HALTING PLANET MIGRATION IN THE EVACUATED CENTERS OF PROTOPLANETARY DISKS

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ABSTRACT

Precise Doppler searches for extrasolar planets find a surfeit of planets with orbital periods of 3–4 days and no planets with orbital periods less than 3 days. The circumstellar distance \( R_0 \), where small grains in a protoplanetary disk reach sublimation temperatures \( \sim 1500 \text{ K} \), corresponds to a period of \( \sim 6 \text{ days} \). Interior to \( R_0 \), turbulent accretion due to magnetorotational instability may evacuate the disk center. We suggest that planets with orbital periods of 3–4 days are so common because migrating planets halt once this evacuated region contains the sites of their exterior 2:1 Lindblad resonances.

Subject headings: astrobiology — circumstellar matter — planetary systems: formation — planetary systems: protoplanetary disks — stars: formation

1. INTRODUCTION

Analytic calculations (Goldreich & Tremaine 1980; Ward 1997a) and numerical simulations (Nelson et al. 2000; Kley, D’Angelo, & Henning 2001) suggest that protoplanets in a protoplanetary disk migrate rapidly into the star they orbit—so rapidly that it is a wonder any planets survive at all. Small protoplanets torque the disk at Lindblad and corotation resonances, and the resulting back torque can propel a planet into the star in a matter of \( 10^3 (M_p/M_\odot)^{-1} \text{ yr} \) (Ward 1997b). Ward (1997b) has dubbed this conundrum the Shiva problem, after the Hindu god of destruction. Large protoplanets may open a gap in the disk via their resonant torques and so become locked to the disk’s viscous spreading, a process that may dump most of the disk and planet onto the star within \( 10^7 \text{ yr} \) or less, depending on the disk viscosity.

Figure 1 shows the distribution of the orbital periods of the innermost Doppler planet candidates, summarizing data from G. Marcy et al. (2002). These candidate planets all orbit stars with masses in the range of 0.7–1.4 \( M_\odot \). Figure 1 suggests that whatever mechanism halted the migration of these planets operates best at an orbital period of \( \sim 3 \text{ days} \). Of the 20 planets with periods less than 20 days, eight have periods in the range of 3–4 days. No planet has a period of less than 2.98 days. This trend appears to be real and not an artifact of observational selection; the primary precise Doppler surveys are complete for Jupiter-mass planets out to a period of \( \lesssim 0.5 \text{ yr} \) (Butler et al. 2000).

Occasionally, the interactions among two planets and a star can leave a planet trapped by stellar tides in a circular orbit at \( \sim 0.04 \text{ AU} \) (Rasio & Ford 1996). Sometimes an accreting planet may overflow its Roche lobe, losing mass to the star, and this process may halt the planet’s migration (Trilling et al. 1998). But these phenomena appear to be rare.

Scenarios in which planets migrate by interacting with a disk of planetesimals without gas (Murray et al. 1998) provide a disk truncation radius where planets may gather: the radius where planetesimals become hot enough to sublimate. The problem with gasless migration schemes is that substantially changing the orbit of a Jupiter-mass planet requires roughly a Jupiter mass of planetesimals.

In contrast, optically thick disks with more than a Jupiter mass of gas appear to be ubiquitous around young stars. Lin, Bodenheimer, & Richardson (1996) have suggested that planet migration ends where the gaseous protoplanetary disk meets the stellar magnetosphere. We suggest an alternative explanation for the pileup of planets near the 3 day period: a gas disk truncated at a temperature of 1500 K by the onset of magnetorotational instability (MRI; Chandrasekhar 1961; Balbus & Hawley 1991).

2. THE THEORY

A planet with orbital period \( p \) and semimajor axis \( a \) interacts with a disk at Lindblad resonance sites, located where the natural epicycle period of the gas in the disk (roughly the Keplerian orbital period) is \( p(m + 1)/m \). The most distant Lindblad resonances from the planet are the \( m = 1 \) and \( m = -2 \), located at roughly 1.59\( a \) and 0.63\( a \), respectively. The planet torques the disk at these resonances, and the back torque from the inner Lindblad resonances tends to add angular momentum to the planet’s orbit, while the back torque from the outer Lindblad resonances tends to remove angular momentum from the planet’s orbit (Goldreich & Tremaine 1980). However, over a wide range of disk pressure and density gradients, the torques from the outer Lindblad resonances dominate the torques from the inner Lindblad resonances, causing the planet to spiral into the star (Ward 1997a).

Consider a planet contained in a protoplanetary disk with an inner truncation radius of \( R_0 \), corresponding to an orbital period of \( P_0 \). When the planet migrates inward to where it has an orbital period \( p \leq 2 P_0 (a \leq 1.59R_0) \), it may begin to migrate inward faster than normal because its interior Lindblad resonance sites lie in the evacuated regions, so the outward torques from these resonances disappear. When the planet reaches an orbital period of \( \frac{2}{3} P_0 (a = 0.63R_0) \), and all of the planet’s inner and outer Lindblad resonances are contained in a central evacuated region, the disk-planet interaction may stall, ending the planet’s migration (Lin et al. 1996). A planet with a gap is not immune; it must also stop migrating at a period of \( \frac{1}{2} P_0 \), where
it can no longer dynamically communicate with enough mass in disk material to substantially affect its orbit.

We propose that protoplanetary disks are evacuated interior to radius \( R_0 \) because of the powerful MRI that afflicts conducting Keplerian disks. Protoplanetary disks may suddenly become conducting where they reach a temperature of 1500 K, where potassium ionizes (Stone et al. 2000), and where dust sublimes, removing recombination sites (Sano et al. 2000). Numerical simulations of saturated MRI show that it can provide a disk \( \alpha \) viscosity (Lynden-Bell & Pringle 1974) in the range of \( \alpha \approx 0.004 \) to \( \alpha \approx 0.1 \) (Hawley, Gammie, & Balbus 1995; Ziegler & Rüdiger 2001) depending on the assumed resistivity. Exterior to \( R_0 \), the MRI may be damped completely (Gammie 1996; Reyes-Ruiz 2001).

In a steady state disk, the accretion rate \( \dot{M} \) is uniform, and continuity dictates that \( \dot{R}Sv_p = \text{constant} \), where \( R \) is the radial coordinate, \( S \) is the surface density, and \( v_p \) is the radial drift velocity. In a viscous accretion disk, \( v_p \approx \nu/R \), where \( \nu \) is the viscosity. So, roughly speaking, \( \Sigma \propto \nu^{-1} \), or using the \( \alpha \) prescription for disk viscosity, \( \Sigma \propto \alpha^{-1} \).

The MRI can plausibly cause the effective \( \alpha \) to climb by a factor of 10–1000 interior to \( R_0 \), which translates into a comparable drop in surface density. When planets reach \( a = 0.63R_0 \) in the centers of disks evacuated by MRI-driven accretion, their migration will slow by this factor of 10–1000. The high viscosity in this zone also acts to inhibit gap formation and close up existing gaps around massive planets.

In radiative transfer models of protoplanetary disks, a surface layer of small grains intercepts the starlight first and rations it to the disk midplane (Calvet et al. 1991; Malbet & Bertout 1991; Chiang & Goldreich 1997; Sasselov & Lecar 2000). These small grains have hotter equilibrium temperatures than a blackbody at a given distance from the star, so they sublimate farther from the star than larger grains do. We can find \( R_0 \) by iteratively solving the radiative equilibrium equation for the temperature of the small grains as a function of distance from the star (Backman & Paresce 1993). We performed such a computation assuming \( \sim 0.1 \mu m \) grains—bodies whose emissive and absorptive efficiencies stay constant at wavelengths shorter than 0.1 \( \mu m \) but decline as \( \lambda^{-1} \) at longer wavelengths. We find that the grains reach 1500 K at \( R_0 = 0.067 \) AU (\( P_0 = 6.3 \) days) for a solar-type star, or \( R_0 = 0.055 \) AU (\( P_0 = 4.8 \) days) for a star with solar luminosity and mass but an effective temperature of 4000 K, a common model for a T Tauri star.

Fig. 1.—Histogram of the orbital periods of the extrasolar planet candidates detected by the precise Doppler technique.

Planet migration in a disk with such an inner truncation radius would halt at \( p \approx P_0/2 = 2.4 \) days, near the observed pileup of precision Doppler planets. The luminosity of a solar-mass star varies over roughly a factor of \( \sim 5 \) during the time from 1 million to 10 million years after its birth (D’Antona & Mazzitelli 1994), so the value of \( P_0 \) relevant to halting the migration of a given planet could conceivably range over a factor of \( \sim 2 \) as a result of this effect. For comparison, if we assume that a 1 Jupiter mass planet has a radius of 2.3 Jupiter radii at an age of 1 million years (Guillot & Showman 2002), we calculate that the orbital period where it overflows its Roche radius is \( \sim 1.3 \) days.

3. Discussion

3.1. Observations of Protoplanetary Disks

The likely hosts of protoplanetary disks are T Tauri stars (\( \lesssim 2 \) M\( \odot \)) and Herbig Ae/Be stars (\( \sim 2–8 \) M\( \odot \)). Near-infrared photometry of Herbig Ae/Be stars reveals a curious pattern. Many of these stars have two-humped infrared excesses; they show a broad emission peak in the mid- or far-infrared and a second emission peak near 3 \( \mu m \) (Lada & Adams 1992). A model in which accretion luminosity powers the near-IR hump requires optically thick gas interior to the dust-sublimation point, a feature not corroborated by the observed spectral energy distributions (Hartmann, Kenyon, & Calvet 1993) or measurements of optical veiling (Ghandour et al. 1994). The near-IR humps appear to represent the thermal emission peak of a population of dust at a temperature of 1500 K (Sylvester et al. 1996; Malfait, Bogaert, & Waelkens 1998). The prominence of these near-IR humps may indicate the importance of \( R_0 \) in the structure of Herbig Ae/Be disks.

Further evidence for the structural importance of \( R_0 \) comes from long-base-line optical interferometry. Millan-Gabet, Schloerb, & Traub (2001) resolved 11 Herbig Ae/Be stars at baselines of 21 and 38 m with the Infrared Optical Telescope Array in the near-infrared. The visibilities of the 11 resolved targets and their near-IR excesses were well modeled by dusty rings with inner radii of 0.3–5 AU, possibly corresponding to \( R_0 \). Measurements of the near-IR sizes of the central regions of other young stars, including some T Tauri stars, with the Palomar Testbed Interferometer (Akeson et al. 2000) and using a single Keck telescope with an aperture mask (Tuthill, Monnier, & Danchi 2001; Danchi, Tuthill, & Monnier 2001) support this association; the observed near-IR sizes show a trend of increasing with the luminosity of the young star, which is consistent with the increase of \( R_0 \) with luminosity (Monnier & Millan-Gabet 2002).

Natta et al. (2001) and Dullemond, Dominik, & Natta (2001) have interpreted the photometric and interferometric observations of Herbig Ae/Be stars as signs that protoplanetary disks may have tall, passively heated inner walls; hot dust on the wall provides the 3 \( \mu m \) emission peak. This inner wall could conceivably represent the zone where the opacity and the surface density suddenly drop in our model. Further high-resolution interferometric studies of Herbig Ae/Be and T Tauri disks should help clarify how disk structure affects planet migration.

3.2. Magnetic Disk Truncation and the X-Wind Theory

Shu et al. (2000) review a theory of the interiors of protoplanetary disks that centers on the interaction between the stellar magnetic field and the inner edge of the conducting gas disk. In this “X-wind” theory, the disk is replaced by magnetic accretion columns and a bipolar wind interior to the radius.
Earlier explanations of halting planet migration (Lin et al. 1996) have pointed to $R_s$ as the critical radius rather than $R_0$.

Directly measuring $R_s$ is difficult. In equilibrium, the stellar rotation period matches the Keplerian period at $R_s$, so measuring the stellar rotation rate and assuming that T Tauri stars range from 0.5 to $\geq$ 8 days (Stassun et al. 1999). Consequently, it is hard to associate the 3 day period of the closest in extrasolar planets with a special stellar rotation rate or with $R_s$.

In the $X$-wind model of chondrule formation, a geometrically thin, optically thick disk of planetesimals interior to $R_s$ suffers mutual collisions and heating from magnetic flares (Shu, Shang, & Lee 1996; Shu et al. 2001). Materials from these planetesimals become protochondrules. In our picture, type I migration helps deliver planetesimals to the magnetically active zone. We imagine a ring of planetesimals collecting near $0.63R_s$. Objects smaller than a few kilometers may migrate in farther than $0.63R_0$ via plasma drag (Shu et al. 1997, 2001).

### 3.3. Torque Reversal

We briefly considered the following alternative mechanism for halting planet migration. Continuing the calculations of Ward (1997a) shows that with only a slight positive temperature gradient ([$R/R_0$]dT/d$R_0$ $\geq$ 0.6; i.e., the disk temperature increases with radius faster than roughly $R_0^{0.6}$), the torque on the planet from disk tides can reverse. Such a positive temperature gradient could conceivably occur where the disk regains sight of the star beyond the shadow of the disk’s tall inner wall. However, the models of Dullemond et al. (2001) suggest that the positive temperature gradient in this region is largely confined to the surface layer of the disk, which does not have enough surface density itself to affect planet migration.

### 4. CONCLUSION

We have painted a picture of planet migration in which inwardly migrating planets run out of gas in the low surface density, rapidly accreting central regions of protoplanetary disks. A good way to test our conjecture that disk temperature—not the stellar magnetic field—determines the orbital radii of the innermost surviving planets is to extend the sample of planet search target stars to include a wider range of stellar masses. For example, we predict that planets around early A-type main-sequence stars will collect at a radius much farther from the star ($\sim$0.3 AU) than the radius where planets around solar-type stars collect. The high rotation rates of main-sequence A stars betray that magnetic disk truncation cannot rescue planets migrating into these stars until they reach near 0.03 AU. Doppler planet search techniques may not work for A stars because of their rotationally broadened spectral lines. However, astrometric searches, transit searches, and direct-imaging searches for extrasolar planets are not so limited.

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