. The dimensionless drag coefficient $C_D \approx 1$ for planets (Weidenschilling 1977b), but can be enhanced by gravitational focusing (Ohtsuki et al. 1998). The gas density $\rho_{\text{gas}} \approx \Sigma/2H$. Because the gaseous disk orbits with sub-Keplerian speeds $\Omega_{\text{gas}} \approx f\Omega_*$, the relative velocity takes the form $v_{\text{rel}} = (1-f) (G M_*/r)^{1/2}$, and the torque becomes

$$T_X = \frac{\pi}{2} C_D (1-f)^2 G M_* R_p^2 \left( \frac{\Sigma}{H} \right).$$

The time evolution of the semi-major axis obeys the differential equation

$$\frac{1}{r} \frac{d}{dt} \left( \frac{r}{1-f} \right) = 2T_X m_p \Omega r^2,$$

where we assume that the orbit remains circular. The migration timescale is given by

$$t_0 \equiv \frac{1}{\pi C_D (1-f)^2 \left( \frac{H}{r} \right)^2 \left( \frac{m_p}{R_p^2} \right)^{1/2}}.$$

For typical parameters, $M_* = 1.0 M_\odot$, $m_p = 1.0 M_p$, $R_p = 1.0 R_\odot$, $\Sigma_1 = 4500\text{ g cm}^{-2}$, $f = 0.66$, and $(H/r)_1 = 0.05$, the timescale $t_0 \approx 70,000\text{ yr}$. For comparison, Type I torques are given by

$$T_I = C_I \left( \frac{m_p}{M_*} \right)^2 \pi \Sigma r^3 (r\Omega)^2 \left( \frac{r}{H} \right)^2,$$

where the dimensionless constant $C_I \approx (1.364 + 0.541 P)/\pi \approx 0.606$ (Ward 1997a; Tanaka et al. 2002). The ratio of the torque $T_X$ to the Type I torque is given by

$$\frac{T_X}{T_I} = \left[ \frac{C_D (1-f)^2}{2C_I} \right] \left( \frac{M_*}{m_p} \right)^2 \left( \frac{R_p}{r} \right)^2 \left( \frac{H}{r} \right)^2 \propto M_*^2 m_p^{4/3} r^{-1/3(q-1)/2}.$$

Figure 1. Regions of $(r, m_p)$ parameter space for which migration from sub-Keplerian flow (with $f = 0.66$) dominates Type I migration. Planetary mass ($M_p$) is plotted vs. the orbital radius (AU). Sub-Keplerian migration dominates in the region below the lines, which are drawn for stellar masses $M_*/M_\odot = 2, 1, 0.5, 0.25$ (top to bottom).

For an Earth-like planet ($m_p = 1 M_\oplus$, $R_p = 1 R_\oplus$) orbiting a solar mass star, $C_D = C_I$, and $H/r = 1/20$, the two torques have almost the same magnitude at $r = 1 \text{ AU}$ when $(1-f) = 0.34$. Since the torque ratio grows with decreasing semi-major axis, sub-Keplerian torques $T_X$ are stronger for $r < 1 \text{ AU}$. The ratio decreases with the planetary mass, so that larger planets are more affected by Type I migration. This torque ratio also depends on the stellar mass, so that sub-Keplerian torques are more important for systems associated with more massive stars.

Figure 1 shows the regions of parameter space $(r, m_p, M_*)$ for which sub-Keplerian migration dominates over Type I migration. Sub-Keplerian torques are relatively stronger in the inner disk, where magnetic effects ($f \neq 1$) are most likely to arise.

Note that this treatment is approximate: the $T_I$ expression neglects magnetic effects, which can be important in these systems (Terquem 2003). In general, $T_I$ should be a function of $f$ (and this calculation should be done in the future). Moreover, this Type I torque is derived for isothermal disks, whereas X-wind disks have temperature gradients, which can affect migration (Paardekooper & Mellema 2006). Finally, the two torques ($T_I, T_X$) are not fully independent—both mechanisms produce disk wakes that can interfere with each other. The comparison shown in Figure 1 is thus subject to future corrections.

2.2. Gaps

In standard treatments of gap formation, parcels of gas flowing past the planet are scattered by its gravitational potential, and deflected through the angle $\theta = (2 G m_p/b v_{\text{rel}}^2)$, where $b$ is the impact parameter of the encounter (PT06). This deflection changes the parcel’s specific angular momentum by the increment

$$\Delta J = \frac{2 K G^2 m_p^2}{b^2 v_{\text{rel}}^2},$$

where the constant $K$ includes corrections arising from the rotating reference frame (Goldreich & Tremaine 1980). The disk angular momentum changes at a rate determined by the integral of $\Delta J$.

In the Keplerian case, the planet moves faster (slower) than disk material on its outside (inside). The planet thus transfers
angular momentum to the outer disk and negative angular momentum to the inner disk, and opens a gap from both directions. However, in a sub-Keplerian disk, the planet moves faster than the disk material on both sides of the potential gap; this complication modifies the gap formation process.

Although supersonic flow ($v_{\text{rel}} \geq c_s$) alters this picture, we start by estimating the angular momentum transferred by “scattering” gas parcels and compare the result to that transferred by viscosity. Consider the disk exterior to the planetary orbit. The planet moves faster than the gas, and angular momentum is transferred outward at the rate

$$\frac{dH}{dt} = \int_{b_{\text{min}}}^{\infty} (\Delta J) \Sigma v_{\text{rel}} \, db = 2K G^2 m_p r \times \int_{b_{\text{min}}}^{\infty} \frac{\Sigma \, db}{b^2 v_{\text{rel}}^2} \approx \frac{2K}{(1-f)^2} \frac{Gm_p^2 r^3 \Sigma}{b_{\text{min}} M_*}, \quad (8)$$

where the integral’s support is concentrated (by assumption) near the minimum impact parameter $b_{\text{min}}$. This expression neglects disk shear terms, which must be included to recover the standard result in the limit $f \to 1$ (compare Equation (8) with PT06).

Gap formation requires that the rate of angular momentum transfer to the disk from “scattering” exceeds the rate at which angular momentum is transferred by viscosity. This condition requires

$$\frac{dH}{dt} \gtrsim 3\pi v \Sigma^2 \Omega, \quad (9)$$

where the viscosity $v$ is parameterized as $v = (2/3) \alpha c_s H$, and the viscosity coefficient $\alpha$ is dimensionless.

Gap formation requires a second condition: the planet’s sphere of influence must be large enough, e.g., the Roche radius $R_K = r(m_p/3M_*)^{1/3}$ must exceed the scale height $H$. The requirement $R_K > H$ places another constraint on the planet mass required for gap opening:

$$\frac{m_p}{M_*} \geq \left( \frac{H}{r} \right)^3. \quad (10)$$

This condition allows the flow to experience nonlinear deviations (Ward 1997a), including shock formation in the vicinity of the planet (Korycansky & Papaloizou 1996). Since this requirement could be modified for high Mach numbers, Equation (10) should be considered as approximate. This constraint allows us to use $b_{\text{min}} = R_K \propto r$ to evaluate the angular momentum transfer rate in Equation (8), and solve Equation (9) to find the planet mass required for gap opening:

$$\left( \frac{m_p}{M_*} \right)^{5/3} \geq \frac{3^{2/3} \pi^2 (1-f)^2}{2K} \frac{\nu}{\Omega r^2} \approx \pi (1-f)^2 \alpha \left( \frac{H}{r} \right)^2. \quad (11)$$

Gaps form when both constraints, Equations (10) and (11), are satisfied (see also Crida et al. 2006). For $\alpha \approx 10^{-3}$, $f = 0.66$, and $H/r = 1/20$, the nonlinear constraint, Equation (10), and the viscous constraint, Equation (11), are comparable, and the mass required for gap clearing is $\sim 100 M_\oplus$ (about one Saturn mass). Because the planet moves faster than the gas on both sides of the gap, the planet readily transfers angular momentum to the outer gap edge, but tends to draw disk material outward from the inner edge. When the planet has sufficient mass (Equation (10)), this material shocks against the wake of the planet. The planet will thus be located closer to the inner gap edge.

2.3. Orbital Evolution

To consider orbital evolution of the planet, we define a dimensionless angular momentum variable $\xi \equiv J/J_1$, where $J = m_p \Omega r^2$, and $J_1$ is the orbital angular momentum at $r = 1$ AU. We also define reduced torque parameters through the ansatz $\Gamma_I \equiv \Gamma_I(J_1)/J_1$ and $\Gamma_X \equiv \Gamma_X(J_1)/J_1$. The equation of motion then becomes

$$\frac{d\xi}{dt} = -\left[ \Gamma_I \xi^{-a} + \Gamma_X \xi^{-b} \right], \quad (12)$$

where the indices $a = 2(p-q)$ and $b = 2p + 3 - q$. For typical values $p = 3/4$ and $q = 1/2$, the torque indices become $a = 1/2$ and $b = 4$. Since the two torques are nearly equal for Earth-mass planets at 1 AU, $\Gamma_X \approx \Gamma_I \approx 10(M\text{yr})^{-1}/(0.1 \text{ Myr})$. Keep in mind that both torque expressions are approximate (see Section 2.1).

For sub-Keplerian torques acting alone, the time required to migrate from a starting location $\xi_0 = J_0/J_1 = (r_0/1 \text{ AU})^{1/2}$ must exceed the central impact parameter $\Gamma X_{I1}$ is given by $\Gamma X_{I1} = \xi_0^{(b+1)/(a+b)}$. Similarly, the time required for Type I torques to move the planet from $\xi_0$ to the star is given by $\Gamma X_{I1} = \xi_0^{(b+1)/(a+b)}$. Since we expect $b \gg a$, sub-Keplerian migration is much faster than Type I migration for planets starting inside $\sim 1$ AU. For planets starting at larger radii, however, Type I torques dominate until the planet reaches $r \sim 1$ AU, where sub-Keplerian torques take over.

The above results assume that the planetary core mass remains constant. However, the core mass must increase with time for giant planets to form, and the torque strengths change as the mass increases. To illustrate this behavior, we use a simplified treatment of planetesimal accretion where the planetary core grows according to

$$\frac{dm_p}{dt} = C_{\text{in}} \pi R_p R_K \Sigma Z \Omega, \quad (13)$$

where $\Sigma Z \propto \Sigma$ is the surface density in solids (Papaloizou & Terquem 1999; Laughlin et al. 2004a). Giant planet formation typically requires $\Sigma Z \approx 130 \text{ g cm}^{-2}$ at $r = 1$ AU, somewhat larger than the MMSN value (Lissauer & Stevenson 2007). For a given density of planetary cores, $\rho_C \approx 3.2 \text{ g cm}^{-3}$, the planetary radius $R_p$ is determined by the mass. After defining a scaled radius $\eta \equiv R_p/R_\oplus$, we write the core accretion process in a dimensionless form

$$\frac{d\eta}{dt} = \gamma \xi^{-(p+1)}, \quad (14)$$

where $\gamma \approx 20 \text{ (Myr)}^{-1}$. We can combine planetary growth with orbital evolution. As the planet grows according to Equation (14), the torques vary with planetary radius, and the equation of motion for $\xi \equiv (r/1 \text{ AU})^{1/2}$ becomes

$$\frac{d\xi}{dt} = -\left[ \Gamma_I \eta^{3\xi-a} + \Gamma_X \eta^{-1\xi-b} + 3\gamma \eta^{-1\xi-2p} \right], \quad (15)$$

where $\Gamma_I = \Gamma_I(\eta = 1)$ and $\Gamma_X = \Gamma_X(\eta = 1)$. When migration reaches $r \lesssim 1$ AU, sub-Keplerian torques become larger than Type I torques and planetary migration takes place more rapidly. If migration starts at larger radii, however, most of the evolution time is spent at larger radii where Type I migration torques prevail. Consequently, sub-Keplerian torques do not substantially change the total migration time for starting radii beyond $r \sim 2$ AU. However, the mass accreted during the
migration epoch is significantly altered due to acceleration of the latter stages. These trends are illustrated by Figure 2, which shows migration times and final masses for planets starting at varying locations $r_0$ with fixed initial mass $m_p = 1M_\oplus$. Here, the equations of motion (Equations (14) and (15)) are integrated using the standard parameter values quoted above.

For completeness, we note that sub-Keplerian flow occurs only in magnetically active disk regions. The flow becomes Keplerian in “dead zones” (Gammie 1996), where this migration mechanism will not operate. However, ordinary Type I migration continues to act within dead zones, so that migration occurs at the standard Type I rate.

3. DISK TRUNCATION

This section considers the implications of disk truncation. In X-wind theory, this inner cutoff radius is given by

$$r_X = \left[ \frac{\mu_\ast^4}{GM_\ast M_D^2 \Phi_{\text{dx}}} \right]^{1/7},$$

(16)

where $\mu_\ast$ is the magnetic dipole moment of the star, $M_\ast$ is the stellar mass, $M_D$ is the mass accretion rate, and $\Phi_{\text{dx}} \approx 1$ is a dimensionless parameter (Ostriker & Shu 1995, S07). Because $r_X$ marks the inner disk boundary, planets cannot migrate inside the X-point through standard migration mechanisms involving disk torques because there is no disk material. The X-point location $r_X \approx 0.05$ AU for typical parameters (C08), and is coincident with the semi-major axes of “hot Jupiters.” Disk truncation through magnetic effects thus provides a natural mechanism for ending migration and explains the observed planets in $\sim 4$ day orbits. However, extrasolar planets have recently been discovered with significantly smaller semi-major axes, $r \approx 0.02$ AU. Although some variation in $r_X$ is expected, the presence of extrasolar planets in these extremely tight orbits represents some tension with expectations from X-wind theory, and suggests the possibility of an additional mechanism.

The presence of these short-period planets can be understood as follows. The location of the X-point depends on the mass accretion rate through the disk. During FU-Ori outburst events, the mass accretion rate is greatly enhanced (Hartmann 2001), and the X-point moves inward (S07). Equation (16) indicates that $M_D$ must increase by a factor $\sim 25$ to move the X-point to $r_X \approx 0.02$ AU as required. Since outburst phases have $M_D \approx 10^{-4} M_\odot \text{yr}^{-1}$, planets can (in principle) migrate inward during these FU-Ori phases.

This simple picture has two complications. First, FU-Ori outbursts are relatively short-lived. The time-averaged mass accretion rate is $M_D \sim 10^{-7} M_\odot \text{yr}^{-1}$. During outbursts, the $M_D$ is $\sim 100$ times larger, so that the outburst duty cycle is correspondingly shorter, and each event lasts only 100–1000 yr. During the outburst phase, the disk extends inward to the desired radii, and migration can take place. However, the planets will not necessarily have enough time to migrate inward far enough during the (short) outburst phases. This issue is made more urgent by the timing of the events: The planets take a relatively long time to form and migrate inward to the “standard” location of the X-point (3–10 Myr). Thus, relatively few FU-Ori outbursts will take place after the planets arrive at $r = r_X \approx 0.05$ AU.

On the other hand, migration will be aided by the fact that the planets might not have time to open up gaps in the disk. As a result, we expect that the migration rates will be faster than the standard Type II migration rates (for giant planets with gaps). The migration rate will be closer to the Type I migration rates, which are fast, and are even faster for larger mass planets (that usually open up a gap).

The second complication is that, because FU-Ori outbursts are short, the star has difficulty in adjusting its rotation period to co-rotate with the disk. During the quiescent phase, the star rotates every $\sim 4$ days, in sync with the inner disk edge at $r \approx 0.05$ AU. During an outburst, the large accretion rate suddenly pushes the disk edge to $r \approx 0.02$ AU. For the star to co-rotate with the new disk edge, it needs 4 times its angular momentum. However, the maximum rate for the star to gain angular momentum is $J \approx M_D r_X \Omega_X$. For $M_D = 10^{-7} M_\odot \text{yr}^{-1}$ and $r_X = 0.02$ AU, it takes 2000–3000 yr to spin up the star, somewhat longer than the timescale for each outburst. As a result, the inner disk edge generally rotates faster than the star, and the magnetic funnel forms a leading spiral. Angular momentum flows into the star and makes the truncation radius smaller than its equilibrium value (Equation (16)). These departures from equilibrium thus allow migrating planets to move even farther inward.

Next we note that the density of gaseous material in the disk midplane is enhanced over the expected value $\rho \approx \Sigma/2H$. Because disk truncation by the funnel flow increases the density by a factor $r/H \sim 40$ at the X-point (Shu et al. 1994), the expected density $\rho_X \approx r \Sigma/2H^2$. This density enhancement has important ramifications.

1. Giant planets that successfully migrate to the X-point at $r \approx 0.05$ AU can be pushed further inward (perhaps to $r \approx 0.02$ AU) during FU-Ori outburst events. With the density enhancement at the disk midplane, the timescale for inward movement can be short ($\lesssim 40$ yr), so that migration can take place during a single outburst.

2. Planetary cores can migrate inward to the X-point on a short timescale, often fast enough that they cannot become gas giants before they reach the inner disk edge. If planetary cores are large enough, they continue to accrete gaseous material while they orbit at the X-point. The density enhancement considered herein provides a corresponding enhancement in the supply of available material. One issue associated with forming hot Jupiters in situ is the lack of gaseous

---

5 Schneider 2009, Extrasolar Planets Encyclopedia, http://exoplanet.eu/catalog-all.php.
material in the inner disk. This gas shortage is largely alleviated for planets at the X-point, both from this density enhancement and from the continuing flow of material into the region (Ward 1997b). On the negative side, high temperatures at the X-point make the gas essentially dust-free. Gas accretion onto planets is limited by cooling processes, which will be compromised if the opacity is too low.

4. CONCLUSION

This Letter presents a new migration mechanism for embedded planets. These bodies experience a headwind due to the sub-Keplerian rotation curve of the gas in magnetically controlled disks, and drag forces drive inward migration. This mechanism dominates over Type I migration (Figure 1) for sufficiently small planets \((m_p \lesssim 1 M_\oplus)\) and/or close orbits \((r \lesssim 1 \text{ AU})\). The total migration time moderately decreases due to sub-Keplerian torques, but the mass accreted by planetary cores during the migration epoch changes more substantially (Figure 2).

The gap-opening process is modified in sub-Keplerian disks because the planet moves faster than the gas (supersonically) both inside and outside its orbit. Gap opening thus requires nonlinear interactions (approximately given by Equation (10)). The estimated mass threshold for gap opening is \(m_p \gtrsim 100 M_\oplus\), and the planet resides near the inner gap edge.

For typical parameters, magnetic truncation of the inner disk occurs at \(r_X \approx 0.05 \text{ AU}\), and thus naturally explains observed extrasolar planets in \(\sim 4\) day orbits. Migration of planets to smaller orbits, as sometimes observed, requires an additional mechanism. During FU-Ori outbursts, the X-point moves inward to the required location \(r_X \approx 0.02 \text{ AU}\) due to the large accretion rate, which also allows fast inward migration. X-wind theory (SO7,C08) thus provides a viable explanation for all of the currently observed short-period planets (long-period planets require additional considerations).

Finally, planetary cores that halt migration at the X-point \((r_X \approx 0.05 \text{ AU})\) can be subjected to a significantly enhanced gas density and a continuing supply of material (including inwardly migrating solids). These features help proto-ho-Jupiters finish forming in their observed \(\sim 4\) day orbits.

This Letter shows that magnetic effects drive sub-Keplerian migration and produce final orbits with \(r \approx r_X \approx 0.02 - 0.05 \text{ AU}\) (from disk truncation). These processes must compete with other mechanisms acting on embedded planets, including Type I migration (Ward 1997a, 1997b), stochastic migration from turbulence (Nelson & Papaloizou 2004; Laughlin et al. 2004b; Nelson 2005; Johnson et al. 2006; Adams & Bloch 2009), runaway migration (Masset & Papaloizou 2003), torques exerted by toroidal fields (Terquem 2003), opacity transitions (Menou & Goodman 2004), and radiative (non-barotropic) effects (Paardekooper & Mellema 2006; Paardekooper & Papaloizou 2008). Future work should study how these processes interact with each other to ultimately form giant planets.

We thank Frank Shu and Greg Laughlin for discussions, and MCTP for hospitality while this work was developed. F.C.A. is supported by NASA grant:NNX07AP17G and NSF grant:DMS-0806756; M.J.C. by grant:NSC-95-2112-M-001-044; and S.L. by grant:CONCyT-48901.

REFERENCES

Adams, F. C., & Bloch, A. M. 2009, \textit{ApJ}, 701, 1381
Adams, F. C., & Shu, F. H. 1986, \textit{ApJ}, 308, 836
Blandford, R. D., & Payne, D. G. 1982, \textit{MNRAS}, 199, 883
Bouvier, J., Alencar, S. H. P., Harries, T. J., Johns-Krull, C. M., & Romanova, M. M. 2007, in Protostars and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil (Tucson, AZ: Univ. Arizona Press), 479
Cai, M., Shang, H., Lin, H.-H., & Shu, F. H. 2008, \textit{ApJ}, 672, 489
Cassen, P., & Moosman, A. 1981, \textit{Icarus}, 48, 353
Chiang, E. I., & Goldreich, P. 1997, \textit{ApJ}, 490, 368
Crida, A., Morbidelli, A., & Masset, F. 2006, \textit{Icarus}, 181, 587
Gammie, C. F. 1996, \textit{ApJ}, 457, 355
Goldreich, P., & Tremaine, S. 1979, \textit{ApJ}, 233, 857
Goldreich, P., & Tremaine, S. 1980, \textit{ApJ}, 241, 424
Hartmann, L. 2001, Accretion Processes in Star Formation (Cambridge: Cambridge Univ. Press)
Johnson, E. T., Goodman, J., & Menou, K. 2006, \textit{ApJ}, 647, 1413
Korycansky, D. G., & Papaloizou, J. C. B. 1996, \textit{ApJS}, 105, 181
Kuchner, M. J. 2004, \textit{ApJ}, 612, 1147
Laughlin, G., Bodenheimer, P., & Adams, F. C. 2004a, \textit{ApJ}, 612, L73
Laughlin, G., Steinacker, A., & Adams, F. C. 2004b, \textit{ApJ}, 608, 489
Lin, D. N. C., Bodenheimer, P., & Richardson, D. C. 1996, \textit{Nature}, 380, 606
Lissauer, J. J., & Stevenson, D. J. 2007, in Protostars and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil (Tucson, AZ: Univ. Arizona Press), 591
Marcy, G., & Butler, P. R. 1996, \textit{ApJ}, 464, L147
Masset, F. S., & Papaloizou, J. C. B. 2003, \textit{ApJ}, 588, 494
Mayor, M., & Queloz, D. 1995, \textit{Nature}, 378, 555
Menou, K., & Goodman, J. 2004, \textit{ApJ}, 606, 520
Nelson, R. P. 2005, \textit{A&A}, 443, 1067
Nelson, R. P., & Papaloizou, J. C. B. 2004, \textit{MNRAS}, 350, 849
Ohtsuki, K., Nakagava, Y., & Nakazawa, K. 1998, \textit{Icarus}, 75, 552
Ostriker, E. C., & Shu, F. H. 1995, \textit{ApJ}, 447, 813
Paardekooper, S.-J., & Mellema, G. 2006, \textit{A&A}, 459, L17
Paardekooper, S.-J., & Papaloizou, J. C. B. 2008, \textit{A&A}, 485, 877
Papaloizou, J. C. B., & Terquem, C. 1999, \textit{ApJ}, 521, 823
Papaloizou, J. C. B., & Terquem, C. 2006, \textit{Rep. Prog. Phys.}, 69, 119
Pringle, J. E. 1981, \textit{ARA&A}, 19, 137
Pudritz, R. E., & Norman, C. A. 1983, \textit{ApJ}, 274, 677
Reipurth, B., Jewitt, D., & Klaus, K. 2007, \textit{Protostars and Planets V} (Tucson, AZ: Univ. Arizona Press)
Shu, F. H., Galli, D., Lizano, S., Glassgold, A. E., & Diamond, P. H. 2007, \textit{ApJ}, 665, 535
Shu, F. H., Lizano, S., Galli, D., Cai, M. J., & Mohanty, S. 2008, \textit{ApJ}, 682, L121
Shu, F. H., Najita, J., Ostriker, E., Wilkin, F., Ruden, S., & Lizano, S. 1994, \textit{ApJ}, 429, 781
Tanaka, H., Takeuchi, T., & Ward, W. R. 2002, \textit{ApJ}, 565, 1257
Terquem, C. 2003, \textit{MNRAS}, 341, 1157
Udry, S., Fischer, D., & Queloz, D. 2007, in Protostars and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil (Tucson, AZ: Univ. Arizona Press), 685
Ward, W. R. 1997a, \textit{Icarus}, 126, 261
Ward, W. R. 1997b, \textit{ApJ}, 482, L211
Weidenschilling, S. J. 1977a, \textit{Ap&SS}, 51, 153
Weidenschilling, S. J. 1977b, \textit{MNRAS}, 180, 57