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DEAD ZONES AND THE FORMATION OF JOVIAN PLANETS

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RESUMEN

Los planetas terminan su fase de acrecentamiento cuando se vuelven tan masivos como para abrir brechas ante la acción de la viscosidad del disco. La predicción de que el espacio abierto, inducido por la masa, está relacionado con la viscosidad del disco implica que las masas planetarias son sensibles a la ionización del disco, en la situación esperada en la que la viscosidad esté impulsada por turbulencia magnética, gracias a la inestabilidad MRI. Mostramos que en las zonas muertas, de baja ionización y donde la inestabilidad MRI no se puede desarrollar, sólo pueden crecer planetas con masas terrestres, mientras que los planetas Jovianos se forman fuera de estas zonas. Las zonas muertas se extienden hasta 5-20 UA dependiendo de la densidad de columna del disco.

ABSTRACT

Planets may complete their accretion when they become massive enough to open gaps in the face of disk viscosity. The prediction that gap-opening mass is related to disk viscosity implies that planetary masses are sensitive to the degree of ionization of the disk in the expected situation that viscosity is driven by magneto-turbulence by the well-known MRI instability. We show that in dead zones - poorly ionized regions wherein the MRI instability is unable to develop - only planets of terrestrial mass can form while Jovian planets form outside such regions. Dead zones extend out to 5-20 AU depending upon the disk column density.

Key Words: **ACCRETION, ACCRETION DISKS — PLANETS AND SATELLITES: FORMATION — STARS: PLANETARY SYSTEMS**

1. INTRODUCTION

The ubiquitous presence of accretion disks around young stars together with the recent discoveries of exosolar planetary systems have opened up exciting new vistas for the theory of planet formation. Given that the typical star probably forms as a member of a star cluster such as the Orion Nebula Cluster (ONC), the typical initial conditions for planet formation are those characterizing the protostellar disks seen in the ONC. Stars and disks in the ONC are no more than a few million years old. The disks are heated by UV irradiation from their central stars. Recent Chandra observations of the ONC also show that protostars produce copious X-rays generated during their protostellar magnetospheric activity that may play an important role in ionizing their surrounding disks (eg. review Feigelson & Montmerle 1999). Finally, once the massive stars turn on as they have in the ONC, the outer reaches of the protostellar accretion disks undergo extensive UV photoevaporation beyond their "gravitational radii" (where gas heating leads to escape from the gravitational field of the central star).

The observed lifetimes of the ONC disks significantly constrain models of Jovian planet formation (see review Bodenheimer & Lin 2002). On the one hand, the core accretion picture - wherein a Jovian planet first must grow a 10-15 Earth mass rocky core through agglomeration before it is sufficiently massive to accrete its massive gaseous envelop - requires something less than 3 million years which is uncomfortably close to the inferred disk lifetimes. On the other, the gravitational instability picture - wherein gravitational instability through the violation of the Toomre Q stability criterion - can occur for sufficiently cool and massive disks within several hundred years which raises the question of why disks persist at all in the face of such rapid gravitational instability.

Regardless of the details of these formation mechanisms, the final mass of a Jovian planet probably depends upon whether or not it manages to open a gap in disk in the face of disk viscosity - growth by accretion from the disk must end when the mass of the planet is sufficient for the latter to occur (Lin & Papaloizou 1985 - LP85). It is straightforward to show that the final mass of a planet in this picture is its "gap-opening mass" which must depend on the disk's viscosity. One of the most important forms of disk viscosity arises from turbulence that is driven

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by the magneto-rotational instability (MRI - eg. review Balbus & Hawley 1998). The transport of angular momentum by the turbulent Maxwell stress that arises from this instability can only occur in regions of the disk that are sufficiently well ionized to ensure that the magnetic field is sufficiently well coupled to the gas. As was first pointed out by Gammie (1996) however, there is a region within a protostellar disk which is dense enough that the ionization from X-rays or cosmic rays is insufficient for this task. Such a region of poor coupling, and hence minimal MRI 'viscosity' is known as a dead zone. In order to elucidate the effect that such zones have on planet formation, Matsumura & Pudritz (2003 - MP03) recently investigated the structure of a dead zone within a particularly well-studied Chiang & Goldreich disk model that matches observations very well (eg. Chiang et al, 2001).

The importance of dead zones for the formation of giant planets has to do with the magnitude of the gap-opening mass within the zone as compared to its exterior. Within a dead zone there is some residual viscosity due to waves driven by protoplanetary cores. However, its value is a few orders of magnitude below that obtained outside of the dead zone at larger disk radii. A simple consequence of this abrupt jump in disk viscosity is that there should be a distinct jump in the masses of planets that can form - with terrestrial mass planets within the dead zone to Jovian and supra-Jovian masses outside - as we emphasized in our recent paper (MP03). We outline our work on the effects of dead zones on planetary masses.

2. GAP OPENING MASSES FOR TURBULENT DISKS

The basic relation linking the mass needed to open up a gap in the face of disk viscosity was derived by LP85. The ratio of the gap-opening mass of a planet (M_p) to the mass of the central star (M_*) can be written

$$\frac{M_{p,turb}}{M_*} \gtrsim \sqrt{40\alpha_{turb}\left(\frac{h}{a_p}\right)^5}, \qquad (1)$$

where α_{turb} represents the effective strength of the viscous force in a Shakura-Sunyaev model scaling - wherein the turbulent viscosity is assumed to scale as $\nu_{turb} = \alpha_{turb} c_s h$ where c_s is the sound speed in the disk and h is the disk pressure scale-height and a_p is the radius of the planet's orbit. This formula when applied for MRI-driven turbulence, assumes that the magnetic field is well coupled to the gas. In other words, the disk must be sufficiently well ionized so that the MRI instability grows in the face of Ohmic dissipation. While detailed simulations show that MRI turbulence cannot be completely modelled as a scalar viscosity, nevertheless they show that the effective disk viscosity is $\alpha_{turb} \simeq 10^{-2} - 10^{-1}$.

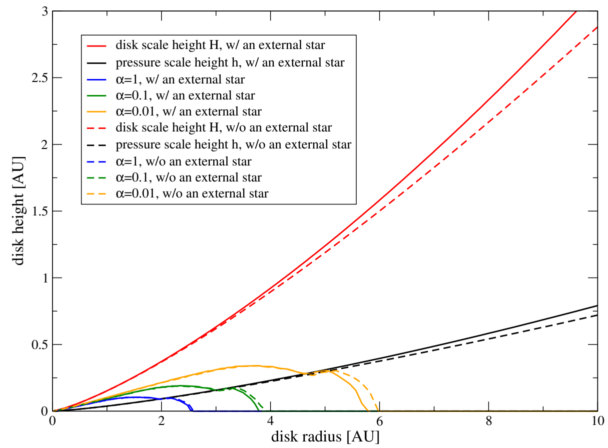

Fig. 1. Dead zones predicted for the total ionizing flux (including cosmic rays - see text), for different levels of disk turbulence, and for a disk column density of $\Sigma_o = 10^3$ g cm^{-2}.

In regions within the disk which are poorly ionized, angular momentum transport can still take place but at a much reduced rate. In the situation in which protoplanetary cores are present - either by gravitational instability or core accretion - the wakes from the protoplanets steepen and shock. There is a net outward transport of disk angular momentum is (eg. Rafikov 2002),

$$\frac{M_{p,damp}}{M_*} \gtrsim$$

$$\frac{2}{3}\left(\frac{h}{a_p}\right)^3 \min\left[5.2Q^{-5/7},\ 3.8\left(Q\frac{a_p}{h}\right)^{-5/13}\right], \qquad (2)$$

where Q is the Toomre parameter. This transport mechanism can also be associated with an effective viscosity parameter of $\alpha_{damp} \simeq 10^{-4} - 10^{-3}$. Taken together, these two results show that the ratio of the effective disk viscosity inside the dead zone to the better coupled region outside is lower by a factor of 100. This translates into a gap-opening mass increase of 100 in going between these two regions - just the ratio of masses of the gas giants to the terrestrial planets in our own solar system. The question is, where is the dead-zone boundary and what gap- opening masses can we expect for the type of protostellar disks that are actually observed?

The dead-zone is that region of a disk within which MRI turbulence fails to develop because of

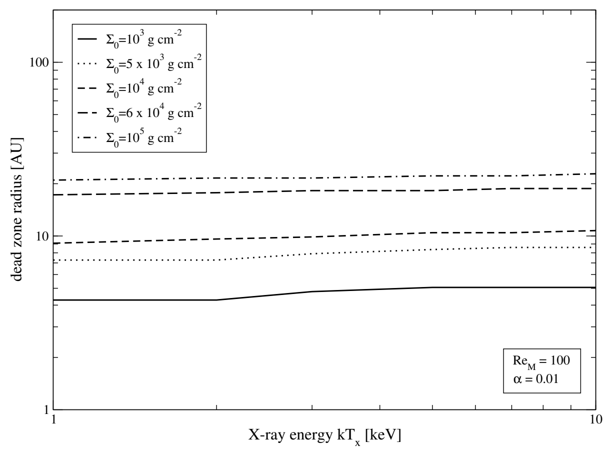

Fig. 2. Dependence of the outer dead zone radius on the X-ray energy, where the ionization is due to the combination of X-rays, cosmic rays (CRs), and radioactive elements. Our critical magnetic Reynolds number is $Re_{m,c} = 100$, and the MRI turbulence is characterized by $\alpha = 0.01$.

poor coupling. Formally, this condition translates into finding that region of the disk in which the growth rate of the MRI instability ($\simeq V_A/h$ where h is a pressure scale-height and V_A is the Alvén speed) is balanced by Ohmic diffusion on that scale ($\simeq \eta/h^2$ where η is the disk diffusivity). This is equivalent to finding those regions for which the magnetic Reynold's number $Re_m \leq 1$. More recent simulations suggests that the critical Re_m for suppressing the MRI instability may more likely be 100 (eg. Fleming et al 2000), and MP03 examine a broad range of critical values. The diffusivity of the field depends on the electron ionization fraction x_e which we calculate in detail for the sum of ionizing agents that include X-rays, cosmic rays, radioactive elements (not important), as well as thermal ionization (important in the innermost regions of the disk) - see MP03 for the details.

We compute the dead zones for disk models that are well constrained by observations. We used the two-layer Chiang et al model for disks that features a higher temperature disk envelope and a lower temperature disk interior. In this model, the disk envelope is heated by UV irradiation from the central TTS by the absorption of radiation by the dust (we have also investigated solutions in which the UV flux is dominated by an external massive star - typical of an ONC type of environment). Half of the emission from these grains then heats the disk interior. The disk is assumed to be in vertical hydrostatic equilibrium and has an envelope scale height

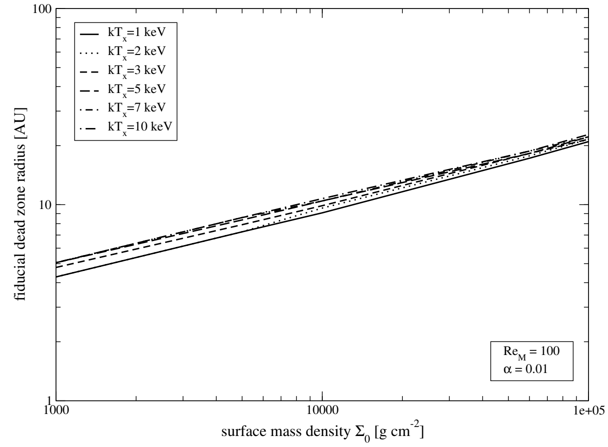

Fig. 3. Dependence of dead zone radius on disk column density.

$H(a)$ that is distinct from its interior pressure scale height $h(r)$ (typically $H(a)/h(a) \simeq 4$). The radial behaviour of the disk column density and pressure scale height scale as $\Sigma(a)/\Sigma_o = (a/AU)^{-3/2}$ and $h(a)/a = (T_i/T_c)^{1/2}(a/R_*)^{1/2}$ where Σ_o is the surface mass density of the disk at 1 A.U. and T_i is the disk interior temperature. We investigated a range of disk models from the minimum mass Solar Nebula ($\Sigma_o \simeq 10^3$ g cm^{-2}) to the heavier disk model advocated by Murray et al (1998) with 10^5 g cm^{-2}.

3. RESULTS

In Figure 1, we show the structure of our Chiang et al disk model in case of illumination of the central TTS as well as illumination by an external massive star at a typical distance (roughly 0.1 pc). The dead zone boundary is traced out by that curve along which the magnetic Reynolds number takes its critical value. The vertical and radial structure of the disk dead zone is shown for different values of the disk MRI 'viscosity', measured by the value of α. We choose the particular critical Reynolds number of $Re_{m,c} = 100$ for all of the plots in this paper, which may be a better choice than a value of unity. The dead zones shown here correspond to the total ionizing flux consisting of X-rays, CRs, and radioactive decays. Not shown in the plot is the effect of thermal ionization which, we calculate, cuts off the dead zone at an inner disk radius of $\simeq 0.07$ AU (a bit hard to resolve in our figure).

It is evident that lower levels of turbulence as measured by the α parameter lead to larger dead zones. Since the gravitational radius at which evaporation of our disk occurs is quite a bit larger than

10 AU for our chosen parameters, external irradiation has little effect on this outcome. We define the radius of the dead zone as that radius at which the entire disk pressure scale height is MRI inactive - ie, the radius at which the $Re_m = 100$ curve cuts into the disk interior from the envelope. Our rationale for this choice is that the well-coupled turbulent zone that lies above our dead zone consists solely of envelope material that is considerably lower in column density. It has recently been shown that if the contrast in column density between an upper well-coupled layer, and a lower, poorly coupled one is sufficiently large, then turbulence cannot propagate into the interior region through the excitation of velocity fluctuations and an associated Reynolds stress (eg. Fleming & Stone 2003, also Reyes-Ruiz, these Proceedings).

There has been considerable discussion in the literature about the respective roles of X-ray versus CR ionization of protostellar disks. We plot the dependence of dead-zone radius on the X-ray energy in Figure 2 for our particular disk models (see MT03 for a greater range of calculations). It can be clearly seen that at the Reynolds number chosen, there is little dependence on the energy of the X-rays constituting part of the total ionizing flux. It is clear that if CR do manage to penetrate to the surface of the disk then they are largely responsible for controlling the ionization structure of the regions beyond the inner thermally-ionized region of the disk. The caveat in this calculation is that the CR are assumed to reach the disk surface. It has been suggested that turbulent MHD winds - such as the solar wind - can sweep out CR in the solar system. In the TTS context, it could be that the outflow regions that are above and below the disk and consisting of MHD disk winds could play the same role. Much more work is needed to establish whether or not this might be possible.

In Figure 3 we show the sensitivity of dead-zone radius to the column density of the disk that is exposed to the total ionizing flux. The X-ray energy again plays little role and one sees a rather robust correlation between column density and dead-zone radius. The range lies between 5 AU for minimum mass, solar nebulae models, up to 20 AU for the dense disks used in Murray et al.

The ultimate goal of our work is to calculate the gap-opening mass of proto-planets within these disk models. Our first results on this are shown in Figure 4 (taken from Matsumura & Pudritz 2004). The bottom most curve in this figure are the predicted

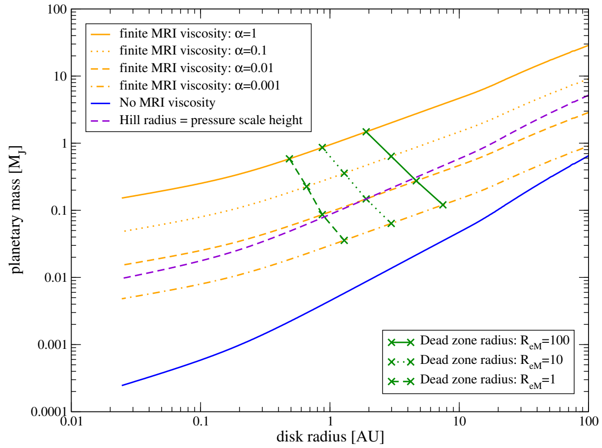

Fig. 4. Predicted planetary gap-opening masses and dead-zone for a minimum mass, solar-nebular model with $\Sigma_o = 10^3$ gm cm^{-2} (from Matsumura & Pudritz 2004). The lowest curve is for minimum viscosity characteristic of dead-zones. Outside of a dead zone, which is demarcated by vertical lines, the gap-opening mass curve follows a line of constant α.

gap-opening masses of planets in regions whose viscosity is solely due to protoplanetary wakes (cf equation 2). This situation, as noted earlier, is expected within the dead zone. Lying above these curves are predictions of disks with various values of finite, MRI viscosity - corresponding to different values of α. For reference, we also plot the masses of planets corresponding to the local Hill radius - taken to be the pressure scale height of the disk interior. This curve is related to the possibility of planet formation by gravitational instability. Finally, shown in directions that are nearly perpendicular to these sets of curves, are the locus of points that demarcate the dead zone outer radius for disk models of different critical magnetic Reynolds number (the inner dead zone radius due to thermal ionization is not shown in this plot, but occurs in the vicinity of 0.07 AU).

Figure 4 shows that there is a clear jump in gap opening mass as one proceeds along a curve of nearly zero viscosity to the point where one hits the dead zone radius - at which one make a sharp transition up to the curve that characterizes MRI viscosity in the well-coupled region beyond. Depending on the precise value of α, one sees that this factor can be as much as 100 or more. The dead zone also occupies a region that is much like the extent of the terrestrial planet region in our own solar system and may be the reason that terrestrial and Jovian planets have such different masses.

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