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MHD waves as extra heating sources for protostellar accretion disks

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Abstract. It is known for quite some time now that the viscosity, represented by the anomalous parameter α in the standard Shakura & Sunyaev model, is not effective in heating the midplane of protostellar accretion disks sufficiently to ensure the occurrence of the Magneto-Rotational Instability (MRI), responsible for setting a magnetohydronamics (MHD) turbulence onto the disk and cause the accretion observed. In this work, we investigate the effects of damping of MHD waves in increasing the ionization fraction in those regions. We consider the damping of Alfvén waves by three mechanisms: the turbulent damping, the non-linear damping and the resonant absorption of surface waves. We assume throughout a specific disk model ($\alpha = 10^{-2}$ and accretion rate $10^{-7}\, M_\odot\, yr^{-1}$), ionized by different processes accordingly to the radial distance to the central object, and simulate a 2D (1D + 1D) accretion disk. We find that, with the exception of the non-linear damping, the mechanisms considered does reduce the extent of the dead zone, both in the radial and vertical direction, even for very small Alfvén waves fluxes. Finally, we compare the temperatures associated with each of those mechanisms with some observational data, obtaining a reasonable agreement, considering the limitations and approximations used in our model.

Resumo. Sabe-se que a viscosidade, representada pelo parâmetro anômalo α no modelo padrão proposto por Shakura & Sunyaev, não é efetiva em aquecer o plano médio do disco suficientemente de forma a permitir a ocorrência da Instabilidade Magneto-rotacional (IMR), responsável por instaurar uma turbulência de origem magnetohidrodinâmica (MHD) no disco e, assim, promover a acreção observada. Nesse trabalho, investigamos os efeitos do amortecimento de ondas MHD em aumentar a fração de ionização nessas regiões. Três mecanimos de amortecimento de ondas Alfvén foram considerados: o amortecimento turbulento, o amortecimento não-linear e o amortecimento ressonante de ondas Alfvén de superfície. Assumiu-se durante todo o trabalho um modelo de disco específico ($\alpha = 10^{-2}$ e taxa de acreção $10^{-7}\, M_\odot\, ano^{-1}$), ionizado por diferentes processos de acordo com a distância radial ao objeto central, e um disco de acreção 2D (1D + 1D) foi simulado. Obtivemos que, com exceção do amortecimento não-linear, os mecanismos considerados diminuem, de fato, a extensão da zona morta, nas direções radial e vertical, mesmo para fluxos de ondas Alfvén extremamente baixos. Finalmente, nós comparamos as temperaturas associadas aos mecanismos considerados com alguns dados observacionais, obtendo uma concordância razoável, dada as limitações e aproximações de nosso modelo.

Keywords. Accretion, accretion disks – Magnetic fields – Plasmas – Stars: pre-main sequence

1. Introduction

The current paradigm of solar-type protostars is that its evolution is intrinsically related to the angular momentum (AM) transport in its surrounding disks. The most important mechanism in driving angular momentum transport in the radial direction in thin non-self-gravitating disks (such as those observed around T Tauri stars) is believed to be the magnetorotational instability (MRI, Balbus & Hawley 1991). This instability is responsible for driving a magnetohydrodinamics (MHD) turbulence in the disk and, thus, cause the accretion of matter onto the central star. However, in order to be effective, the MRI requires a certain level of ionization of the disk gas, since it demands the disk particles to be frozen in the magnetic field lines. Very early on, Gammie (1996) suggested that this instability may not be operative, when only vicous dissipation is considered (Shakura & Sunyaev 1973), at the disk midplane, where the densities are too high and temperatures too low. He then called this region *dead zone* and introduced the concept of layered accretion: this so called *dead zone* would be sandwiched between the disk surface regions, where MRI is indeed effective - the so called, *active zones* - and the accretion would take place only at the disk surface, leaving the disk midplane in a laminar state. After that, several works have studied the extent and properties of this *dead zone* and its effects on the star and planets formation and evolution (e.g. Fromang et al. 2002; Ilgner & Nelson 2006; Martin et al. 2012; Dzyurkevich et al. 2013; Charnoz et al. 2019).

Our main goal is, therefore, study extra heating mechanims that could act in the disk midplane and then increase the ionization fraction, allowing the occurrence of the MRI. In order to do so, we consider the damping of MHD waves as a non-thermal heating mechanism, in particular, the damping of Alfvén waves (AW). The damping of AW was already studied in a variety of astrophysical scenarios (e.g. Jatenco-Pereira & Opher 1989; Evans et al. 2012), in particular in heating accretion disks associated with T Tauri stars (e.g. Vasconcelos et al. 2000; Jatenco-Pereira 2013). In the present work, we consider three mechanisms for the damping of Alfvén waves: the turbulent damping, the non-linear (NL) damping and the resonant absorption of surface Alfvén waves (SW).

2. The model

We have adopted the α prescription by Shakura & Sunyaev (1973), along with the layered model by Gammie (1996), and have assumed that the disk may be approximated as being geometrically thin and optically thick. Besides, we have assumed that the disk radiates as a black body (BB), which allow us to obtain the disk effective temperature using only the energy flux liberated by viscous dissipation and the BB flux.

Another very important hypothesis is regarding the magnetic field geometry. We have assumed that the field is dominated by the dipolar magnetic field from the star and that, due to the fact that the vertical extent of the disk is very thin, we may approximate the field as being constant in the $\hat{z}$ direction, in the sense that we get:

$$\boldsymbol{B} = B_0(r)\,\hat{z}. \tag{1}$$

Aditionally, if we adopt the Alfvén waves energy density, ϵ_A, as being given by the parametrization proposed by Vasconcelos et al. (2000):

$$\epsilon_A = \rho f^2 v_A^2, \tag{2}$$

where f is a free parameter less or equal than unity and $v_A = B/\sqrt{4\pi\rho}$ corresponds to the Alfvén velocity, we may write the damping rates associated with each of the mechanisms considered as:

$$\gamma_T = B^{1/2}(f v_A), \tag{3a}$$

$$\gamma_{NL} \propto \frac{c_s}{v_A}\frac{e\pi}{m_i c}\Big(\frac{\epsilon_A}{B}\Big), \tag{3b}$$

$$\gamma_{SW} \propto \frac{v_A}{L_0}\Big(\frac{v_{A0}^2}{v_A^2}\Big)\frac{1}{1+M}, \tag{3c}$$

where 3a, 3b and 3c denotes the damping rate associated with the turbulent, non-linear and resonant mechanisms, respectively. In the equations above, c_s, e, m_i and c represents the sound velocity, the electron charge, the ion mass and the light velocity. Besides, we define M as the Alfvénic Mach number, v_{A0} is the Alfvén velocity calculated at the disk midplane and v_A is the Alfvén velocity calculated at a given height z. The free initial parameter $L_0 = 10^{-5}\,H_0$ corresponds to the initial damping length, where H_0 is the disk scale height evaluated at a radial distance of 0.1 AU.

In addition, in order to obtain the extent of the dead zone in our simulated disk, we have adopted the following ionization mechanisms: X-rays from the central star, thermal ionization by alkali ions and ionization by cosmic rays (e.g. Fromang et al. 2002; Ilgner & Nelson 2006; Martin et al. 2012).

3. Results and discussion

Using the damping rates given by Equation 3a-3c, we may obtain the amount of energy liberated by each of these mechanisms, through:

$$D = \int_0^H \frac{\Phi}{v_A}\gamma dz, \tag{4}$$

with $\Phi = \epsilon_A v_A$ and H the corresponding disk height. Throughout this work we have considered a disk model defined by: $M_* = 0.7\,M_\odot$, $\dot{M} = 10^{-7}\,M_\odot\,yr^{-1}$, $\mu = 2.33$, $\alpha = 0.01$ and internal radius $R_i = 5\,R_\odot$. We display our main results in Figures 1 and 2.

In Figure 1 the extent of the dead zone is shown before and after the consideration of the damping mechanisms. The full line represents the total column density, while the dashed line corresponds to the column density of the active region when only the viscous dissipation is considered. The dotted and dot-dash lines are from the SW and turbulent damping, respectively. The NL mechanism did not affected the size of the dead zone. In Figure 2 we show the effective temperatures obtained with our model: again, the NL mechanism does not differ significantly from the standard model, while the SW and turbulent mechanism significantly increase the disk temperature. In both figures, we set $f = 1\times10^{-2}$ for the SW mechanism and $f = 2.5\times10^{-2}$ for the turbulent and NL damping. We see that the SW and turbulent mechanisms describes, rather nicely, the observed points.

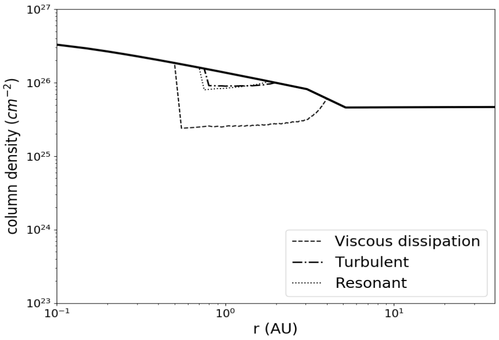

Figure 1. Representation of the dead zone extent.The dead zone corresponds to the difference between the full line and the other curves.

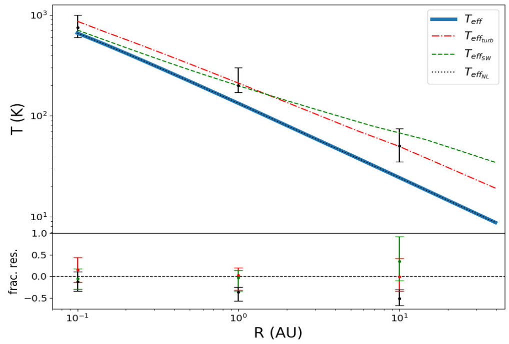

Figure 2. Temperatures obtained with our simulations. The black points are measured data of the Ophiuchus nebulae taken from Andrews & Williams (2007). Also, in the bottom panel, we show the residual values obtained for the simulated temperatures.

4. Conclusions

We have considered 3 extra heating sources associated with the damping of Alfvén waves, the turbulent, NL and SW, as a means to reduce the extent of the dead zone and make AM transport effective in a larger region of the disk. We have found that while the NL damping is quite ineffective in reducing the dead zone, the SW and turbulent mechanism does provoke a significant reduction in this region extent. Also, those last two mechanisms produce temperature profiles which are a good description of the observational data. Thus, the turbulent damping and SW may be good candidates of extra heating sources in accretion disks.

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