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THE MAGNETO-ROTATIONAL INSTABILITY IN PROTOPLANETARY DISKS

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RESUMEN

En este trabajo se presenta una revisión del problema de la acreción de masa a través de los discos protoplanetarios. Se hace énfasis especialmente en el papel jugado por la inestabilidad magnetorotacional (MRI) en el transporte de momento angular a través del disco. Se discuten las condiciones para el desarrollo de la MRI en las regiones débilmente ionizadas de discos protoplanetarios. Encontramos que la estratificación vertical del nivel de ionización, resultado de partículas y fotones externos de alta energía, inhibe el desarrollo de la inestabilidad aun más del que se encuentra en modelos con ionización uniforme. Se discute también la inducción de una viscosidad anómala en la llamada zona muerta de los modelos de acreción en capas, por las fluctuaciones en velocidad del material en las zonas activas que la rodean. Concluimos que el transporte de momento angular a través de la zona muerta ocurre con una eficiencia comparable a la de las zonas activas vecinas. Esto implica que los modelos actuales de discos protoplanetarios basados en la idea de acreción en capas deben ser revisados en favor de modelos 1-D con un coeficiente de viscosidad variable.

ABSTRACT

We review the current understanding of how mass accretion takes place in protoplanetary disks. Particular emphasis is placed on the role played by the magneto-rotational instability (MRI) in the transport of angular momentum across the disk. We discuss the conditions for the development of the MRI in the poorly ionized regions of protoplanetary disks. We find that the vertical stratification of the ionization degree, resulting from the incidence of extraneous energetic particles or photons, hinders the development of the MRI to a greater degree than that resulting in uniform ionization models. We also discuss the anomalous viscosity induced in the so-called dead zone by the velocity fluctuations of gas in the neighboring active layers in layered accretion models for protoplanetary disks. We conclude that angular momentum transport through the dead zone occurs at a comparable efficiency to surrounding active layers. This implies that current protoplanetary disk models based on the idea of layered accretion, must be revised in favor of 1-D models with a radially varying viscosity coefficient.

Key Words: **HYDRODYNAMICS — UNSTABILITIES — PLANETARY SYSTEMS : FORMATION — ACCRETION : ACCRETION DISKS**

1. INTRODUCTION

One of the main problems in the understanding of the process of planetary system formation is having reliable models for the physical conditions and evolution of protoplanetary disks. The strong interrelation between the evolution of the gaseous component, dependent on the distribution of "viscous" and self-gravity torques, and that of the dusty component, impacting dust opacity, as well as the dependence on external factors, has not permitted the development of a standard model for protoplanetary disks. There is a consensus however, in that for most of their lifetimes, disk models are based on the formalism of geometrically thin, viscous accretion disks.

Accretion disks are generally believed to evolve driven by an effective "viscous" torque, due to the

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turbulent state of gas and magnetic fields, within them. In the seminal paper of Balbus & Hawley (1991) the elusive instability giving rise to accretion disk turbulence was finally pinpointed. The so-called Balbus-Hawley or magnetorotational instability (also referred to as MRI hereafter) relies on the existence of a magnetic field threading the disk and sufficient coupling between such field and the disk material (Jin 1996). It is a linear and local instability whose evolution to the nonlinear regime has been shown to lead to sustained turbulence and an effective torque as that required by accretion disk models. The requirements for the MRI to develop are believed to be satisfied in most accretion disk scenarios, except in protoplanetary disks.

In the accretion disks believed to exist around many young stars, generally called protoplanetary disks, the degree of ionization of gas in all but the innermost regions is very low. In most current models (for example Ruden & Pollack 1991, Stepinski 1998) the disk's midplane temperature drops from a few thousand Kelvin in the vicinity of the central star to a few hundred degrees at the location of the terrestrial planets. Hence, beyond a fraction of an AU, where even the thermal ionization of alkali metals is impossible, the degree of ionization near the midplane, and with it the electrical conductivity, drops sharply (Stepinski 1992). External sources such as galactic cosmic rays (Stepinski 1992) and high energy radiation from the central star (Najita et al. 1996) may still ionize the top layers of the disk so that material near the surfaces of the disk is well coupled to the magnetic field (Dolginov & Stepinski 1994).

Under the assumption that the only source for disk turbulence is the magnetic shear instability, and that in a stratified medium it operates as in the uniform case the stratification of the electrical conductivity in protoplanetary disks translates into a scenario of layered accretion as suggested by Gammie (1996). In such scenario, the ionization degree in the innermost regions and top surfaces of the disk is sufficiently high to allow good coupling between the gas and the magnetic field. The opposite occurs beyond a certain radius near the midplane, so that the BH instability may develop, and angular momentum transport may occur only in the well ionized layers near the surface of the disk. Gammie (1996) called these the active layers (AL) and labeled the middle region as the dead zone (DZ), where the BH instability may not develop. He calculated the steady state structure of the disk assuming mass accretion may occur through the AL. Although a steady state solution for the disk structure was found, it involved the constant deposition of material in the DZ, which was left out of the calculation, leading to the eventual gravitational instability of the dead layer.

These calculations have been recently extended by Stepinski (1999) who, in addition to considering the time dependent scenario, incorporates the possibility of having a finite viscosity, i.e. non-zero, in the DZ. No explanation of the origin of the dead layer viscosity is given in such work, it is incorporated adopting Shakura & Sunyaev's prescription with different values of the parameter $\alpha_{\rm SS}$ for the active and dead layers. Results are found to depend on the ratio between the $\alpha_{\rm SS}$ in the AL and the value of $\alpha_{\rm SS}$ in the DZ, called β by Stepinski (1999). In general, his results indicate that, depending on the value of β, the evolution of protoplanetary disks, the basic ambient of planetary system formation, could be drastically different from that predicted by most current models for protoplanetary disks. Such differences are important if β is much less than unity. In such case, the studies of Stepinski (1999) indicate the existence of a limit-cycle behavior due to the layered nature of the accretion process. The disk properties exhibit rapid time variability, on a timescale of 1000 to 10000 years. A similar conclusion is reached by Armitage et al. (2001) who incorporate the effect of self-gravity in transporting angular momentum in the outer regions of the disk.

Given the importance of having consistent models of protoplanetary disks as a *necessary* step to develop planet formation theories, in this paper we review the assumptions leading to the model of layered accretion. We begin by analyzing the development of the MRI in the linear regime in a vertically stratified medium. This gives us a criterion to determine at which radial locations the MRI will arise. Next, we analyze the efficiency of angular momentum transport in the DZ. Our basic hypothesis is that the hydrodynamic fluctuations of the AL will propagate into the DZ giving rise to a net, positive $\phi - r$ component of the Reynolds stress, thus leading to angular momentum transport and mass accretion through the DZ. Our aim is to determine the value of the parameter β of Stepinski (1999) to asses the importance of layered accretion on the evolution of protoplanetary disks.

2. LINEAR ANALYSIS OF THE MRI

On the basis of a quasi-global, linear analysis of the MRI we obtain a criteria for the development of the MRI in disks with a strong vertical stratification of the ionization degree, and hence of the magnetic

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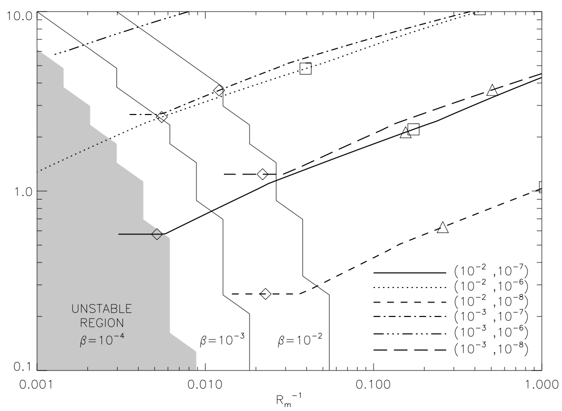

Fig. 1. Corresponding values of R_m and l_o for various disk models. In the linestyle legend the numbers in parenthesis indicate (α , $\dot{M}$). The leftmost edge of each line corresponds to R_m and l_o values at 60 AU. In each case, the triangle and diamond indicate the values at 1 AU and 10 AU respectively. Squares mark the outer boundary of the inner well ionized region, inwards of which the MRI easily develops.

diffusivity also (Reyes-Ruiz 2001). The vertical ionization degree profile is taken from studies of the ionization state of protoplanetary disks as those of Dolginov & Stepinski (1994) and Stepinski (1992).

When applied to typical α-disk models for a protoplanetary disk, the criteria allows us to determine where the MRI will develop. We have done this for a series of models, characterized by the value of α and the mass accretion rate, $\dot{M}$ (given here in $M_\odot/yr$. The results are summarized in figure 1, where R_m and l_o are plotted for various disk models ranging over typically quoted values for α and $\dot{M}$. Also indicated in the figure are the regions of instability for different values of the magnetic field strength as expected for protoplanetary disks.

Using figure 1 we can see for example, that a disk characterized by $\alpha = 10^{-3}$ and $\dot{M} = 10^{-8} M_\odot/\mathrm{yr}$ (long dashed line) will be stable everywhere unless the seed magnetic field is strong enough that the plasma parameter β is $\sim 10^{-2}$. In such case, the region between a few tenths of an AU (the triangle marks 1 AU) to almost 10 AU (marked by the diamond symbol) will be stable to the MRI.

We conclude from our analysis that for most protoplanetary disk models, in a broad region between a fraction of an AU and a few AU, the MRI does not develop *at all*. Outwards of this "dead" region, our analysis suggests that the MRI may develop as proposed in the layered accretion scenario. Even further out, as the stratification of the ionization degree decreases, the MRI may develop across the whole vertical extent of the disk as in the innermost active region.

3. VISCOSITY IN THE "DEAD" ZONE

Following the results described in the previous section to determine the distribution of viscous torques in protoplanetary disks, we continue our study looking at the dynamical state of gas in the so-called dead zone.

To do this we consider a passive layer of gas around the disk midplane (the dead zone) surrounded by turbulent (active) layers near the disk surfaces. Numerical simulations using the ZEUS-3D code where performed modeling the region of study as a shearing box. Turbulence in the active layers was generated introducing a forcing term as used in previous studies of driven turbulence in accretion disks (Brandenburg & von Rekowski 2001) to mimic MHD turbulence generated by the MRI.

We start our simulations from a relaxed state reached by the system without the effect of the forcing term. The results depend mainly on 2 parameters; the relative thickness of the active layer, H_a/H, where H_a is the thickness of each active layer, and the strength of the forcing term. Figure 2 shows the temporal evolution of the volume averaged kinetic energy density in the y-velocity fluctuations (upper panel) and the volume averaged xy component of the Reynolds stress. The latter is the main responsible for the transport of angular momentum across the disk and is typically identified as a viscous stress. The case shown in figure 2 is characterized by a relative active layer thickness corresponding to $H_\mathrm{a}/h = 0.5$.

Generally, the temporal evolution proceeds as follows. Once the forcing term is turned on, turbulent velocity fluctuations in the active layers quickly give rise to fluctuations in the dead zone. After a few orbital periods, the volume averaged kinetic energy density in the y-velocity fluctuations in the dead zone becomes comparable to the corresponding quantity in the active layers. After approximately 10 orbital periods the volume averaged xy component of the Reynolds stress in the dead zone also reaches a magnitude comparable to its value in the neighboring active layers. After ~ 10 orbital periods, both quantities oscillate around an equilibrium value for as long as the simulations last. In the simulations shown, after 38 orbital periods the forcing term is turned off and the system quickly relaxes, returning to the equilibrium keplerian flow.

A qualitatively similar result is found for different

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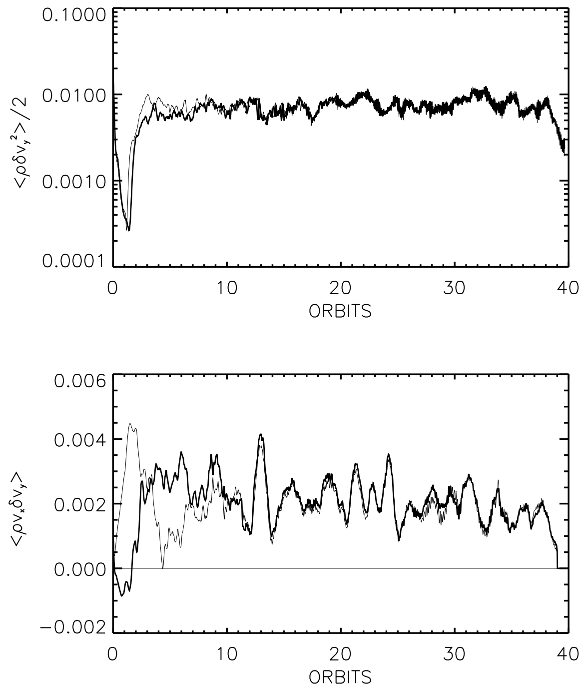

Fig. 2. Temporal evolution of the volume averaged kinetic energy density in the y-velocity fluctuations (upper panel) and the xy component of the Reynolds stress (lower panel) for case of thick active layers, $H_{\rm a}/H = 0.5$. The thin lines show values corresponding to the active layers and the thick lines correspond to the dead zone.

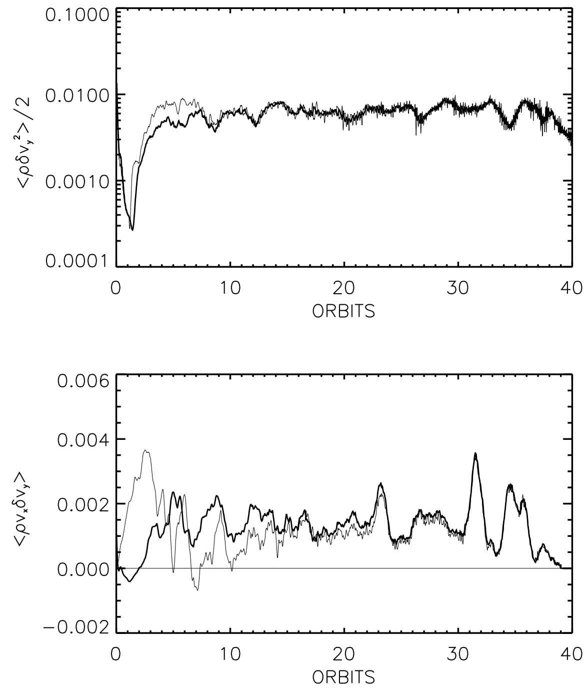

Fig. 3. Temporal evolution of the volume averaged kinetic energy density in the y-velocity fluctuations (upper panel) and the xy component of the Reynolds stress (lower panel) for case of thick active layers, $H_{\rm a}/H = 0.1$. The thin lines show values corresponding to the active layers and the thick lines correspond to the dead zone.

values of the relative active layer thickness. Figure 3 shows the temporal evolution of the volume averaged kinetic energy density in the y-velocity fluctuations, K_y, and the volume averaged xy component of the Reynolds stress, T_{xy}, for case of thin active layers, $H_{\rm a}/H = 0.1$.

We have carried out several simulations with different values of the relative thickness of the active layers and different strengths for the forcing term. We have found that both parameters have little effect on the ratio of dead zone to active layers average K_y and T_{xy} once an equilibrium state is reached. Both ratios equilibrate near unity for all cases computed. There is a difference in the time taken to reach this equilibrium with cases characterized by thinner layers and weaker forcing taking somewhat longer (up to 20 orbital periods). Also, there is difference in the equilibrium value for both K_y and T_{xy} in the dead zone and active layers, cases characterized by thinner layers and weaker forcing reach smaller values of K_y and T_{xy} in the system.

These results imply that the turbulent motions in the active layers give rise to a net xy component of the Reynolds stress in the so-called dead zone, leading to radial angular momentum transport and inward mass accretion. The efficiency for angular momentum transport in the dead zone, typically measured by the parameter α, is comparable to the value in the active layers. In view of these results we suggest a more appropriate name for this region would be the *neutral* zone.

It is important to point out that, in contrast to the neutral zone, in the active layers an additional source of "viscosity" is the Maxwell stress. According to numerical simulations, the effect of the magnetic field in well ionized regions yields an effective α a few times greater than that resulting from the Reynolds stress alone (for a review see Balbus & Hawley 1998). Hence, the ratio of α parameters in the neutral zone and active layers, $\alpha(\text{dead})/\alpha(\text{act})$, is expected to be between 2 and 4 once the effect of the Maxwell stress in the active layers is taken into account. Although there is a difference in the viscous torque between active layers and the neutral region, according to Stepinski (1999) there are only small differences in the structure and evolution of such a system with respect to a disk without vertical stratificiation.

4. CONCLUSIONS

According to our results, the development of a layered accretion scenario is unlikely since: 1) where the stratification is strong, the instability does not arise and 2) where the stratification is weak and the MRI may develop preferentially near the disk surfaces, turbulence in these active layers gives rise to significant viscous stress in the presumably dead zone.

Consequently, current protoplanetary disk models based on the layered accretion scenario must be revised in favor of 1-D models with a non-uniform α parameter. These models would typically be active, i.e. MHD turbulence would give rise to significant viscosity, in the innermost and outermost parts. Depending on the model parameters, outwards of the inner active region the disk could have a region of zero turbulent viscosity (if the ionization stratification is very strong) followed by a region characterized by a lower value of α than the inner or outer active regions, corresponding to the region in our simulations.

In the evolution of such disks one must incorporate other factors, such as self-gravity, which could become important in the development of the neutral, in-viscid region where the MRI does not develop.

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