DEAD ZONES AND THE ORIGIN OF PLANETARY MASSES

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ABSTRACT

Protoplanets accrete material from their natal protostellar disks until they are sufficiently massive to open a gap in the face of the disk’s viscosity that arises from the magnetorotational instability. By computing the ionization structure within observationally well-constrained disk models, we demonstrate that poorly ionized, low-viscosity “dead zones” stretch out to 12 AU within typical disks. We find that planets of terrestrial mass robustly form within the dead zones while massive Jovian planets form beyond. Dead zones will also halt the rapid migration of planets into their central stars. Finally, we argue that the gravitational scattering of low-mass planets formed in the dead zone, to larger radii by a rapidly accreting Jupiter beyond, can explain the distribution of planetary masses in our solar system.

Subject headings: accretion, accretion disks — MHD — planetary systems: formation — planets and satellites: general — solar system: formation — stars: pre–main-sequence

Online material: color figures

1. INTRODUCTION

Current models for planet formation suggest that Jovian planets are formed either through gas accretion onto cores with \( \sim 10 \) Earth masses that are themselves assembled out of planetesimals (Mizuno 1980; Pollack et al. 1996) or through gravitational collapse when protostellar disks become cold and/or dense enough to be locally gravitationally unstable (Boss 1997; Mayer et al. 2002). However, independent of how their protoplanetary cores were formed, planets must open gaps in their natal disk before they become isolated. Ultimately, it is the process of gap-opening that terminates their growth or at least severely restricts their final masses. A planet must be sufficiently massive to tidally open a gap in the face of the disk’s viscosity, which acts to fill in a forming gap (Lin & Papaloizou 1993; Ida & Lin 2004).

In this Letter, we calculate the gap-opening masses within protostellar disk models that are well constrained by the observations and analyzed in Matsumura & Pudritz (2003, hereafter MP03) and show that there should be a distinct break in planetary masses akin to the difference between terrestrial and Jovian planetary masses. The reason for this break is that protostellar disks are likely to contain regions of very low viscosity—dead zones—in which the planetary gap-opening mass is much smaller than in regions of normal viscosity. In § 2, we lay out the theory of gap-opening masses in turbulent disks. We updated our MP03 disk models to include the effect of a nearby OB star, additional ionization sources, dust grains, as well as the turbulence driven in a dead zone by active layers (§ 3) and find that terrestrial mass planets form within the dead zones, while gas giant planets form outside of them (§ 4). Finally, in § 5, we apply our results to show that dead zones can halt the rapid inward migration of protoplanets and that scattering of low-mass planets in the dead zone to larger disk radii by a rapidly accreting gas giant beyond could explain the structure of our own solar system.

2. GAP-OPENING MASSES AND DISK VISCOSITY

The minimum gap-opening mass in a fully turbulent region of a protostellar disk, \( M_{\text{p, turb}} \), is attained when the angular momentum transport rate by a disk’s turbulent viscosity becomes equal to that by a planetary tidal force (Lin & Papaloizou 1993). It is readily shown that the gap-opening mass depends only on a disk aspect ratio \( h/r_p \) (\( h \) is the local pressure scale height of a disk and \( r_p \) is an orbital radius of the planet) and the turbulent viscosity parameter \( \alpha_{\text{turb}} \). For the case that the disk’s turbulence is absent, we applied the minimum gap-opening mass \( M_{\text{p, damp}} \) obtained by Rafikov (2002). Lin & Papaloizou (1993) also calculated a gap-opening mass in an inviscid disk by assuming that the density waves shock and damp immediately, but this requires a rather large planetary mass—the mass inside the Hill radius \( r_H = h \). Rafikov (2002) showed that the density waves excited by a much smaller planet eventually shock and lead to the gap formation. The ratio of the gap-opening planetary mass for a region that is fully turbulent, compared to that for an inviscid disk, can be written as

\[
\frac{M_{\text{p, turb}}}{M_{\text{p, damp}}} \geq 2.5 \sqrt{\alpha_{\text{turb}} \left( \frac{h}{r_p} \right)^{-23/26}} Q^{5/13},
\]

in all cases relevant to our disk model, where \( Q = \Omega c_s/\pi G \Sigma \) is the Toomre parameter that measures the gravitational stability of the disk, \( \Omega \) is the Keplerian angular velocity, and \( \Sigma \) is the surface mass density. For standard parameters, the critical mass ratio is of the order \( M_{\text{p, turb}}/M_{\text{p, damp}} \sim 100 \), which is comparable to the mass difference between terrestrial and Jovian planets.

A major source of a disk’s viscosity is thought to be hydrodynamical turbulence that is driven by the magnetorotational instability (MRI; Balbus & Hawley 1998). This mechanism requires good coupling between the partially ionized gas of the disk and the magnetic field. Poor coupling, which occurs when this gas is not ionized sufficiently, leads to the formation of a so-called dead zone, wherein the MRI disk viscosity is effectively zero. The spatial extent of a dead zone has been calculated by many authors (Gammie 1996; Sano et al. 2000; Glassgold et al. 2000; Fromang et al. 2002; MP03). Physically, the size of a dead zone can be determined by the condition that the local growth rate of the MRI turbulence \( (\approx \nu_{\text{A}}/h) \) becomes smaller than the Ohmic diffusion rate \( (=\eta/h^2) \), where \( \eta \) is the magnetic diffusivity and \( \nu_{\text{A}} \equiv B/(4\pi \rho)^{1/2} \sim \alpha_{\text{turb}} c_s \) is the Alfvén speed (\( \rho \) is the mass density, \( B \) is the magnetic flux density, and \( c_s \) is the sound speed). Detailed numerical cal-
culations show that this occurs when the ratio of these two growth rates, known as the magnetic Reynolds number,

$$\text{Re}_m = \frac{V_h h}{\eta},$$  \hspace{1cm} (2)

is less than a critical value of $\text{Re}_{m,\text{crit}} = 10^{-10}$ (Fleming et al. 2000). We use $\text{Re}_{m,\text{crit}} = 10^{-5}$ and $\alpha_{\text{turb}} = 10^{-3}$–1 in this Letter. Since the magnetic diffusivity $\eta$ is inversely proportional to the electron fraction, the MRI turbulence tends to be absent in poorly ionized regions of the disk.

In the surface layers of a disk, MRI turbulence will always be present and can drive vertical oscillations into the dead zone below. This process leads to angular momentum transport whenever the dead zone is not significantly denser than the active layers: $\Sigma_{\text{surf}}/\Sigma_{\text{MS}} \leq 10$ (Fleming & Stone 2003), where $\Sigma_{\text{surf}}$ and $\Sigma_{\text{MS}}$ are the surface mass density of the dead zone and the active layers, respectively. Therefore, the “true” dead zone should satisfy both conditions, and we calculated it using a self-consistent model for the disk structure.

3. DISK MODEL

Most stars are thought to be formed in star clusters such as the Orion Nebula cluster. A protostellar disk in such an environment will be irradiated by nearby luminous ($10^{3}$–$10^{6} L_\odot$) OB stars in the cluster. At the outer part of the protostellar disk, the disk heating by the UV radiation from a central T Tauri star (TTS) is overwhelmed by the combined radiation field of the nearby OB stars. As the outer disk temperature increases, the disk flares more strongly, and therefore planets are expected to have a higher gap-opening mass. Recently, Robberto et al. (2002), hereafter RBP02, improved the self-consistent model of passive protostellar disks of Chiang & Goldreich (1997) by taking into account the effect of an external OB star. They showed that the disk aspect ratio changes significantly. We used their model to calculate the vertical structure of a disk around a TTS that is exposed to OB stars.\(^2\)

Following RBP02 and without loss of generality, we assume that a disk is oriented face-on with respect to an O star that is located at a typical distance of 0.1 pc from the disk and has the luminosity of $L_\odot = 6 \times 10^{6}$ ergs s$^{-1}$ and a Strömgren radius of $R_{\text{str}} = 10^{18}$ cm. In all of our models, we adopt the disk surface mass density at 1 AU of $\Sigma_0 = 10^{3}$ or $10^{4}$ g cm$^{-2}$, which is equivalent to a disk mass inside 100 AU of $\sim 10^{-1}$ or 0.1 $M_\odot$, respectively ($M_\odot$ is the mass of the Sun). These disk masses are typical for TTSs (Hartmann et al. 1998; Kitamura et al. 2002).

The electron fraction that controls the magnetic diffusivity of disks is determined by the balance between ionization and recombination. For the ionization sources, we include X-rays from the central star and a nearby O star, cosmic rays, radioactive elements, as well as the uniform ionization by radioactive elements, as well as the thermal collisions of alkali atoms. Among these, X-rays from the central star and cosmic rays are the two major ionizing sources of protostellar disks (e.g., MP03). Protostellar X-rays may be generated within large loops of the stellar magnetic field that result from reconnection during magnetosonic accretion, as shown in time-dependent calculations (e.g., Hayashi et al. 1996). We assume that magnetic loops extend out to distances $(r, z) = (2 R_* , 2 R_*)$ from the stellar surface and adopt a typical TTS’s X-ray luminosity $L_x = 10^{36}$ ergs s$^{-1}$ and temperature $k T_x = 2$ keV (E. Feigelson 2003, private communication). We also assume that cosmic rays propagate along field lines and that the strength of cosmic rays is constant across the disk surface. Both ionization rates as well as uniform ionization by radioactive elements, as well as the uniform ionization by radioactive elements, as well as the thermal collisions of alkali metals (potassium) due to heating by the central star, following Fromang et al. (2002). They showed that there is a magnetically active zone at the innermost radii ($r \leq 0.1$ AU). We find, however, that the thermal ionization effect is killed if we take account of the recombinations on grains (see below). Our dead zone stretches from the inner disk radius to a few tens of AU. We also find that the X-ray ionization by a fiducial nearby O star with the X-ray luminosity $L_x = 10^{34}$ ergs s$^{-1}$ and temperature $k T_x = 2$ keV is too weak to affect the ionization structure of the disk.

For recombination processes, we considered the reactions among electrons, molecular ions, metals, and grains. At disk density $n \geq 10^{12}$ cm$^{-3}$, grains are very effective at reducing the charge in disks and hence increasing the diffusivity $\eta$. Were it not for the stimulation of turbulence in the body of the disk from the envelope, our detailed calculations, which followed the method by Umebayashi & Nakano (1990) and Fromang et al. (2002), show that very extensive dead zones—out to 16–29 AU—are to be expected.\(^3\) However, this “stimulated” turbulence limits the extent of a dead zone to smaller radii, typically 12–25 AU for our two fiducial disk column densities.

4. RESULTS

We show the spatial structure of disks as well as their internal dead zones in Figures 1 and 2, which correspond to disk column densities of $\Sigma_0 = 10^{3}$ and $10^{4}$ g cm$^{-2}$, respectively. Three curves show the disk height $z_{\text{surf}}$ where the magnetic Reynolds number $\text{Re}_m$ reaches its critical value of $10^3$ for $\alpha_{\text{turb}} = 0.01$, 0.1, and 0.001 from inside to outside. Also shown is the disk height $z_{\text{surf}}$ where the surface mass density ratio of below and above it is equal to 10: $\Sigma_{\text{below}}/\Sigma_{\text{above}} = 10$ (dashed line). We define the dead zone as the region where $z \leq z_{\text{surf}}$ and $z_{\text{surf}} > z_{\text{surf}}$, the intersection of $z_{\text{surf}}$ and $z_{\text{surf}}$ marks the outer dead zone radius. As the magnetic field becomes stronger (the parameter $\alpha_{\text{turb}}$ becomes larger), the dead zone becomes smaller. For a standard disk ($\Sigma_0 = 10^{3}$ g cm$^{-2}$) with ($\text{Re}_m, \alpha_{\text{turb}} = (10^3, 0.01$), we find that the dead zone stretches from the inner edge of a disk to 12 AU and encompasses the terrestrial planet region in our solar system (0.3–2 AU). For a moderately heavy disk ($\Sigma_0 = 10^{4}$ g cm$^{-2}$), the dead zone radius becomes 25 AU. These results agree well with previous works (e.g., Sano et al.

\(^1\) Recent numerical simulations by Fleming et al. (2000) defined the magnetic Reynolds number as $\text{Re}_m = \rho c h / \eta$ and determined the critical value in the range of $10^{-1}$–$10^{-9}$. In our definition of $\text{Re}_m = \rho c h / \eta$, ($\text{Re}_m, \alpha_{\text{turb}} = (10^3, 0.01$) and (10$^2$, 0.01) correspond to their $\text{Re}_m = 10^4$ and 10$^3$, respectively.

\(^2\) We compared three different grain models that give the emissivity difference of , the dead zone would be only slightly larger.\(^3\) To be consistent with the disk model, we assumed all grains have the same radius of 0.1 $\mu$m. Our electron fraction for a solar nebula model is about 2 orders of magnitude larger than the one obtained by Sano et al. (2000), because we ignore grains of charge $\pm 2e$. With their electron fraction and our choice of $\text{Re}_m = 10^3$, the dead zone would be only slightly larger.
2000). It may be possible that cosmic rays do not ionize disks because they are swept away by disk winds. In this case, disk ionization is determined primarily by X-rays from the central star and an external star. The dead zone radii then become slightly larger (14 AU for $\Sigma_0 = 10^3$ g cm$^{-2}$ and 36 AU for $\Sigma_0 = 10^4$ g cm$^{-2}$).

In Figures 3 and 4, we show the calculated gap-opening masses of planets for disks with $\Sigma_0 = 10^3$ and $10^4$ g cm$^{-2}$, respectively. Both disks are gravitationally stable (we find $Q_{\text{min}} > 3$ in our $\Sigma_0 = 10^4$ g cm$^{-2}$ model) so that planet formation by gravitational instability should not occur in these disk models. The upper parallel horizontal lines show the gap-opening masses with various viscous parameters, while the lower solid horizontal line shows the gap-opening masses in an inviscid disk. Vertical lines with crosses indicate the extent of a dead zone. A thick solid line shows the fiducial gap-opening mass throughout the disk.

In the core accretion scenario, the minimum gap-opening mass inside the dead zone is dictated by wave damping (lowermost line), while outside, the minimum gap-opening mass is determined by the strength of the MRI viscosity and hence the strength of the magnetic field (the value of $\alpha_{\text{turb}}$). The predicted planetary mass therefore makes a distinct jump upward to a value determined by the value of $\alpha_{\text{turb}}$ outside the dead zone. Our fiducial cases, shown in Figures 3 and 4 with a thick solid line, corresponds to $\alpha_{\text{turb}} = 0.01$ outside the dead zone. This $\alpha_{\text{turb}}$ value is suggested by observations of protostellar disks on scales $\sim 10$–100 AU (Hartmann et al. 1998; Kitamura et al. 2002). Along this line in Figure 3, we find the gap-opening mass becomes equal to an Earth mass $M_E$ at $\sim 0.7$ AU and a Jupiter mass $M_J$ at $\sim 17$ AU. Our results show that Jupiter or more massive gas...
giant planets must form outside the dead zones while terrestrial and perhaps even ice giant planets (see § 5) are likely to form within them.

5. AN INTEGRATED PICTURE FOR SOLAR SYSTEM FORMATION

Our results show that massive planets in our fiducial disk models form beyond 12 AU. This further supports the need of planet migration as an explanation of the observed exosolar systems. The presence of a dead zone may solve a nagging problem of migration theory—there is no general mechanism of halting a planet’s migration into the central star. The standard migration picture consists of two types of migration. When a protoplanet is not very massive, it migrates through the disk without opening a gap (type I). As a protoplanet gains a sufficient mass, it opens a gap in the disk and subsequently migrates with the disk on a viscous timescale (type II). The type I migration is roughly 2 orders of magnitudes faster than the type II migration (Ward 1997; Terquem 2003). This means that in an inviscid region like a dead zone, a migrating planet will be stalled as soon as it opens a gap (Chiang et al. 2002). Since the presence of finite dead zones is a robust feature of the protostellar disks, they may act as natural barriers that prevent the rapid loss of planets into their central stars.

The planetary masses predicted by our disk model (and others) increase with disk radius. In our solar system, this is not observed—the lower mass ice giants Uranus and Neptune are found at larger radii (19.2 and 30.1 AU, respectively). One scenario that can explain this mass sequence is the photoevaporation of the disk that reduces the surface mass density significantly beyond ~15 AU within ~10^7 yr (Adams et al. 2004), but this may be too long for currently accepted disk lifetimes.

We suggest an alternative—the gravitational scattering of lower mass protoplanets from within the dead zone to much larger radii by a gas giant located just outside of it. Numerical experiments (Thommes et al. 1999) have shown that a rapidly accreting Jupiter can scatter a more slowly growing protoplanetary core on an interior orbit as the former’s Hill sphere expands. The scattered low-mass body will ultimately circularize its orbit by dynamical friction at sufficiently large disk radii to be decoupled from the scatterer. This scenario has the distinct advantage of building the cores of ice giants much faster because it happens in the inner region of the disk. This process may occur naturally in our disk model. For example, in Figure 3 along the curve (Reπ, α_turb) = (10^5, 0.01), we find that a 0.74MJ planet is formed just outside the dead zone at r = 12 AU, while the maximum mass just inside the dead zone is 0.08MJ—which is roughly equal to the mass of an ice giant planet. The inner core(s) would be scattered when the disk gas becomes sufficiently tenacious so that the eccentricity can be excited.

An inevitable consequence of a dead zone is that material from the well-coupled region beyond its outer edge will accumulate at this interface. The increasing column density of such an annulus may push the dead zone outward in radius and may even become gravitationally unstable. We are currently investigating these time-dependent problems.

In conclusion, we have calculated planetary gap-opening masses in standard mass (~0.01 M_J) and moderately heavy (~0.1 M_J) disk models that are exposed to a nearby O star. With widely accepted values of (Reπ, α_turb) = (10^5, 0.01), we have found that the dead zone stretches out to 12 AU for the standard mass disk. We have shown that there is a distinct and model-independent range of planetary masses within the dead zone compared to the well-coupled zone beyond. With (Reπ, α_turb) = (10^3, 0.01), this corresponds to terrestrial mass planets ([2.4 × 10^{-4}MJ-8.3 × 10^{-3}MJ]) versus Jovian mass planets [(0.74-7.6)MJ]. The robust nature of our results leads us to conclude that dead zones are typical in protostellar disks and may play a central role in determining the masses of planetary families as well as their fates.

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