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Dynamics of the inner edge of the dead zone in protoplanetaty disks

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Abstract. In protoplanetary disks, the inner boundary between an MRI active and inactive region has recently been suggested to be a promising site for planet formation. A set of numerical simulations has indeed shown that vortex formation mediated by the Rossby wave instability is a natural consequence of the disk dynamics at that location. However, such models have so far considered only the case of an isothermal equation of state, while the more complex thermodynamics of this region may have strong consequences on disk properties because of thermal ionization. Gas is heated by turbulent dissipation and radiatively cools on long timescales because disks are optically thick.

Using a mean field model of the dynamics of that boundary, Latter and Balbus (2012) have shown that this complexity can lead to situations in which the active/dead interface moves systematically inward or outward, depending on the initial conditions. This is because turbulent activity is controlled by ohmic resistivity that is itself a sensitive function of temperature. Such a behavior suggests, as observed in young stellar object, a non-steady accretion onto the central star.

Using the Godunov code Ramses, we have performed 3D global numerical simulations of protoplanetary disks that relax the isothermal hypothesis in order to check the above scenario. We confirm the existence of such MRI fronts, thus validating the mean field approach described above. As shown by Latter and Balbus (2012), MRI fronts tend to stop at a critical radius. We argue that the typical front velocity crucially depends on turbulent diffusion of temperature. The diffusivity of temperature due to turbulence is measured to be order of H^2/Ω where Ω is the local orbital time and H the typical height of the disk.

1 Introduction

Recently it has been found that accretion mismatch at the interface between the active zone and the dead zone in protoplanetary disks form a pressure maxima[1] at that critical radius. It could lead, as a result of the rossby wave instability, to vortex formation [2]. Vortex are known to be suitable locations for dust accumulation and coagulation: planet formation. Previous studies have been done under the locally isothermal approximation while a complex interplay between thermodynamical processes and turbulence takes place in the inner part of the disk: Turbulent activity depends on resistivity η that is a function of temperature. The latter is set by turbulence which closes the feedback loop. This

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non isothermal behaviour has been investigated using a mean field model ([3]). The results show that the inner edge of the dead zone is not static (has assumed by [1] and [2]) but exhibits a dynamical behaviour. The authors called this phenomenon an *MRI front*. We performed non locally isothermal MHD simulations to test the validity of the mean field approach and to study the implication of thermodynamical processes on vortex and pressure maxima formation.

2 Setup and basic checks

We run 3D MHD simulations using the RAMSES code ([7] and [4]) with a uniform grid. Being interested in the inner edge behaviour at the mid-plane, we do not take into account vertical stratification and work in the cylindrical approximation ([10], [11], [9]). The initial magnetic field is purely toroidal and the total net flux is zero. We assume a classical cooling function:

$$Q_e = \sigma\rho(T^4 - {T_0}^4)$$

while turbulent heating is captured by solving the equation on total energy. We use a perfect gas equation of state. We first run an ideal MHD case ($\eta = 0$) to test our implementation of the thermodynamical processes. The good agreement between the radial profile we obtain and the expectation of a classical α-disk model validates our code (see figure 1).

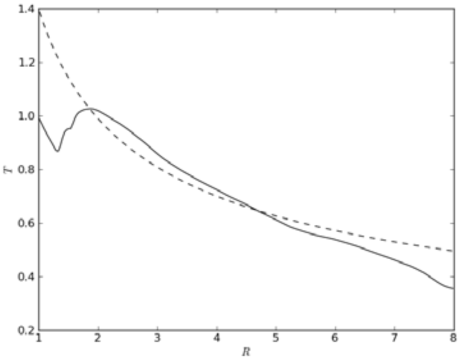

Figure 1. Temperature profile from MHD simulation: solid line, Temperature profile from α-disk model: dashed line.

To complete the feedback loop, we link resistivity and temperature. Instead of using the Saha's equation (see [5] and [6]), we model this relation using a step function for simplicity:

$$\eta(T) = \begin{cases} \eta_0, & \text{if } T > T_{MRI} \\ 0, & \text{else.} \end{cases} \tag{1}$$

Such a form capture the strong sensitivity of resistivity in Saha's law around the threshold T_{MRI}.

3 Results

3.1 MRI fronts

At the initial state, the gas is in a turbulent state from $R = 1.5$ to $R = 3.5$ and a dead zone extends from $R = 3.5$ to the outer boundary of the simulation domain. The angular size of the domain is set to $[0; \frac{\Pi}{2}]$, a smaller size than needed to trigger vortex formation and strong Rosby waves. Avoiding formation of those structures, we remove the heating they induce which interfer with result and ban a clear interpretation of front propagation process. As expected by Latter and Balbus ([3]), the inner edge exhibits a dynamical behavior: higher temperatures in the active zone diffuse inside the dead zone, causing the resistivity to decrease and hence triggering turbulence. As a result an MRI-front propagates outward and seems to tend to a critical radius $R_c = 6.5$ (see figure 2) set by T_{MRI} prescription. Inward motions of fronts (not shown here) are also possible by setting T_{MRI} to the appropriate values. Note that the critical radius is bounded between the radius where heating by the central star is enough to ionize the gas and the radius where turbulent heating is not strong enough to ionize gas: $0.01 < Rc < 3$ [3].

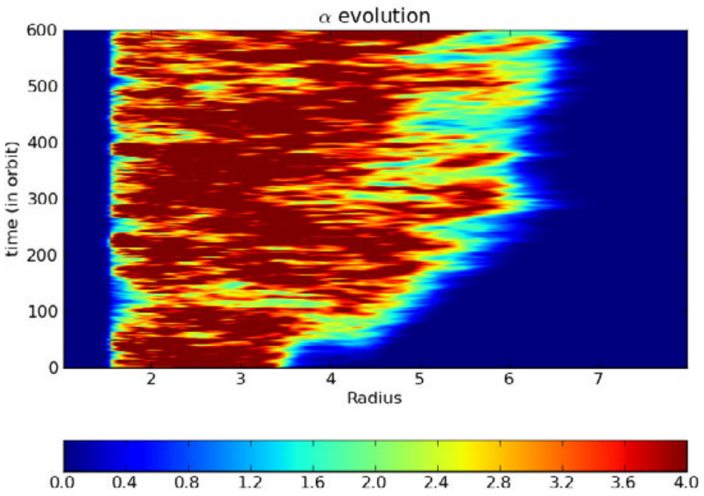

Figure 2. Space time diagram of turbulent activity, MRI fronts.

The front velocity is controlled by the turbulent diffusion of temperature fluctuations because it is the slowest process in the problem. We measure in MHD simulation a front velocity about $4.5\ 10^{-2}\ H/\Omega$ with H and Ω, the typical scale height and the rotation period at $R = 1$.

3.2 Structure of the interface

To study the formation of structures like bumps and vortices at the interface, we run a second simulation where the threshold value in resistivity is chosen to have $R_c = 4.5$. Figure 3 shows that, when the front has reached it's final position, a density bump can form. This density maximum has a non axisymetric shape (see contours of figure 3) because of vortex formation, in agreement with the results of locally isothermal simulations ([2]).

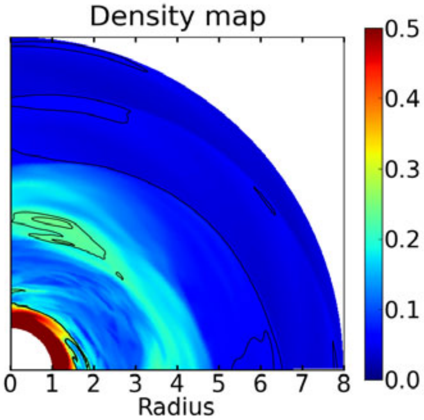

Figure 3. Density map, 300 orbits after relaxing front locking position. Contours of density (three level shown) are drawn with black lines.

4 Conclusion

Using MHD numerical simulation of partially ionized protoplanetary disks, we validate the mean field approach developed in this context by [3]. We confirm that the inner edge of a dead zone can move fast inward or outward on long distances (few astronomical units). From the comparison between the two models we draw a simple picture of the MRI front phenomenon. Finally, we find that computing the dead/active zone interface profile self-consistently with ionisation physics marginally impact the formation of vorticies at the interface.

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