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The role of non-ideal MHD effects and Alfvén waves damping in protostellar accretion disks

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Abstract. The transport of angular momentum and matter are key mechanisms in understanding the evolution of protostellar accretion disks around young Solar-type stars. In the recent years, the role of non-ideal MHD effects in those objects has been widely explored and it is now known that those effects have a significant impact on the viability of the Magneto-Rotational Instability (MRI) and the transport of angular momentum, as a whole. In general, those terms tend to suppress the development of the MRI. On the other hand, we have previously proposed the damping of surface Alfvén waves as a viable mechanism to increase the ionization fraction of disks, thus, ensuring the efficiency of the MRI in a larger region. Since the non-ideal MHD terms directly impact on the magnetic flux of the plasma, they will also influence on the propagation of MHD waves, such as the Alfvén waves, and, consequently, on the overall efficiency of the damping process. Therefore, in this work, we investigate the consequences of the non-ideal MHD effects on the extra heating associated with the waves damping and assess if those terms can, indeed, increase the waves energy dissipation, especially the Ohmic and ambipolar diffusion, which are known to be dissipative mechanisms. In this early stage, we have made an analytical analysis regarding the effects of those two dissipative non-ideal mechanisms, which allowed us to define the behaviour of the plasma properties, and compare it with the plasma dynamics when only viscosity acts on the waves damping.

Resumo. O transporte de momento angular e matéria são mecanismos fundamentais para o entendimento da evolução de discos de acreção protoestelares associados à estrelas do tipo solar jovens. Nos últimos anos, o papel de efeitos MHD não-ideais nesses objetos tem sido fortemente explorado. Sabe-se que estes efeitos têm um impacto significativo sobre a viabilidade da Instabilidade Magneto-Rotacional (MRI, do inglês *Magneto-Rotational Instability*) e sobre o transporte do momento angular no disco. De maneira geral, esses termos tendem a suprimir o desenvolvimento da MRI. Por outro lado, nós propusemos anteriormente o amortecimento de ondas Alfvén de superfície como um mecanismo viável para aumentar a fração de ionização desses discos, assegurando, assim, a eficiência da MRI em uma maior porção desse objeto. Como os termos MHD não-ideias impactam diretamente o fluxo magnético do plasma, eles também influenciarão na propagação de ondas MHD, como as ondas Alfvén, e, consequentemente, na eficiência total do processo de amortecimento. Portanto, neste trabalho, nós investigamos as consequências dos efeitos MHD não-ideais no aquecimento extra associado ao amortecimento das ondas e se esses termos são capazes de aumentar a dissipação de energia das ondas, em particular o efeito Ohmico e a difusão ambipolar, que são conhecidos por serem efeitos dissipativos. Neste estágio inicial do trabalho, nós realizamos um estudo analítico a respeito destes dois mecanismos não-ideais dissipativos, o que nos permitiu definir o comportamento das propriedades do plasma, e compará-lo com a dinâmica do plasma quando apenas a viscosidade atua no amortecimento das ondas.

Keywords. Accretion, accretion disks – Magnetohydrodynamics (MHD) – Stars: pre-main sequence

1. Introduction

The evolution of young Solar-type stars is strongly connected to the transport of angular momentum (AM) and matter in protostellar accretion disks. However, a lot of debate still exists around the main mechanism responsible for AM transport in those objects and its efficiency. For a long time, the Magneto-rotational Instability (MRI), proposed by Balbus & Hawley (1991), was considered the best candidate to describe the transport of AM, and consequently accretion process, in those objects. However, early on, Gammie (1996) noticed that the MRI could be suppressed in the inner regions of the disk, where the ionization fractions are too low to allow the development of this instability (the so called *dead zones*). Indeed, this prediction was made by means of the Ohmic resistivity, one of the non-ideal MHD effects. Since then, a lot of investigation was made regarding the impact of all three non-ideal MHD effects (the Ohmic resistivity, Hall effect and ambipolar diffusion) in those disks, mainly in the recent years, since, due to the weak level of ionization in these environments, those effects largely impact the gas dynamics. Bai & Stone (2013) have found that the typical layered accretion proposed by Gammie (1996) fails when ambipolar diffusion is considered, since this effect largely reduce or even suppress the development of the MRI. Lesur et al. (2014) also investigated the role of non-ideal MHD effects on those disks through 3D numerical simulations and, besides recovering the results of Bai & Stone (2013), also found that, in some cases, the Hall effect could 'revive' the dead zones due to large-scale Maxwell stresses. The overall results of these studies, however, is that, due to the low ionization levels of the disk particles, the MRI alone is insufficient to describe the observed accretion rates (e.g. Bai & Stone 2013; Gressel et al. 2015). With this in mind, we have proposed an extra heating mechanism, associated with the damping of surface Alfvén waves (SAW), which could, in principle, transfer heat to the medium, increasing the environment's temperature and, thus, its ionization fraction. In this initial model only the viscosity was considered. Now, we intent to include all three non-ideal MHD effects in our analysis as they deeply affect the propagation of MHD waves, such as Alfvén waves. Since only the Ohmic resistivity and ambipolar diffusion are dissipative effects and damps the MHD waves, albeit in different manners, we focused our investigation, initially, in those two effects, which required similar procedures. The Hall effect, on the other hand, modifies the topology of the magnetic field only, not introducing dissipation (e.g. Wardle & Salmeron 2012), which requires a different treatment and it will not be considered in the present work. Therefore, the main goals of this work are:

- Include the non-ideal MHD effects on the analytical perturbative analysis regarding the damping of SAW, associated with the disk rotation;
- Analyse if the non-ideal MHD effects can, indeed, increase the waves energy dissipation, especially the Ohmic and ambipolar diffusion, which are known to be dissipative mechanisms;
- Apply the resulting energy flux to the disk structure to evaluate its impact on the viability of the MRI (or, correspondingly, in the reduction of the dead zone extent).

2. Non-ideal MHD effects on the damping of surface Alfvén waves

In order to analyse the impact of the Ohmic resistivity and ambipolar diffusion on the resonant absorption of SAW, we applied a local approximation and restricted our analysis to the vicinity of a reference point, r_0, which rotates with an angular frequency, Ω_0. We then constructed a new cartesian frame, centered at r_0. In this new configuration, the radial shear associated with the disk differential rotation becomes simply written as (e.g. Lesur 2021):

$$v_0 = -q\Omega_0 x\hat{\boldsymbol{y}}, \tag{1}$$

where q is obtained from the rotation profile $\Omega \propto r^{-q}$. Besides, we assume a vertical initial magnetic field, $\boldsymbol{B_0} = B_0(x)\hat{\boldsymbol{z}}$, and that all the equilibrium quantities depends only on the radial variable (i.e. the x-coordinate). We also assumed imcompressible disturbances, which is justified with the fact that we are only analysing Alfvén waves in the present work.

The MHD equations, under the influence of the two non-ideal effects considered are:

$$\partial_t \rho + \boldsymbol{\nabla}.(\rho \boldsymbol{v}) = 0, \tag{2a}$$

$$\partial_t \boldsymbol{v} + \boldsymbol{v}.\boldsymbol{\nabla}\boldsymbol{v} = -\frac{1}{\rho}\boldsymbol{\nabla}P + \frac{(\boldsymbol{\nabla}\times\boldsymbol{B})\times\boldsymbol{B}}{4\pi\rho} - 2\Omega_0\hat{\boldsymbol{z}}\times\boldsymbol{v} + \Omega_0^2(2qx\hat{\boldsymbol{x}} - z\hat{\boldsymbol{z}}), \tag{2b}$$

$$\partial_t \boldsymbol{B} = \boldsymbol{\nabla}\times\left[(\boldsymbol{v}+\boldsymbol{v_B})\times\boldsymbol{B} - \eta(\boldsymbol{\nabla}\times\boldsymbol{B})_{\parallel}\right], \tag{2c}$$

where $||$ refers to the direction of the initial magnetic field, and $\boldsymbol{v_B}$, in the absence of the Hall effect, is given by:

$$\boldsymbol{v_B} = \eta_P \frac{(\boldsymbol{\nabla}\times\boldsymbol{B})_{\perp}\times\hat{\boldsymbol{B}}}{B}, \tag{3}$$

where $\eta_P = \eta + \eta_A$ is the Pedersen diffusivity (e.g. Wardle & Salmeron 2012).

We then applied to our system perturbations of the form: $\boldsymbol{B} = (\boldsymbol{B_{1x}}, \boldsymbol{B_{1y}}, \boldsymbol{B_0} + \boldsymbol{B_{1z}})$, $\boldsymbol{v} = (\boldsymbol{v_{1x}}, \boldsymbol{v_0} + \boldsymbol{v_{1y}}, 0)$, $\rho = \rho_0 + \rho_1$, $p = p_0 + p_1$, where the perturbed quantities were written as:

$$g(x, y, z, t) = g(x)\exp[i(-\omega t + k_z z + k_y y)], \tag{4}$$

where ω is the frequency of the perturbation, and k_y and k_z are the 'azimuthal' and 'vertical' wavenumbers, respectively. Now, if we assume that the width of the interface, a, where we restrict our analysis, is really thin, $a/r_0 \ll 1$, we may postulate that $\Omega_0 a/v_A \ll 1$. We also apply an additional restriction over the wavenumbers of the perturbation, $k_y a \ll 1$ and $k_y \gg k_z$.

Using the solution in the equilibrium, that dictates:

$$\frac{1}{\rho_0}\left[\partial_x p_0 + \frac{B_0\partial_x B_0}{4\pi}\right] = -(2q-3)\Omega_0^2 x, \tag{5}$$

we can describe the perturbation as a whole with the aid of only two ODE: one written in terms of the radial Lagrangian displacement, $\xi_x = iv_{1x}/\overline{\omega}$, where $\overline{\omega} = \omega + k_y q\Omega_0 x$, and the total pressure perturbation, $p_T = p_1 + B_0 B_{1z}/4\pi$. In the vicinity of the resonance point, $x = x_A$, where $\overline{\omega}^2 \sim \omega_A^2$, the pair of equations for the Ohmic resistivity is given by:

$$(\overline{\omega}_\eta^2 - \omega_A^2)\partial_x\xi_x = k_y C_A \tag{6a}$$

$$\frac{(\overline{\omega}_\eta^2 - \omega_A^2)}{\rho_0}\partial_x p_T = 2\overline{\omega}\Omega_0 C_A, \tag{6b}$$

and for the ambipolar diffusion:

$$(\overline{\omega}_{\eta_A}^2 - \omega_A^2)\partial_x\xi_x = k_y C_A \tag{7a}$$

$$\frac{(\overline{\omega}_{\eta_A}^2 - \omega_A^2)}{\rho_0}\partial_x p_T = 2\overline{\omega}\Omega_0 C_A, \tag{7b}$$

where $C_A = k_y p_T/\rho_0 - 2\overline{\omega}\Omega_0\xi_x$=cte, $\overline{\omega}_\eta^2 = \overline{\omega}^2 - i\eta\overline{\omega}\partial_x^2$ and $\overline{\omega}_{\eta_A} \equiv \overline{\omega}^2 + i\overline{\omega}k_z^2\eta_A$. Note that Equations 6 and 7 are virtually the same, the exception being the definitions of $\overline{\omega}_\eta^2$ and $\overline{\omega}_{\eta_A}$, which is expected since these two effects have the same outcomes, only in different ways, as expressed by the above expressions.

3. Final remarks and next steps

With the differential equations for ξ_x and p_T we are able to obtain the 'jumps' associated with the resonance of the surface Alfvén waves and then obtain the damping rate associated with these processes. We are now implementing those 'jumps' in our numerical code in order to obtain the quantitative impact of these non-ideal effects on the energy dissipation and, finally, on the transport of angular momentum and the extension of the dead zone. Finally, we intend to do a similar analysis regarding the Hall effect.

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