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Mauricio Reyes Ruiz / E. Pérez Tijerina / F. J. Sánchez Salcedo
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EVOLUTION OF PROTOPLANETARY DISCS DRIVEN BY MHD TURBULENCE AND OTHER AGENTS

Mauricio Reyes-Ruiz,[1] E. Pérez-Tijerina,[2] and F. J. Sánchez-Salcedo[3]

RESUMEN

Después de revisar el estado de nuestro conocimiento de cómo opera la inestabilidad magnetorotacional (MRI) en discos protoplanetarios, presentamos resultados preliminares sobre la evolución de tales sistemas, basándonos en la predicción de distribución espacial de torcas viscosas. Se construyen modelos unidimensionales de discos α para los discos protoplanetarios incorporando diferentes valores del parámetro α para reflejar los diferentes agentes que participan en la evolución de los discos. Tomamos en cuenta los efectos de viscosidad turbulenta debido a la MRI, de torcas de autogravedad (prescritas en términos de una viscosidad efectiva) y de otros agentes viscosos caracterizados por una eficiencia reducida. La estructura y evolución resultante para los discos es drásticamente diferente a la predicha por modelos de discos con α uniforme o por modelos de acreción en capas.

ABSTRACT

After reviewing our current understanding of how the magnetorotational instability (MRI) operates in protoplanetary disks, we present preliminary results on the dynamical evolution of such systems, based on the predicted spatial distribution of viscous torques. One-dimensional, α-disk models are constructed for protoplanetary disks incorporating different values of the α parameter to reflect different agents giving rise to the torques driving disk evolution. We take into account the effects of turbulent viscosity resulting from the MRI, of torques resulting from self-gravity, prescribed in terms of an effective viscosity, and of other agents characterized by a less efficient turbulent viscosity. The resulting disk structure and evolution is drastically different than that predicted by uniform α models or by layered accretion models for protoplanetary disks.

Key Words: **ACCRETION, ACCRETION DISKS — MAGNETOHYDRODYNAMICS: MHD — STARS: PLANETARY SYSTEMS: PROTOPLANETARY DISKS**

1. INTRODUCTION

Theoretical models for protoplanetary discs have been constructed taking into account several dynamical factors. Among these, self-gravity instabilities and the so-called magnetorotational instability are currently considered as the most important agents driving disc evolution. Recently, results of both linear analysis (Richard 2003) and numerical simulations (Khlar & Bodenheimer 2003) suggest that one should also expect the existence of hydrodynamical turbulence in protoplanetary disks, alltough probably with a reduced efficiency in transporting angular momentum. The evolving distribution of torques due to either of these mechanisms defines the physical properties of the gas within protoplanetary discs and hence, it sets the stage for the process of planetary system formation.

The ability of the MRI or any other factors in the transfer of angular momentum depends on the physical conditions in the disc. Self-gravity instabilities are known to be the dominant agent driving disc evolution in the commonly called formation stage, when infall from the parent molecular cloud is still taking place. The precise role of self-gravity instabilities in the transport of angular momentum at other times during the disk evolution is not clear at present. We address this issue briefly in this paper.

Subsequent evolution of protoplanetary discs is believed to be driven by "viscous" torques resulting from MHD turbulence, generated by the MRI, and possibly with the contribution of hydrodynamic turbulence, particularly in those regions where the MRI can not develop. Although specific details vary considerably among studies of the criteria and spatial distribution of the MRI (Jin 1996, Blaes and Balbus 1994, Sano and Miyama 1999, Reyes-Ruiz 2001, Fromang et al. 2002) most coincide in finding the existence of three distinct regions in protoplanetary discs. An inner active region, extending up to a fraction of an AU, where thermal ionization of alkali

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[1] Instituto de Astronomía-UNAM, Ensenada, México.

[2] Presently at Facultad de Ciencias-UANL, Monterrey, México.

[3] Instituto de Astronomía-UNAM, México, D.F., México.

metals may lead to a ionization degree sufficient for the development of the MRI. An outer region, starting after a few AU, where external agents, namely energetic particles or photons from the central star, or galactic cosmic rays, can penetrate the disk and lead to the required ionization degree. And an intermediate region where, at most, the MRI can only be excited in thin layers (active layers) near the disk surfaces, where ionization due to external agents can lead to the emergence of the MRI. Sandwiched between these active layers is a region where external ionizing agents can not penetrate and hence the neutral gas is decoupled from the magnetic field.

On the assumption that no source of angular momentum transport is present in the dead zone, Gammie (1996) proposed a layered accretion scenario in which the structure of the disk has significant consequences for the process of planet formation. However, as has been recently shown by Fleming & Stone (2003) and Reyes-Ruiz et al (2003), turbulence in the active layers gives rise to significant viscous torques in the presumed dead zone. Consequently, the structure and evolution of protoplanetary disks is not as that predicted by evolutionary models of layered disks (Stepinski 1999, Armitage et al. 2001). In this paper we compute the evolution of protoplanetary disks taking into account these recent results on the distribution of viscous torques across the so called dead zone. In our opinion, these imply that radial, one-dimensional models, in which the intermediate region is modeled as a region of lower viscosity, may be sufficient to capture the essential features of protoplanetary disk structure and evolution.

2. LINEAR ANALYSIS OF THE MRI

On the basis of a quasi-global, linear analysis of the MRI, Reyes-Ruiz (2001) obtained a criteria for the development of the MRI in disks with a strong vertical stratification of the ionization degree, 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.

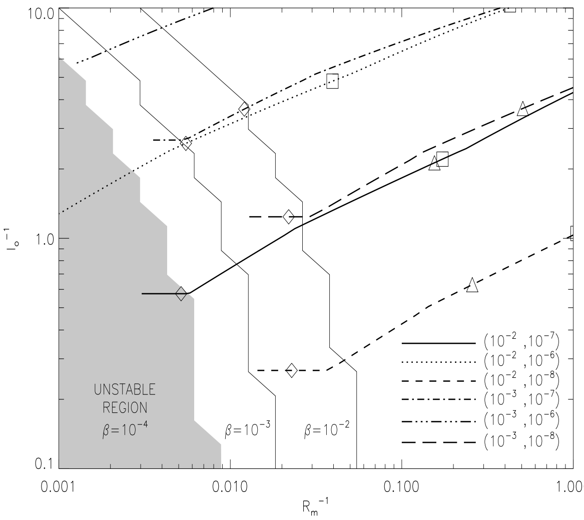

Fig. 1. Corresponding values of R_m and l_o for various disk models. In the linestyle legend the numbers in parenthesis indicate (α , $\dot{M}$). The leftmost edge of each line corresponds to R_m and l_o values at 60 AU. In each case, the triangle and diamond indicate the values at 1 AU and 10 AU respectively.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

Figure 1 shows for for example, that a disk characterized by $\alpha = 10^{-3}$ and $\dot{M} = 10^{-8} M_{\odot}$/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 linear 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

We have studied the dynamical state of gas in the so-called dead zone at radii where the MRI may lead to layered accretion. 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 (Reyes-Ruiz et al. 2003). Numerical simulations using the ZEUS-3D code where performed modeling the region of study as a shearing

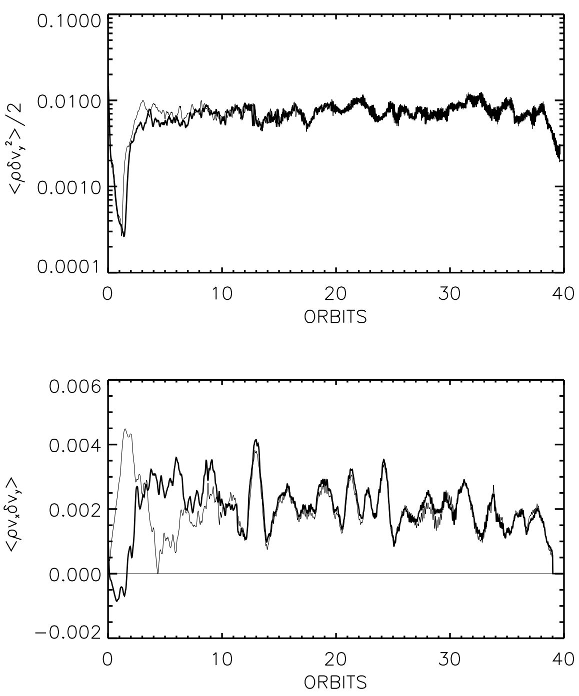

Fig. 2. Temporal evolution of the volume averaged kinetic energy density in the y-velocity fluctuations (upper panel) and the $x - y$ component of the Reynolds stress (lower panel) for case of thick active layers, $H_{\rm a}/H = 0.1$. The thin lines show values corresponding to the active layers and the thick lines correspond to the dead zone.

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 the relative thickness of the active layer, $H_{\rm a}/H$, where $H_{\rm a}$ is the thickness of each active layer and H is the disc half thickness. Figure 2 shows the temporal evolution of the volume averaged kinetic energy density in the y-velocity fluctuations, $K_y =< \rho \delta v_y^2 > /2$ (upper panel) and the volume averaged xy component of the Reynolds stress, $T_{xy} =< \rho v_x \delta v_y >$. 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 $H_{\rm a}/h = 0.1$. A qualitatively similar result is found for different values of the relative active layer thickness.

We have found that the ratio of both K_y and T_{xy} in the dead zone to their corresponding values in the active layers, balance near unity for all cases computed after about 10 rotational periods. 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. These results are compatible with more recent, full-MHD numerical simulations of a similar disk configuration conducted by Fleming & Stone (2003).

It is important to point out that magnetic stresses, dominant in the active layers, are not important in the dead zone. Hence, if an effective α is used to incorporate the effect of Reynolds and Maxwell stress into a viscosity prescription, the α parameter corresponding to the dead zone should be a factor of 3 or 4 smaller than the value at the active layers.

4. EVOLUTION OF PROTOPLANETARY DISKS

On the basis of the results described above, we propose to model protoplanetary disks as 1D accretion discs with a nonuniform α parameter. At disc radii where the MRI can not emerge, according to the linear criterion described above, the α parameter is taken to be a lower value, α_{hydro}, presumably resulting from hydrodynamic turbulence or a reduced vertically averaged value from a layered accretion scenario. We also verify at each radii whether the disc is gravitationally unstable by computing the Toomre parameter, $Q_T = C_s\Omega/\pi G\Sigma$. When $Q_T < 1.5$ we include the effect of selfgravity by adding an effective viscosity following Lin & Pringle (1987).

Figure 3 shows the evolution of the disc global properties, disc mass, disc radius and mass accretion rate, for a fiducial model having $\alpha = 0.01$ in the active regions and $\alpha = 0.001$ in regions where the linear criterion for the MRI to develop is not met. In this model, angular momentum resulting from self gravity instabilities is never an important factor.

The evolution of the disc structure is illustrated in Figure 4, where radial profiles of the surface density, Σ and the midplane temperature, T, are shown.

5. 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

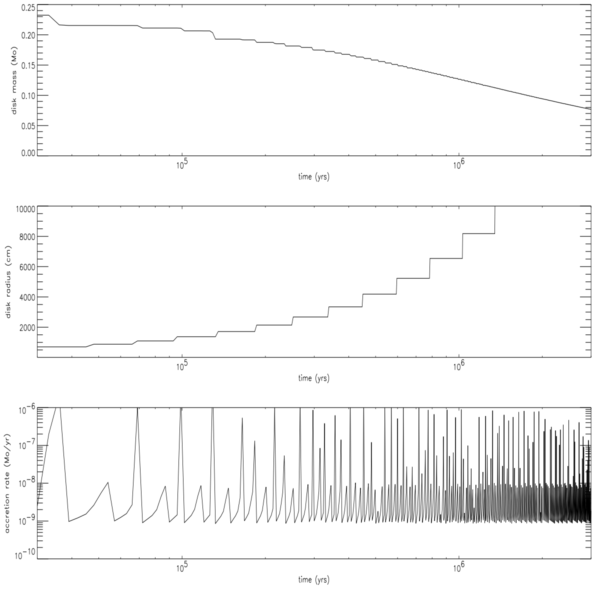

Fig. 3. Evolution of the global properties of a protoplanetary disc characterized by an $\alpha = 0.01$ in the active regions and $\alpha = 0.001$ in regions where the MRI is not present. Plots correspond to disc mass in solar masses (top panel), disc radius in AU (middle panel) and mass accretion rate onto the central star in $M_\odot$/yr (bottom panel).

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. Such models have been constructed and preliminary results indicate that the presence of the dead region leads to a disk structure and evolution significantly different from that of layered or uniform α models. In comparison to uniform α models, the disk structure of our fiducial model shows an accumulation of material, and significantly greater midplane temperatures in the intermediate dead region, which extends from less to 0.1 AU to approximately 4 AU after 10^6 years (see Figure 4).

Also, as shown in Figure 3, the evolution of disk is not as quiescent as for uniform α models, having brief episodes of increased mass accretion going from a base value of 10^{-9} $M_\odot$/yr up to 10^{-6} $M_\odot$/yr on a timescale of about 10^4 yr. Further studies are needed to asses the relevance of this apparently important disc evolution features on the process of planet formation.

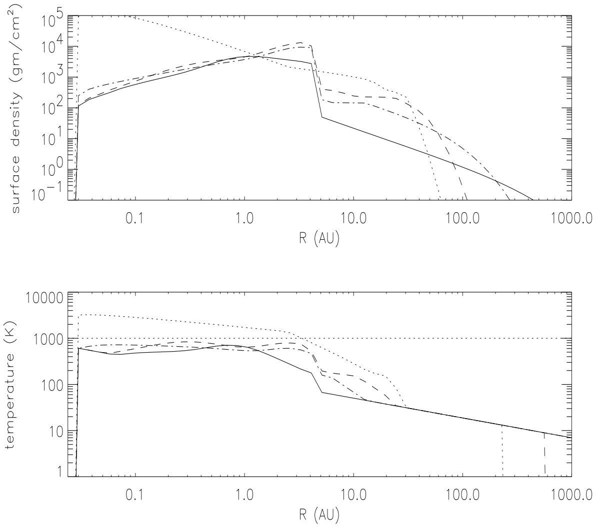

Fig. 4. Radial profiles of Σ and T at different times for the same model of Figure 3. Profiles at the initial condition (dotted line), $10^{4.5}$ yr (dashed line), $10^{5.5}$ yr (dash-dotted line) and $10^{6.5}$ yr (solid line) are shown.

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