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Heating mechanisms of protostellar accretion disks

N. F. S. Andrade & V. Jatenco-Pereira

[1] Instituto de Astronomia, Geofísica e Ciências Atmosféricas e-mail: natalia.fernanda.andrade@usp.br e-mail: vera.jatenco@iag.usp.br

Abstract. Accretion disks are commonly found around young stars, such as T Tauri stars. In order to occur the transport of matter to the star, the particles of the disk need to loose some of their rotational energy and fall towards the central object. The most promising mechanism of angular momentum transport is the magneto-rotational instability (IMR). However, this instability requires that the particles be coupled to the magnetic field lines. For this to happen, at least a fraction of the particles needs to be charged. As the temperatures through the disk are low, the ionization rates are also very small. Thus for the IMR to occur through the whole disk, the temperatures must be higher. There are in the literature models that include the damping of Alfvén waves as an additional heating source, besides the viscous heating mechanism, in particular, the non linear, turbulent and dust-cyclotron damping. In this work, a numerical code was developed to simulate the disk using the four mechanisms cited. It was then made an analysis of their efficiency as a function of the radial distance and the initial conditions.

Resumo. Discos de acreção são comumente encontrados ao redor de estrelas jovens, como as estrelas T Tauri. Para com que ocorra o transporte de matéria, as partículas necessitam de perder um pouco de sua energia de rotação e "cair" em direção ao objeto central. O mecanismo mais promissor de transporte de momento angular é a instabilidade magneto-rotacional (IMR). Entretanto, para com que esta instabilidade ocorra, as partículas necessitam de estar acopladas às linhas do campo magnético. Para com que isso ocorra, pelo menos uma fração das partículas necessitam de estar carregadas. Poranto, para que a IMR ocorra em toda a extensão do disco, as temperaturas necessitam de ser mais altas. Na literatura, existem diversos modelos que incluem o amortecimento de ondas Alfvén como uma fonte adicional de calor, além da dissipação viscosa, em particular, os amortecimentos não linear, turbulento e cíclotron da poeira. No presente trabalho, um código numérico foi desenvolvido que simula os quatro mecanismos supracitados. Foi, então, realizada uma análise de suas eficiências em função da distância radial e das condições iniciais.

Keywords. accretion disks – Alfvén waves – heating mechanisms

1. Introduction

The formation process of low-mass stars envolves the collapse of molecular clouds as well as the formation of a accretion diks, which will be responsible for the transport of matter towards the central object. In order for the transport to happen, it is necessary that the particles of the disk loose some of their rotation energy and fall towards the star. The most promising mechanism of angular momentum transport is the magneto-rotational instability (IMR), proposed by Balbus & Hawley (1991). However, in order for the instability to take place it is necessary that the temperature in the disk increases to ensure that there is a minimal fraction of ionization (Gammie, 1996). There are several works in the literature that use the damping of Alfvén waves as an extra heating mechanism for the disk.

In this work, we use the standard model proposed by Shakura & Sunyaev (1973) and the layered model proposed by Gammie (1996) along with three extra heating mechanisms of damping of Alfvén waves, non-linear, turbulent and dust-cyclotron damping, studied by Vasconcelos et al. (2000) and Jatenco-Pereira (2013), in order to make an analysis of the efficiency of these mechanisms as a function of the radial distance.

2. Material and methods

Assuming a geometrically thin and optically thick disk (Shakura & Sunyaev, 1973) divided in layers (Gammie, 1996) and adopting the opacity law given by Bell & Lin (1994), a numerical code was constructed to simulate the disk. The numerical code computed the parameters of the disk, such as the intensity of the magnetic field, the central temperature, the volumetric and superficial density and the scale height, the temperatures given by the viscous dissipation alone and the temperatures generated by the damping of Alfvén waves. In order to calculate the temperatures we supposed that the disk irradiates as a black body, so that the temperature is obtained as follows:

$$T^4 = \frac{D}{\sigma} \quad (K), \tag{1}$$

where D is the energy flux dissipated by the viscosity and by the damping of Alfvén waves and σ is the Stefan-Boltzmann constant.

The energy flux dissipated by the damping of the waves is Φ/L, where L is the damping lenght and Φ is the wave flux, which is given by:

$$\Phi = \rho < \delta\ v^2 > v_A, \tag{2}$$

where ρ is the disk volumetric density, v_A is the Alfvén velocity and δv is the magnitude of the velocity perturbation.

Knowing that the density energy of the Alfvén waves is:

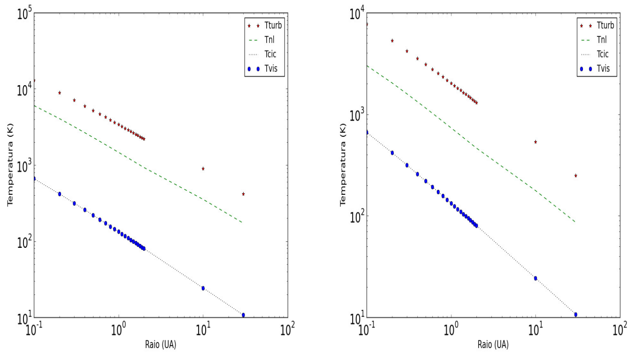
$$\epsilon_A = \frac{1}{2}\rho < \delta v^2 > + \frac{1}{2} < \delta B^2 > /(4\pi), \tag{3}$$

and using the equipartition of energy

$$\frac{1}{2}\rho < \delta v^2 > = \frac{1}{2} < \delta B^2 > /(4\pi), \tag{4}$$

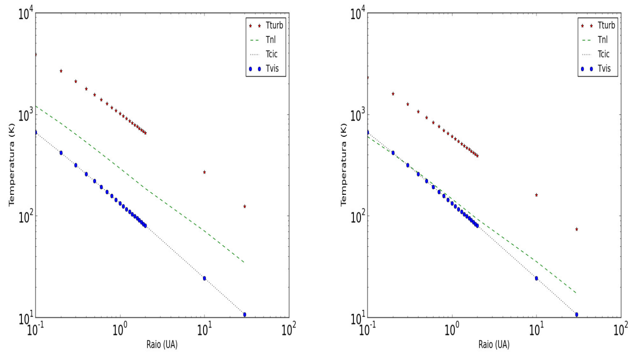
we have that:

$$\Phi = \frac{< \delta B^2 >}{(4\pi)} v_A. \tag{5}$$



(a) Temperature profile with f = 0,01.
(b) Temperature profile with f = 0,005.

Figure 1. Temperature profile for wave fluxes of 0.01 and 0.005. In red, are the temperatures generated by the turbulent damping, in green the temperatures generated by the non-linear damping and in black the temperatures generated by the dust-cyclotron damping. The blue dots represents the temperatures of the viscous dissipation, which is invariant with the wave flux.



(a) Temperature profile with f = 0,002.
(b) Temperature profile with f = 0,001.

Figure 2. Temperature profile for wave fluxes of 0.002 and 0.001. In red, are the temperatures generated by the turbulent damping, in green the temperatures generated by the non-linear damping and in black the temperatures generated by the dust-cyclotron damping. The blue dots represents the temperatures of the viscous dissipation, which is invariant with the wave flux.

But, as the perturbation of the magnetic field has to be a fraction of the initial magnetic field, we can write:

$$< \delta B^2 > /(4\pi) \;=\; f^2 B^2/(4\pi), \tag{6}$$

where f is a free parameter. Hence, we have that the wave flux if given by:

$$\Phi = \frac{f^2 B^2}{(4\pi)} v_A = f^2 \rho v_A^3 \quad (erg\ cm^{-2}\ s^{-1}). \tag{7}$$

3. Results

For a non-dusty disk and considering only viscous dissipation and the turbulent and non-linear mechanisms, as proposed by Vasconcelos et al. (2000), it was obtained that the most efficient mechanism is the turbulent, which shows temperatures of $\sim$ 1000 K at the innermost regions and $\sim$ 50 K at 100 AU.

For a dusty disk (Jatenco-Pereira, 2013) and considering viscous dissipation and the non-linear, turbulent and dust-cyclotron mechanisms, it was obtained the temperature profile shown in Figure 1.

4. Conclusions and perspectives

For a dusty disk we can see that the dust-cyclotron damping is the less efficient among the mechanisms of damping of Alfvén waves, since that even for small values of the Alfvén waves flux, the turbulent and non-linear mechanisms still produce temperatures superiors to the cyclotron. Besides, we obtained that the dust-cyclotron damping shows similar temperatures of viscous dissipation.

In the continuity, we intend to investigate a way of coupling the three mechanisms of damping of Alfvén waves, in order to maximize the heating of the disk.

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