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Damping of Alfvénic waves in the partially ionized solar chromosphere

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Abstract

Observations show the magnetohydrodynamic (MHD) waves are ubiquitous in the solar atmosphere. Alfvén waves are a particular class of transverse MHD waves driven by magnetic tension. Due to plasma inhomogeneity in the direction perpendicular to the magnetic field, MHD waves are damped by resonant absorption. In addition, the plasma in the photosphere and the chromosphere is only partially ionized, so that MHD waves are also damped by ion-neutral collisions. Here we compare the efficiency of resonant absorption and ion-neutral collisions for the damping of Alfvénic waves in magnetic flux tubes. We conclude that in the solar chromosphere Alfvénic waves with observed periods are more efficiently damped by resonant absorption than by ion-neutral collisions.

1 Introduction

Observations show the ubiquitous presence of propagating Alfvénic waves in the solar atmosphere [4, 16, 17, 9, 10]. The observed Alfvénic waves are believed to play an important role for the heating of the solar atmosphere [5, 2]. The observed waves have been interpreted as propagating kink waves in magnetic flux tubes [18, 11, 15, 14]. Resonant absorption, caused by plasma inhomogeneity in the direction transverse to the magnetic field, is a natural and efficient damping mechanism for kink waves in fully ionized plasmas [6]. However, the plasma in the solar chromosphere is only partially ionized. In partially ionized plasmas, ion-neutral collisions are another mechanism able to damp Alfvénic waves [8, 3, 12, 1, 20].

In fully ionized plasmas the damping length due to resonant absorption is inversely proportional to the wave frequency [15]. The purpose of the present work is to assess the impact of ion-neutral collisions on the damping and to determine whether the resonant damping length remains inversely proportional to the frequency when the plasma is partially ionized or, on the contrary, this dependence is modified by the effect of ion-neutral collisions. We perform a general study of the damping of resonant Alfvénic waves in partially ionized flux tubes using the multifluid theory. We consider arbitrary values of the ion-neutral collision frequency and perform a particular application to the solar atmosphere.

2 Equilibrium and basic equations

We consider a partially ionized plasma composed of two fluids, i.e., an ionized fluid made by ions and electrons, and a neutral fluid. Both fluids interact by means of ion-neutral collisions. We use cylindrical coordinates, namely r, φ, and z for the radial, azimuthal, and longitudinal coordinates. We consider a straight and constant magnetic field, $\mathbf{B} = B\hat{e}_z$. Since we study Alfvénic waves, which are insensitive the the sound speed of the plasma, we neglect gas pressure, i.e., we adopt the so-called $\beta = 0$ approximation, where β refers to the ratio of the gas pressure to the magnetic pressure. This simplification neglects the plasma displacement along the magnetic field direction, but it is an appropriate approximation to study Alfvénic waves which are transversely polarized. In addition, we assume that the equilibrium density is a function of r alone, so that the equilibrium is uniform in both azimuthal and longitudinal directions. Under these conditions, the basic equations of our investigation are

$$\rho_{\mathrm{i}} \frac{\partial \mathbf{v}_{\mathrm{i}}}{\partial t} = \frac{1}{\mu} \left(\nabla \times \mathbf{b} \right) \times \mathbf{B} - \rho_{\mathrm{i}} \nu_{\mathrm{ni}} \left(\mathbf{v}_{\mathrm{i}} - \mathbf{v}_{\mathrm{n}} \right), \tag{1}$$

$$\rho_{\mathrm{n}} \frac{\partial \mathbf{v}_{\mathrm{n}}}{\partial t} = -\rho_{\mathrm{i}} \nu_{\mathrm{ni}} \left(\mathbf{v}_{\mathrm{n}} - \mathbf{v}_{\mathrm{i}} \right), \tag{2}$$

$$\frac{\partial \mathbf{b}}{\partial t} = \nabla \times \left(\mathbf{v}_{\mathrm{i}} \times \mathbf{B} \right), \tag{3}$$

where $\mathbf{v}_{\mathrm{i}}$ and $\mathbf{v}_{\mathrm{n}}$ are the velocities of ions and neutrals, respectively, $\mathbf{b}$ is the magnetic field perturbation, ρ_{i} and ρ_{n} are the densities of ions and neutrals, respectively, μ is the magnetic permittivity, and ν_{ni} is the neutral-ion collision frequency.

3 Spatial damping of kink waves

We assume that the wave guide is a straight magnetic cylinder of radius R, which is composed of an internal region with constant ion density $\rho_{\mathrm{i}1}$, a nonuniform transitional layer of thickness l, and an external region with constant ion density $\rho_{\mathrm{i}2}$. In the nonuniform layer the density changes continuously from the internal to the external values in the interval $R - l/2 < r < R + l/2$. Hereafter, indices '1' and '2' refer to the internal and external regions, respectively. For the sake of simplicity, we assume that the neutral density, ρ_{n}, follows the radial dependence of the ion density, so that the ratio $\alpha = \rho_{\mathrm{n}}/\rho_{\mathrm{i}}$ is constant. The neutral-ion collision frequency, ν_{ni}, is also constant to simplify matters.

Since the equilibrium quantities are functions of r alone, we can put the perturbations proportional to $\exp\left(im\varphi + ik_z z\right)$, where m and k_z are the azimuthal and longitudinal wavenumbers, respectively. To investigate kink waves we set $m = 1$. We express the temporal dependence of the perturbations as $\exp\left(-i\omega t\right)$, with ω the frequency. The dispersion relation of Alfvénic kink waves is obtained in the thin tube (TT) and thin boundary (TB) approximations (see [15, 13]). For propagating waves the TT approximation is equivalent to the low-frequency approximation, i.e., $\omega R/v_{\rm k} \ll 1$, with $v_{\rm k}$ the kink wave phase velocity defined as

$$v_{\rm k} = \sqrt{\frac{\rho_{\rm i1} v_{\rm Ai1}^2 + \rho_{\rm i2} v_{\rm Ai2}^2}{\rho_{\rm i1} + \rho_{\rm i2}}}. \tag{4}$$

In the TB approximation we set $l/R \ll 1$. This enables us to use the jump conditions for the perturbations at the Alfvén resonance position as boundary conditions at the wave guide boundary. A detailed explanation of this method can be found in [6]. The jump conditions in a partially ionized plasma were derived in [13].

For fixed and real ω, the solution of the dispersion relation is a complex k_z. The imaginary part of k_z, namely $k_{z\rm I}$, is related to the damping of the wave. The amplitude of the propagating wave is proportional to $\exp\left(-z/L_{\rm D}\right)$, with $L_{\rm D} = 1/k_{z\rm I}$ the damping length. After a long but straight-forward process (see details in [13]) we find the expression of $L_{\rm D}$ in the TT and TB approximations as,

$$\frac{1}{L_{\rm D}} \approx \frac{1}{L_{\rm D,RA}} + \frac{1}{L_{\rm D,IN}}, \tag{5}$$

with $L_{\rm D,RA}$ and $L_{\rm D,IN}$ the damping lengths due to resonant absorption and ion-neutral collisions, respectively, given by

$$L_{\rm D,RA} = 2\pi\mathcal{F} v_{\rm k} \frac{R}{l} \frac{\zeta+1}{\zeta-1} \frac{1}{\omega} \left(\frac{\omega^2 + \nu_{\rm ni}^2}{\omega^2 + (1+\alpha)\,\nu_{\rm ni}^2} \right)^{1/2}, \tag{6}$$

$$L_{\rm D,IN} = 2 v_{\rm k} \frac{\left(\omega^2 + (1+\alpha)\,\nu_{\rm ni}^2\right)^{1/2} \left(\omega^2 + \nu_{\rm ni}^2\right)^{1/2}}{\alpha \omega^2 \nu_{\rm ni}}, \tag{7}$$

with $\zeta = \rho_{\rm i1}/\rho_{\rm i2}$ the ion density contrast and F a numerical factor that depends on the form of the density profile in the inhomogeneous region. For example, $F = 4/\pi^2$ for a linear profile and $F = 2/\pi$ for a sinusoidal profile.

4 The case of the solar chromosphere

In the solar chromosphere the expected value of the collision frequency is much higher than the frequency of the observed waves (see [3]). The minimum value of the neutral-ion collision frequency in the solar chromosphere is of the order of 10 Hz, while the dominant frequency in the observations of chromospheric waves by [10] is around 22 mHz. Hence we perform the limit $\nu_{\rm ni} \gg \omega$ and Equations (6) and (7) become

$$L_{\rm D,RA} \approx 2\pi\mathcal{F} v_{\rm k} \frac{R}{l} \frac{\zeta+1}{\zeta-1} \frac{1}{\sqrt{1+\alpha}} \frac{1}{\omega}, \tag{8}$$

$$L_{\rm D,IN} \approx 2 v_{\rm k} \frac{\sqrt{1+\alpha}}{\alpha} \frac{\nu_{\rm ni}}{\omega^2}. \tag{9}$$

In the realistic limit $\nu_{\rm ni} \gg \omega$ the damping length due to resonant absorption is inversely proportional to the frequency as in the fully ionized case (see [15]), while the damping length

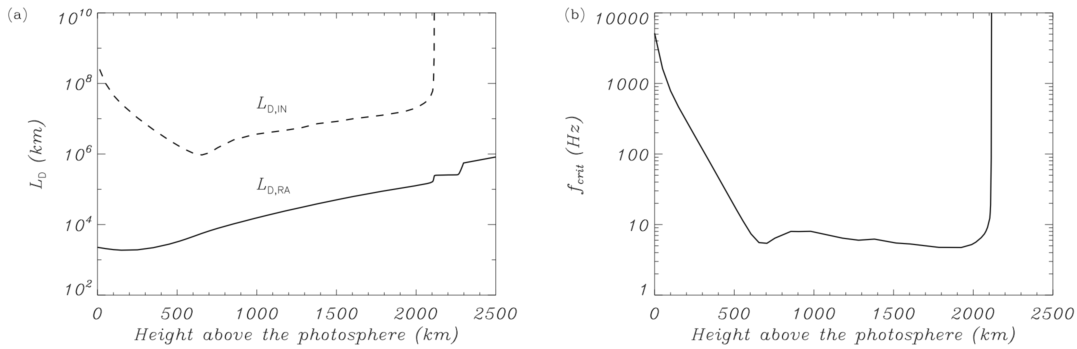

Figure 1: (a) $L_{\mathrm{D,RA}}$ (solid line) and $L_{\mathrm{D,IN}}$ (dashed line) vs. height above the photosphere for a wave period of 45 s. (b) Critical frequency in Hz, $f_{\mathrm{crit}} = \omega_{\mathrm{crit}}/2\pi$, vs. height above the photosphere.

due to ion-neutral collisions is inversely proportional to the frequency squared. Thus, Equations (8) and (9) predict that high-frequency waves are damped by collisions while low-frequency waves are damped by resonant absorption. The critical wave frequency, ω_{crit}, for which the efficiency of both mechanisms is the same is

$$\omega_{\mathrm{crit}} = \frac{1+\alpha}{\alpha}\frac{\zeta+1}{\zeta-1}\frac{l}{R}\frac{\nu_{\mathrm{ni}}}{\pi\mathcal{F}}. \tag{10}$$

We perform an application to the solar atmosphere. We take the variation of the physical parameters with height from the VALC model [19] and use the chromospheric magnetic field model of [7]. We plot in Figure 1(a) the damping lengths as functions of height for a wave period of 45 s. This is the dominant period of the chromospheric waves observed by [10]. The damping length due to resonant absorption increases with height. This is an effect of the increase of the kink velocity, v_{k}, with height (see [14]). At low heights, $L_{\mathrm{D,RA}}$ is comparable to the thickness of the whole chromosphere, meaning that a large fraction of wave damping occurs in the lower chromosphere before the wave reaches the coronal level. On the contrary, $L_{\mathrm{D,IN}}$ is always several orders of magnitude longer than $L_{\mathrm{D,RA}}$. It is found that $L_{\mathrm{D,IN}}$ reaches its minimal value at 700 km above the photosphere, approximately. At this height the collision frequency is also minimal. On the contrary, $L_{\mathrm{D,IN}}$ increases dramatically when the plasma gets fully ionized around 2100 km above the photosphere. On the other hand, Figure 1(b) displays the critical frequency (Equation (10)) as a function of height. At all heights the critical frequency is much higher than the frequency of the observed waves. This result points out that resonant absorption is always the dominant damping mechanism.

5 Conclusion

Here we have investigated the damping of Alfvénic waves in partially ionized plasmas. We have obtained expressions for the damping lengths due to resonant absorption and due to ion-neutral collisions. In the limit of high collision frequencies, the damping length due to resonant absorption is inversely proportional to the frequency, whereas the damping length due to ion-neutral collisions is inversely proportional to the square of the frequency. We have applied the theory to the case of kink waves propagating from the photosphere to the corona. We find that waves with frequencies similar to those observed are more efficiently damped by resonant absorption than by ion-neutral collisions.

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