DEAD ZONES AS THERMAL BARRIERS TO RAPID PLANETARY MIGRATION IN PROTOPLANETARY DISKS

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ABSTRACT

Planetary migration in standard models of gaseous protoplanetary disks is known to be very rapid (\(\sim 10^5\) years), jeopardizing the existence of planetary systems. We present a new mechanism for significantly slowing rapid planetary migration, discovered by means of radiative transfer calculations of the thermal structure of protoplanetary disks irradiated by their central stars. Rapid dust settling in a disk’s dead zone—a region with very little turbulence—leaves a dusty wall at its outer edge. We show that the back-heating of the dead zone by this irradiated wall produces a positive gradient of the disk temperature, which acts as a thermal barrier to planetary migration which persists for the disk lifetime. Although we analyze in detail the migration of a super-Earth in a low-mass disk around an M star, our findings can apply to a wide variety of young planetary systems. We compare our findings with other potentially important stopping mechanisms and show that there are large parameter spaces for which dead zones are likely to play the most important role for reproducing the observed mass–period relation in longer planetary periods.

Key words: accretion, accretion disks – planets and satellites: formation – protoplanetary disks – radiative transfer – turbulence

Online-only material: color figures

1. INTRODUCTION

Extrasolar planets (ESPs) have an unexpected distribution of orbital radii around their host stars (Udry et al. 2007)—ranging from about 0.02 to 70 astronomical units (AU).\(^2\) In particular, ESPs are observed to obey a mass–period (M–P) relation wherein lower mass planets end up in short-period orbits around their host stars (Udry & Santos 2007). The predominance of very short period planets is generally thought to arise as a consequence of planetary migration. As an example, the tidal interaction of a planet with its surrounding gaseous disk excites density waves in the disk at so-called Lindblad resonances. These waves exert a torque back on the planet which results in a net angular momentum transfer between them (Goldreich & Tremaine 1980). Planets may also exchange angular momentum with the gas inside of their horseshoe region (Ward 1991). For locally isothermal protoplanetary disks with smoothly declining distributions of disk column density and temperature with radius, the net torque generally leaves a planet spiraling inwards through the disk (Tanaka et al. 2002), i.e., the torque exerted by the outer wake is marginally stronger than that of the inner wake (Ward 1997). Many calculations and simulations show that the migration timescale of planets in such “standard” disk models is very short—roughly 2 orders of magnitude smaller than the disk lifetime (1–10 Myr; Ward 1997; Nelson et al. 2000; Tanaka et al. 2002; D’Angelo et al. 2003). Why are there any planetary systems at all?

The key to understanding the M–P relation and the survival of planetary systems is in how the dynamics of planetary motion is coupled to the properties and structure of the protoplanetary disks. As an example, Schlaufman et al. (2009) focused on the surface density transition that can be produced at the location of the ice-line, where a local pressure maximum can act as an accumulation point for planetesimals (Kretke & Lin 2007). If it is assumed that type I migration is much slower than predicted in locally isothermal disk models, this feature could account for planets with orbital radii 0.1–2 AU. Obviously, a physical explanation for slower migration is needed.

In this Letter, we present a new slowing mechanism of rapid type I migration—which may occur for planets with masses that are too low to open up a gap in their disks (massive planets can tidally form a gap and undergo type II migration). We show, by means of Monte Carlo radiative transfer simulations, that dead zones—the dense inner disk region wherein turbulence cannot be readily excited (Gammie 1996)—support a thermal barrier to migration. One of the most important consequences is that the thermal barrier could account for planets at larger orbital radii. In Section 2, we outline our disk model and discuss tidal torques. In Section 3, we analyze how the presence of a thermal barrier impacts the migration rates of low-mass planets. In Section 4, we discuss potential issues for the M–P relation by comparing our stopping mechanism with others.

2. DISK MODEL AND TIDAL TORQUES

Protoplanetary disks are known to be heated by radiation from the central star (Chiang & Goldreich 1997; D’Alessio et al. 1998; Hasegawa & Pudritz 2010, hereafter HP10). This radiation mainly determines the thermal structure of disks (Kenyon & Hartmann 1987). This is because viscous heating dominates stellar irradiation heating only within about 1 AU for the classical T Tauri star systems (CTTs; D’Alessio et al. 1998) and only within about 0.1 AU for lower mass stars such as M stars (HP10).

Detailed modeling of the spectral energy distributions emitted by disks has shown that \(s = -1\) for disks where the disk surface density \(\Sigma \propto r^{-1}\) (D’Alessio et al. 1998). It is well established that the sign of a net torque exerted on planets depends on two central properties of disks, their surface density and temperature (e.g., Ward 1997). The thermal structure therefore plays a critical role in controlling the direction of planetary migration. In disks without internal structure, the disk temperature \(T \propto r^{-1}\) at the
mid-plane steadily decreases \((t < 0)\) and planetary migration is steadily inward.

The point is that disks are not simple power-law structures. The strength of turbulence within them varies considerably, with very low levels occurring in dense regions called dead zones (Gammie 1996) that initially extend over roughly 10 AU in disks (Matsumura & Pudritz 2006) and then gradually shrink in size as disk material is accreted onto the central star (Matsumura et al. 2009, hereafter MPT09). Turbulence in disks is most likely excited by the magnetorotational instability (MRI; Balbus & Hawley 1991). The MRI requires good coupling between ions and magnetic fields, which is largely absent in the dead zone—that inner, high-density region in which the ionization due to the X-rays from the central star and cosmic rays is suppressed.

Dust is the dominant absorber of stellar radiation in disks, although its total mass is 100 times smaller than that of gas (Dullemond et al. 2007). Many observations imply that it has a density distribution that is different from the gas distribution, which is derived assuming vertical hydrostatic equilibrium (Kenyon & Hartmann 1987). Dust settling, a consequence of its size distribution (Dullemond & Dominik 2004a), is ubiquitous in protoplanetary disks around any young star (HP10 and references herein). The dust scale height depends upon the amplitude of disk turbulence which keeps it suspended in the gravitational field of the disk (which is determined by the central star; Dubrulle et al. 1995).

We demonstrated in HP10 that dust settling in dead zones results in the appearance of a limited region in which the disk temperature can actually increase with radius—a radial temperature inversion. In this Letter, we adopt the torque formula (Ward 1997; Menou & Goodman 2004; Jing-Condell & Sasselov 2005) in which only the Lindblad torque is considered. This is because the corotation torque is readily saturated (i.e., is canceled out) in dead zones in our radiatively heated disk model. We compare the libration timescale (i.e., the timescale for gas to complete an orbit in the horseshoe region), \(\tau_{\text{lib}} \approx 8\pi r_p/5\Omega_p \zeta_r\), with the viscous timescale, \(\tau_{\text{visc}} \approx x_s^2/3v\), where the half-width of the horseshoe region is \(x_s/r_p = 1.68(M_p r_p/M_s h_p)^{1/2}\) (Paardekooper & Papaloizou 2009), the kinematic viscosity is \(v = \alpha h^2 \Omega_p \zeta_p\) (Shakura & Sunyaev 1973), and the disk scale height is \(h\). Our numerical results give \(h_p/r_p \approx 0.05\), so that the critical value of turbulence, \(\alpha_{\text{crit}}\), below which the corotation torque is saturated (and therefore negligible), is

\[
\alpha_{\text{crit}} = 0.01 \left(\frac{M_p}{5M_\oplus}\right)^{3/2} \left(\frac{M_\ast}{0.1M_\odot}\right)^{-3/2} \left(\frac{h_p/r_p}{0.05}\right)^{-7/2}.
\]

Since the dead zone has \(\alpha = 10^{-5}\), we can safely neglect the corotation torque for \(M_p \gtrsim 0.5M_\oplus\) in the dead zone of our disk model. In addition, we confirmed that, in the active region where the corotation torque is generally unsaturated, both Lindblad and corotation torques result in inward migration in our disk model (Paardekooper et al. 2010). Thus, exclusion of the corotation torque in the active region does not affect our findings in our disk model. We note that corotation torque may be unsaturated in dead zones for sufficiently small planetary masses, but the exact limit will depend on knowing the disk scale height that is established by the host star. Furthermore, our torque formula takes into account the effects of vertical disk thickness by diluting the gravitational force of a planet by \(z\) (Jang-Condell & Sasselov 2005).

3. RESULTS

We performed numerical simulations of the thermal structure of two-dimensional disks by solving the radiative transfer equation with a Monte Carlo method (Dullemond & Dominik 2004b; HP10). We included the effects of vertical hydrostatic balance, dust settling, a dead zone, and the gravitational field of a planet embedded in the disk. The tidal torque is calculated as described in Section 2, and incorporates our numerical data, in order to calculate the migration time.

Figure 1 presents the thermal and density structure of a disk with a 5 \(M_\oplus\) planet placed at 8 AU. The top and bottom panels show the dust and gas densities by color, respectively. Since we define the disk temperature as the mass-averaged temperature of dust, both panels show the identical temperature structure which is represented by contours. The thick line denotes the Hill radius \(r_H = r_p(M_p/3M_\oplus)^{1/3}\). In this Letter, we adopt, without loss of generality, a dead zone which is 6 AU in size. Dead zones enhance dust settling because of the low turbulent amplitude there. Since disks have inner dead, and outer active regions for turbulence, the transition of the density distribution of dust occurs at the outer edge of the dead zone. This leaves a marked step in the dust scale height behind—in effect a wall of dust. The additional stellar energy absorbed at the wall is distributed by radiative diffusion (Y. Hasegawa & R. E. Pudritz 2010, in preparation) since the optical depth at this region is high. The resulting radial “thermal inversion”—i.e., a region of increasing temperature with increasing disk radius—is shown in Figure 2. An analytic fit to our data shows that this back-heated region in the dead zone has a positive temperature gradient described by a power-law \(T \propto r^{t}\) with \(t > 3/2\).

We show in Figure 3 (top) that this radial thermal inversion causes the migration rate to be positive (the migration time becomes negative—bottom panel); i.e., planets migrate outward in the region with the positive temperature gradient. The physical explanation of this behavior is that the increasing function of disk temperature changes the disk’s pressure distribution which in turn causes the position of the outer Lindblad resonances to be further from the planet than the inner ones (Artymowicz 1993). This results in outer torques that are much weaker than the inner ones.3 Figure 3 (bottom) also shows that the planets very slowly

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3 We will show in a forthcoming paper that the Lindblad torque becomes negative when \(-t/2 < -7/4\) (Y. Hasegawa & R. E. Pudritz 2010, in preparation).
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Figure 1. Density and temperature structures of disks with a $5 \ M_\oplus$ mass planet located at 8 AU. For both panels, the density is denoted by colors [g cm$^{-3}$] as shown in colorbar, and the disk temperature is denoted by contours [K] (both panels show the identical temperature since the disk temperature is defined by taking the mass-average of the dust temperatures). The size of a dead zone is 6 AU. Top: the dust density. Bottom: the gas density. The thick black circle denotes the Hill sphere $r_H = r_p (M_p/3M_\ast)^{1/3}$, where $r_p$ and $M_p$ is the position and mass of a planet, respectively, and $M_\ast$ is the stellar mass. A wall-like structure appears at the boundary between the active and dead zones in the dust distribution while it is not in the gas.

(A color version of this figure is available in the online journal.)

Figure 2. Disk temperature in the disk mid-plane. The solid line is for the case of dead zone, the dashed line is the analytical model of disk temperature (Chiang & Goldreich 1997), and the dashed-dot line is for analytical fit to a positive temperature gradient. The size of a dead zone, which is 6 AU, is indicated by the vertical solid line.

enter the region of torque reversal—as seen by the strong positive “spike” in the migration time. These regions correspond to radii at which $dT/dr \simeq 0$ (see Figure 2) at the inner and outer resonances, making the torque difference between them very small.

We emphasize that the positive temperature gradient arising from the wall-like dust structure is achieved for the case of a finite transition region, $\Delta r \lesssim 10h$, in the value of turbulent $\alpha$ (HP10). Although, for simplicity, we adopt a sharp spatial transition from the active to the dead zone in this Letter ($\Delta r = 0$), our above results are valid for the case of $\Delta r \simeq h$, since the positions of Lindblad resonances are typically offset from the planets by $2h/3$ (Artymowicz 1993). In addition, it is interesting that the migration timescale of the M star system is similar to that of CTTS ($\sim 10^3$–$10^5$ years) for the other two cases (well mixed, dust settling). This is because the tidal torque is scaled by $\Sigma(h/r)^{-2}$. A more detailed discussion of them is presented in Y. Hasegawa & R. E. Pudritz (2010, in preparation).

4. DISCUSSION

4.1. Thermal Barrier versus Density Barrier at Outer Dead Zone Radius

We find that the dusty wall produces a radial temperature inversion that is a thermal barrier for rapid type I planetary migration. Whereas the torque balance in the well-coupled active zone forces planets to migrate inward, once they encounter the radial thermal inversion region, the torque balance reverses, and they move out of the region. Thus, planets are trapped there if they originally migrate from the active region beyond the dead zones, or even if they formed close to the outer edge of the dead zone.

The astrophysical implications of this result are very important since we have shown that dusty protoplanetary disks with dead zones possess an innate mechanism for strongly slowing planetary migration within them, provided that the corotation torque is saturated. While such a thermal barrier exists for any size of dead zone (HP10), its effectiveness is probably most important for lower mass disks, as we now show.

The density structure of disks evolves with time due to viscous evolution. MPT09 found that the difference of $\alpha$ between the active and dead regions produces a steep density gradient at the boundary and the location of their jump moves inward with time over the long ($\sim 10$ Myr) viscous timescale of the dead zone. This density gradient at the outer dead zone boundary also plays an important role in slowing down or stopping type I migration, provided that planets migrate from larger disk radii. The inner
torques become larger than the outer ones in the density gradient region, resulting in the reflection of migrating planets off the density gradient (MPT09).

The relative importance of these two dead zone mechanisms is controlled by the ratio of dust settling \( \tau_{\text{set}} \approx \Sigma / \sqrt{2 \pi \rho_d \Omega K_{\text{ep}}} \) and the viscous \( \tau_{\text{vis}} \) timescales, where \( \rho_d \) is the bulk density of dust and \( a \) is the grain size of dust. We find that the critical condition \( \tau_{\text{set}} / \tau_{\text{vis}} \geq 1 \) for dominance of the density versus thermal barriers presented by a dead zone is

\[
\Sigma \left( \frac{h}{r} \right)^2 \geq 25 \left( \frac{\alpha}{10^{-5}} \right)^{-1} \left( \frac{\rho_d}{1 \text{ g cm}^{-3}} \right) \left( \frac{a}{1 \text{ mm}} \right) \equiv C_{\text{crit}}. \tag{2}
\]

This implies that a density barrier is dominant for sufficiently large values of \( \Sigma \) and \( h/r \). For disks around CTTs with a typical dead zone size (\( \approx 10 \) AU), \( \Sigma h/r^2 \sim 300 \) g cm\(^{-2} \times (0.4)^2 \sim 2C_{\text{crit}} \) (Chiang & Goldreich 1997), which indicates that a density barrier is dominant. For disks around M stars with a typical dead zone size (\( \approx 5 \) AU), \( \Sigma h/r^2 \sim 20 \) g cm\(^{-2} \times (0.05)^2 = 2 \times 10^{-3} C_{\text{crit}} \) (Scholz et al. 2007), which implies that a thermal barrier is dominant. Generally, we find that a thermal barrier becomes weaker in the late stages because of accretion which reduces the density at the outer edge of the dead zones.

4.2. Comparisons with Other Possible Stopping Mechanisms and Potential Effects on the M–P Relation

It is well known that tidal interaction and angular momentum exchange with the central star (Lin et al. 1996) and the creation of a hole in the inner part of disks by the presence of a stellar magnetosphere (Shu et al. 1994; Lin et al. 1996) cannot reproduce the whole of the observed M–P relation. This is because such barriers become important only for planets approaching very close to the central star. Most ESPs, however, have observed orbital radii from about 0.02 AU to 10 AU (Udry & Santos 2007). Thus, while these barriers may play a role in piling up ESPs in the vicinity of the star, they have difficulty in predicting planets with larger orbital radii.

Stochastic migration provides another mechanism for controlling planetary migration. It arises when disks undergo magneto-hydrodynamic turbulence (Nelson & Papaloizou 2004; Laughlin et al. 2004), which is the outcome of the MRI (Balbus & Hawley 1991). Stochastic torques tend to reduce the timescale for planetary survival, however (Johnson et al. 2006). In a few exceptional cases, planets can diffuse out to large disk radii where they can survive longer. Planets within the dead zones cannot perform random walks because turbulent torques are reduced by about 2 orders of magnitude there and consequently would undergo steady inward type I migration (Oishi et al. 2007). Thus, stochastic migration is unlikely to be the main barrier to rapid type I migration.

Is our thermal barrier sufficiently wide to stop planets scattered into the dead zone by stochastic effects? We consider a characteristic length scale for turbulent diffusion defined by \( \Delta r_{\text{turb}} = \sqrt{\nabla \tau_r = h \sqrt{\sigma_r / \Omega L^{-1}}} \), where \( \tau_r \) is the correlation time of turbulence. We adopt a value \( \tau_r = 0.5 \Omega^{-1} \) (Nelson & Papaloizou 2004) and find that \( \Delta r_{\text{turb}} \approx 0.02 \) AU at \( r = 6 \) AU. This is shorter than the width of the thermal barrier (\( \sim 2 \) AU). Therefore, stochastic motions due to turbulence are unlikely to affect the migration stopping mechanism at the thermal barrier.

Corotation torques are also potentially important for slowing or stopping planets. In both barotropic and adiabatic disks, corotation torque associated with a radial vortensity gradient may work as a barrier around the region of inner edge of the dead zone (\( \sim 0.01–0.1 \) AU; Fromang et al. 2002; Masset et al. 2006; MPT09) because it becomes positive due to a positive surface density gradient, resulting in outward planetary migration (Masset et al. 2006). However, the location of the barrier is almost constant with time because stellar irradiation controls it, and consequently this barrier is important only for planets in the vicinity of the star. In adiabatic disks, corotation torque associated with a radial entropy gradient may also act as a barrier because it becomes large and positive around the region with a large (in magnitude), negative entropy gradient (Paardekooper & Mellema 2006; Baruteau & Masset 2008; Paardekooper & Mellema 2008; Paardekooper & Papaloizou 2008). Thus, corotation torque may be important to the M–P relation in certain regimes of planetary mass and disk heating, as noted above.

Our mechanism has a movable barrier that shrinks from larger disk radii on the 10 Myr (for CTTs) viscous timescale of the dead zone. As a concrete example, this shrinkage of the dead zone could explain the recent detected super-Earth at 2 AU around an M star (Beauchieu et al. 2006). This is because a super-Earth is likely to be the most massive planet that would surely form in a low-mass disk and is therefore most likely to have been formed beyond the outer dead zone radius and left behind as the dead zone shrinks away.

We conclude that the stopping mechanisms arising from dead zones—via thermal and density gradients—are important barriers to rapid planetary migration. We have shown that the thermal barrier that arises from disk irradiation by a heated dust wall is robust and may be most important in the earlier phases of disk evolution and for the evolution of low-mass systems, as found around M stars as an example. Dead zones may provide the most significant slowing mechanism of type I migration that is needed to explain the longer period of population of the M–P relation, which will be checked in future population synthesis models.

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