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Time damping of non-adiabatic MHD slow and thermal waves in a prominence medium: Effect of a background flow

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ABSTRACT

Material flows are typical features of prominences and are routinely observed in Hα, UV and EUV lines. Therefore, including a magnetic field-aligned background flow, we study the effect of flows on the damping of non-adiabatic magnetohydrodynamic (MHD) waves in a magnetised unbounded prominence medium, and we explore the observational implications. We have linearised the non-adiabatic MHD equations and, considering only field-aligned propagation, we focus our study in the behaviour of thermal and slow waves. When a flow with a constant speed is present, two slow waves, with different periods, appear, while the damping time remains unchanged. On the other hand, the thermal wave becomes in this case a propagating wave, with finite period, while its damping time remains also unmodified. As a consequence of the changes in the periods produced by the flow, the damping per period of the different waves is modified. In the case of slow waves, and for a fixed flow speed, the damping per period of the high-period slow wave is increased while the opposite happens for the low-period slow wave, and the strongest finite damping per period, for the high-period slow wave, is obtained for flow speeds close to the non-adiabatic sound speed. In the case of the thermal wave, a finite value for the damping per period is obtained for any non-zero flow speed, and in this case the strongest finite damping per period is obtained for values of the flow speed close to zero. Furthermore, we point out that there is the possibility to have slow and thermal waves having the same period, the same damping time, or both simultaneously, which makes the proper identification of the waves for an external observer extremely difficult. Then, if flows are ubiquitous in prominences the observational determinations of periods and damping per period, made by an external observer, include its effect, and for a proper identification, information about the wavelength, flow speed and perturbations should be needed, which constitutes a truly difficult observational task.

1. Introduction

Flows seem to be an ubiquitous feature in prominences and filaments and are routinely observed in Hα, UV and EUV lines. In Hα quiescent filaments typical velocities between 5 and 20 km/s are found (Zirker et al., 1998; Lin et al., 2003, 2007) and, due to physical conditions in prominence plasma, they seem to be field-aligned. Higher velocities have been also reported in the case of active filaments. Another interesting feature observed in filament flows is counterstreaming, which consists in simultaneous flowing in opposite directions within closely spaced adjacent threads (Zirker et al., 1998).

On the other hand, the presence of small-amplitude oscillations in quiescent prominences has been widely reported (Ballester, 2006; Banerjee et al., 2007) and, up to now, only the time damping of these oscillations has been determined unambiguously from observations. Reliable values for the damping time, τ_D, have been derived, from different Doppler velocity time series, by Molowny-Horas et al. (1999) and Terradas et al. (2002), in prominences, and by Lin (2004), in filaments. The values of τ_D thus obtained are usually between 1 and 4 times the corresponding period, and large regions of the prominence/filament display similar damping times. Furthermore, some determinations about the wavelengths of the MHD waves, probably responsible for prominences/filament oscillations, have been obtained. For instance, Molowny-Horas et al. (1997) determined a maximum value of 20,000 km, while Terradas et al. (2002) obtained values of 67,500, 50,000 and 44,000 km. Also, Lin et al. (2007) have determined the wavelength of oscillations in filament threads obtaining a value of about 3000 km.

Small-amplitude oscillations in quiescent prominences have been interpreted in terms of MHD waves (Oliver and Ballester,

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2002; Ballester, 2006) and explanations for the time damping of prominence oscillations based on linear non-adiabatic MHD waves have been proposed (Carbonell et al., 2004; Terradas et al., 2001, 2005; Soler et al., 2007).

Taking into account the presence of flows and time damped oscillations in prominences/filaments, our main aim here is to include a background flow in the prominence medium and to explore the theoretical and observational effects produced by its presence on the time damping of non-adiabatic MHD waves. The layout of the paper is as follows: in Section 2, the equilibrium model and some theoretical considerations are presented; in Section 3, the main results are discussed; finally, in Section 4, conclusions are drawn.

2. Basic equations and theoretical considerations

2.1. Linearised equations

As a background model, we use a homogeneous unbounded medium threaded by a uniform magnetic field along the x-direction, and with a field-aligned background flow. The equilibrium magnitudes of the medium are given by

$$p_0 = \text{const.}, \quad \rho_0 = \text{const.}, \quad T_0 = \text{const.},$$
$$\mathbf{B_0} = B_0\hat{e}_x, \quad \mathbf{v}_0 = v_0\hat{e}_x,$$

with B_0 = constant and v_0 = constant. The effect of gravity has been ignored and the basic MHD equations for the discussion of non-adiabatic MHD waves are:

$$\frac{D\rho}{Dt} + \rho\nabla\cdot v = 0, \tag{1}$$

$$\rho\frac{D\mathbf{v}}{Dt} = -\nabla p + \frac{1}{\mu}(\nabla\times\mathbf{B})\times\mathbf{B} + \rho g, \tag{2}$$

$$\rho T\frac{Ds}{Dt} + \rho L(\rho, T) - \nabla\cdot(\kappa\cdot\nabla T) = 0, \tag{3}$$

$$\frac{\partial\mathbf{B}}{\partial t} = \nabla\times(\mathbf{v}\times\mathbf{B}), \tag{4}$$

$$\nabla\cdot\mathbf{B} = 0, \tag{5}$$

$$p = \frac{\rho RT}{\tilde{\mu}}, \tag{6}$$

where $\frac{D}{Dt} = \frac{\partial}{\partial t} + \mathbf{v}\cdot\nabla$ is the material derivative for time variations following the motion. In Eq. (3), the term $\nabla\cdot(\kappa\cdot\nabla T)$ represents the thermal conduction, although in our case perpendicular thermal conduction has been neglected, and L is the heat-loss function which depends on the local plasma parameters. In the case of an equilibrium with uniform temperature, such as we consider here, the heat-loss function is

$$L(\rho_0, T_0) = 0.$$

Usually, in solar applications this function represents the difference between an arbitrary heat input and a radiative loss function which, in our case, has been chosen as the optically thin radiative loss function (Hildner, 1974). Then, our heat-loss function is given by

$$L(\rho, T) = \chi^*\rho T^\alpha - h\rho^a T^b, \tag{7}$$

χ^* and α being piecewise functions depending on the temperature (Hildner, 1974). The use of an optically thin plasma radiative cooling seems to be a reasonable approach for coronal, or almost coronal, conditions, while it may not be valid for prominence conditions because they are optically thick. In this case, the radiative losses from the internal part of the prominence are greatly reduced and this can be represented by changing the exponent α in the cooling function, for temperatures $T \leqslant 10^4$ K, from $\alpha = 7.4$ to 17.4 (Milne et al., 1979) or $\alpha = 30$ (Rosner et al., 1978), as well as by changing χ^* accordingly (Carbonell et al., 2004). Finally, the last term in Eq. (7) represents an arbitrary heating function which can be modified by taking different values for the exponents a and b. In our case, different heating scenarios have been considered, and the values taken into account for exponents a and b in Eq. (7) are (Rosner et al., 1978; Dahlburg and Mariska, 1988)

(1) Constant heating per unit volume ($a = b = 0$).
(2) Constant heating per unit mass ($a = 1, b = 0$).
(3) Heating by coronal current disipation ($a = 1, b = 1$).
(4) Heating by Alfvén mode/mode conversion ($a = b = 7/6$).
(5) Heating by Alfvén mode/anomalous conduction damping ($a = 1/2, b = -1/2$).

Considering small perturbations from the equilibrium in the form

$$\mathbf{B}(t,\mathbf{r}) = \mathbf{B}_0 + \mathbf{B}_1(t,\mathbf{r}), \quad p(t,\mathbf{r}) = p_0 + p_1(t,\mathbf{r}),$$
$$\rho(t,\mathbf{r}) = \rho_0 + \rho_1(t,\mathbf{r}), \quad T(t,\mathbf{r}) = T_0 + T_1(t,\mathbf{r}),$$
$$\mathbf{v}(t,\mathbf{r}) = \mathbf{v}_0 + \mathbf{v_1}(t,\mathbf{r}),$$

we linearise the basic equations (1)–(6) to obtain

$$\left(\frac{\partial}{\partial t} + \mathbf{v}_0\cdot\nabla\right)\rho_1 + \rho_0\nabla\cdot\mathbf{v}_1 = 0, \tag{8}$$

$$\rho_0\left(\frac{\partial}{\partial t} + \mathbf{v}_0\cdot\nabla\right)\mathbf{v}_1 = -\nabla p_1 + \frac{1}{\mu}(\mathbf{B}_0\cdot\nabla)\mathbf{B}_1 - \frac{1}{\mu}\nabla(\mathbf{B}_0\cdot\mathbf{B}_1), \tag{9}$$

$$\left(\frac{\partial}{\partial t} + \mathbf{v}_0\cdot\nabla\right)(p_1 - c_s^2\rho_1) = (\gamma-1)(\mathbf{B}_0\cdot\nabla)\left[\frac{\kappa_\parallel}{B_0^2}(\mathbf{B}_0\cdot\nabla)T_1\right] - (\gamma-1)\rho_0(L_\rho\rho_1 + L_T T_1), \tag{10}$$

$$\left(\frac{\partial}{\partial t} + \mathbf{v}_0\cdot\nabla\right)\mathbf{B}_1 = \nabla\times(\mathbf{v}_1\times\mathbf{B}_0), \tag{11}$$

$$\nabla\cdot\mathbf{B}_1 = 0, \tag{12}$$

$$\frac{p_1}{p_0} - \frac{\rho_1}{\rho_0} - \frac{T_1}{T_0} = 0, \tag{13}$$

where $\kappa_\parallel = 10^{-11}T^{5/2}$, and $c_s^2 = \frac{\gamma p_0}{\rho_0}$, is the adiabatic sound speed squared. In the above linearised equations, the important difference with respect to the non-adiabatic case without flow is the operator $\frac{\partial}{\partial t} + \mathbf{v}_0\cdot\nabla$ (Goedbloed and Poedts, 2004). Since the medium is unbounded we can perform a Fourier analysis in plane waves and assume perturbations behaving like $e^{i(\omega t - \mathbf{k}\cdot\mathbf{r})}$, and with no loss of generality we choose the z-axis so that the wavevector $\mathbf{k}$ lies in the xz-plane, so that

$$\mathbf{k} = k_x\hat{\mathbf{e}}_x + k_z\hat{\mathbf{e}}_z.$$

Then, the above operator becomes $i(\omega - k_x v_0)$, which points out that in the presence of a background flow the frequency suffers a Doppler shift given by $k_x v_0$ and that the wave frequency, ω, for the non-adiabatic case with flow can be obtained from

$$\omega = \Omega + k_x v_0, \tag{14}$$

Ω being the wave frequency for the non-adiabatic case without flow. On the other hand, these frequencies can be described in a different manner, Ω corresponds to the frequency measured by an observer linked to the flow rest frame, while ω would correspond to the frequency measured by an observer linked to an external inertial rest frame.

Then, the following scalar equations are obtained:

$$\Omega\rho_1 - \rho_0(k_x v_x + k_z v_z) = 0, \tag{15}$$

$$\Omega\rho_0 v_x - k_x p_1 = 0, \tag{16}$$