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Damping of Slow Magnetoacoustic Waves in an Inhomogeneous Coronal Plasma

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Abstract. We study the propagation and dissipation of slow magneto-acoustic waves in an inhomogeneous viscous coronal loop plasma permeated by uniform magnetic field. Only viscosity and thermal conductivity are taken into account as dissipative processes in the coronal loop. The damping length of slow-mode waves exhibit varying behaviour depending upon the physical parameters of the loop in an active region AR8270 observed by TRACE. The wave energy flux associated with slow magnetoacoustic waves turns out to be of the order of 10^6 erg cm^{-2} s^{-1} which is high enough to replace the energy lost through optically thin coronal emission and the thermal conduction below to the transition region. It is also found that only those slow-mode waves which have periods more than 240 s provide the required heating rate to balance the energy losses in the solar corona. Our calculated wave periods for slow-mode waves nearly match with the oscillation periods of loop observed by TRACE.

Key words. Sun: corona—active region—coronal loops—TRACE—MHD waves—heating.

1. Introduction

The temperature of the solar corona is of the order of 10^6–10^7 K and it is much higher than the underlying photospheric temperature (6000 K), indicating the presence of heating mechanisms. Detailed reviews on this topic are in Narain & Ulmschneider (1990, 1996), Browning (1991), and Zirker (1993). MHD waves play an important role in solar and astrophysical contexts. An important class of coronal heating mechanism is the magnetohydrodynamic (MHD) wave heating mechanism, which relies on the dissipation of wave energy to provide the necessary heating (Osterbrock 1961; Gorden & Hollweg 1983; Kumar *et al.* 2006; Kumar & Kumar 2006). MHD waves generated by footpoint motions of coronal loops are capable to carry the sufficient amount of energy, and their dissipation via viscosity, thermal conductivity, resistivity, and radiation heats the coronal magnetic loops. Aschwanden (2004a) pointed out that MHD oscillations and waves with acoustic phase speeds carry insufficient energy to contribute significantly to coronal heating, whereas MHD oscillations and waves with Alfvénic phase speed carry an energy flux that is comparable to the coronal losses due to radiation and thermal conduction, and thus potentially contribute to the heating of active region loops or postflare loops. Coronal MHD waves, oscillations and solar coronal heating theories have been discussed by several researchers (Aschwanden 2004b; Nakariakov 2003). In this paper, we will study the dissipation of slow MHD waves in an inhomogeneous, compressible, and low-β coronal loop plasma through viscosity and thermal conduction. The paper is organized as follows. In section 2, we present a summary of coronal loop observations taken by TRACE, and the estimations of total energy losses in the coronal loops. The description of the physical model, the governing equations, and general dispersion relation are presented in section 3. In section 4, dispersion relation is solved numerically and the results for different coronal loop parameters are shown. Finally, conclusions are drawn in section 5.

2. Summary of observations and energy losses in coronal loops

Aschwanden *et al.* (1999) have analyzed a sequence of TRACE 171 Å and 195 Å images of an active region AR 8270 on 14 July 1998 during which a flare (GOES M4.6) was reported with a start time around 12:55 UT in the temperature range of 1.0–1.5 MK. The oscillating loops show evidence of strong damping, the amplitude of the oscillations decreases by more than 50% in several oscillation periods. The geometric and physical parameters of transverse oscillations in 26 coronal loops have also been measured by Aschwanden *et al.* (2002) in the 171 Å and 195 Å wavelength bands observed by TRACE. The average values of parameter for the oscillating loops reported by Aschwanden *et al.* (1999, 2002) observed by TRACE are given in Table 1.

For the optically thin part of the atmosphere, such as the transition region and the corona, the radiative losses per unit volume are (Priest 1982):

$$Q_{\text{rad}} = 10^{-18.66} T^{-1/2} n_e^2, \tag{1}$$

the conductive losses based on the assumption made by Krall (1977) can easily be derived,

$$Q_{\text{cond}} = \frac{5.14 \times 10^{-7} T^{7/2}}{2L^2}, \tag{2}$$

where L is the loop half length. The sum of these two loss terms (radiative loss and conductive loss terms) gives the minimum heating rate necessary to sustain the coronal

Table 1. Loop parameters reported by Aschwanden *et al.* (1999, 2002) observed by TRACE.

Parameter	TRACE	
Loop length	110 ± 53 Mm	130 ± 30 Mm
Loop width	8.7 ± 2.8 Mm	7.2 ± 0.80 Mm
Oscillation period	321 ± 140 s	276 ± 25 s
Decay time	580 ± 385 s	
Electron density	$(6.0 \pm 3.3)10^8$ cm^{-3}	$(2.0 \pm 0.6)10^8$ cm^{-3}
Temperature	(1.0–1.5)10^6 K	(1.0–1.5)10^6 K
Magnetic field	3.0–30.0 G	~ 20.0 G
Reference	Aschwanden *et al.* (2002)	Aschwanden *et al.* (1999)

loops at a temperature of the order of 2 MK. Corresponding to the loop parameters discussed in Table 1, the minimum required damping rate for slow-mode waves to sustain the coronal loops at such high temperatures can be determined by equating the volumetric wave heating rate to the sum of the radiative and the conductive losses as $\nu U = Q_{\rm rad} + Q_{\rm cond}$, where ν is the wave energy heating rate and is twice the wave-amplitude damping rate, $\mathrm{Im}(\omega)$, U is the mean energy density of the wave and can be determined as the product of the equilibrium mass density ρ_0 and the square of the rms velocity amplitude.

3. Physical model and dispersion relation

We consider the coronal loop as a static, straight, gravitation-less, low-β plasma slab with half-length L along the Z-axis of the cartesian coordinate system. The plasma is permeated by a uniform straight magnetic field ($\mathbf{B} = B_0\hat{e}_z$) and the density is inhomogeneous along z-direction. We have assumed that there is no background flow $\mathbf{V}_0 = 0$, and viscosity and thermal conduction are considered as dissipative mechanisms. The inhomogeneity of the plasma is introduced by a continuously varying density

$$\rho_0(z) = \rho_c \exp\left(\frac{-z}{L}\right), \tag{3}$$

where ρ_c is the coronal mass density and z is the height from coronal base. Therefore, $T_0(z) \sim p_0/\rho_0$, implies that the plasma temperature T_0 attains higher value at the loop top.

The basic one-dimensional MHD equations governing the plasma motion in coronal loops are the equation of continuity, equation of momentum, energy equation, and equation of state, used by De Moortel & Hood (2003).

When we linearize the set of equations (1)–(4) of De Moortel & Hood (2003) under first-order approximation and assuming that all the variables are of the form $f = A \exp i(kz - \omega t)$, we obtain the following dispersion relation for the wavenumber k as a function of frequency ω:

$$Lk^4 + Mk^3 + Nk^2 - \omega^3 = 0, \tag{4}$$

where

$$L = \frac{4\eta_0}{3}(\gamma - 1)\kappa_p \frac{T_0}{p_0\rho_0}\omega + i(\gamma - 1)\kappa_p \frac{T_0}{\rho_0},$$

$$M = (\gamma - 1)\kappa_p \frac{T_0}{\rho_0} k_\rho,$$

$$N = \omega C_S^2 - \frac{4i\eta_0}{3\rho_0}\omega^2 - i(\gamma - 1)\kappa_p \frac{T_0}{p_0}\omega^2.$$

Here all units are considered in cgs. The dispersion relation (4) is a fourth order polynomial in wavenumber k and, it has been solved numerically for the different loop parameters given in Table 1. The numerical solution of equation (4) gives the complex k's. The damping length of the slow-mode waves is given by the inverse of k_i, i.e., the imaginary part of the wavevector k. The mechanical energy flux density of the magnetoacoustic wave, F, given by Pekünlü *et al.* (2001) is

$$F = \rho\langle\delta v^2\rangle\frac{\delta\omega}{\delta k}, \tag{5}$$

where $\delta\omega/\delta k$ is the group velocity of the wave which is determined from the dispersion relation (4), $\langle\delta v^2\rangle$ is the square of the rms velocity amplitude.

4. Results and discussion

Figure 1 shows the variation of damping length of the slow-mode waves as a function of height from the coronal base. The damping length is the distance over which the amplitude of the wave drops to $1/e$ times of its original amplitude. We found that the short period waves lie near the base of the corona and an increase in the wave period as a result increases the damping length of the waves. Figure 1 depicts that the damping length of the wave increases very slowly with the height from the coronal base until it reaches up to 9.0×10^8 cm and thereafter the damping length of the wave sharply increases and becomes maximum around $z = 3.0 \times 10^9$ cm (height from the coronal base). The maxima of the curves become more prominent as the wave period increases and shifts towards the right corresponding to the long period waves. A decrease in the damping length is observed for a particular coronal base height range 4.0×10^9 cm to

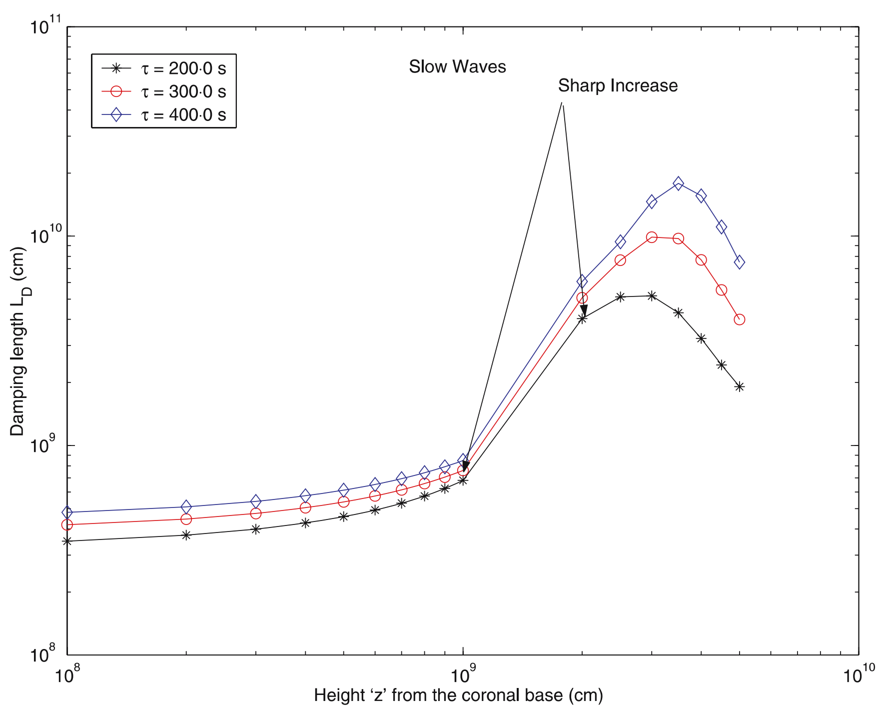

Figure 1. The variation of damping length with height for slow waves with parameters $T_c = 1.0 \times 10^6$ K, $L = 1.0 \times 10^{10}$ cm, and $\rho_c = 1.67 \times 10^{-15}$ gm cm^{-3}.

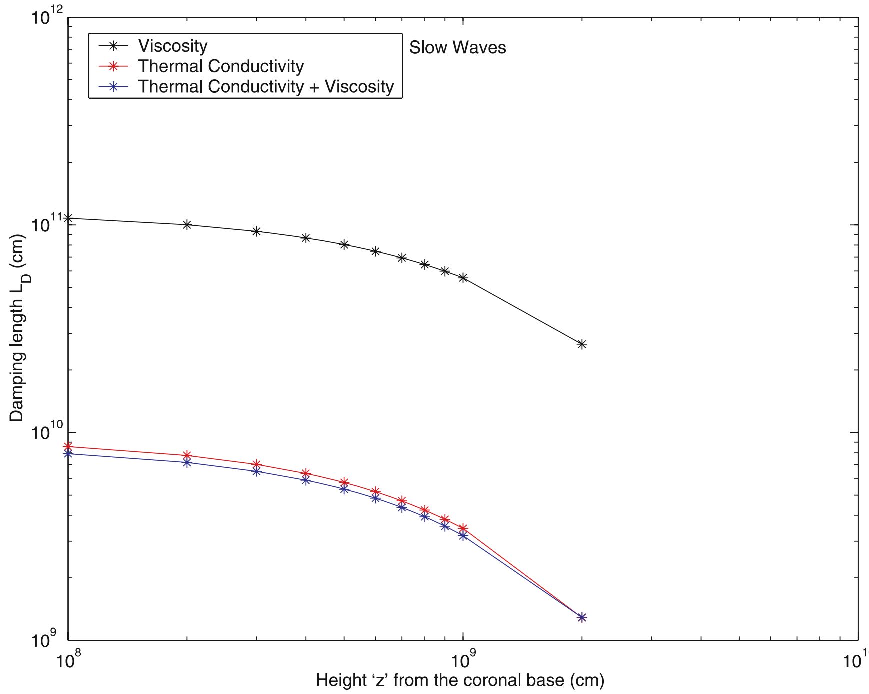

Figure 2. The variation of damping length with height for slow waves with parameters $T_c = 1.0 \times 10^6$ K, $L = 1.0 \times 10^{10}$ cm, $\tau = 200$ s, and $\rho_c = 1.67 \times 10^{-15}$ gm cm^{-3}.

6.0×10^9 cm, meaning that mechanical energy is deposited faster in the loop at around (40,000 km). If we consider solar coronal loop with loop half length more than that considered in Fig. 1, then the maxima of the curves shift towards the higher values of z than that of Fig. 1. Figure 2 shows the variation of damping length with the height from coronal base in the coronal loop (Table 1) when different dissipative mechanisms such as viscosity and thermal conductivity are taken into account simultaneously and separately. If we consider the propagating wave in the coronal loop damped through viscosity alone, we find larger damping length in comparison with the loop half length for all possible coronal base heights. Therefore, the dissipation of mechanical energy of the waves via viscosity cannot balance the energy losses in coronal loops. However, if we consider the thermal conductivity alone as a dissipative mechanism in the coronal loop, we find smaller damping length in comparison with the loop half length for all possible heights from the coronal base. It means that the thermal conductivity is more efficient dissipation mechanism than the viscosity within the coronal loops in order to balance the energy losses.

5. Conclusions

Our investigation of the slow magnetoacoustic wave dissipation in the coronal loops leads us to conclude that slow magnetoacoustic waves carry sufficient energy flux to heat the solar corona. If we consider the non-thermal broadening of the coronal lines as claimed by Saba & Strong (1991), the wave energy flux density turns out to be of the order of 10^6 erg cm^{-2} s^{-1}, which is high enough to replace the energy losses via radiation and conduction below to the transition region and chromosphere. We found that only those slow-mode waves which have periods more than 240 s may provide the required heating rate to balance the energy losses in the solar corona. Our calculated wave periods for slow-mode waves in the presence of viscosity and thermal conductivity are consistent with the oscillation periods of loops observed by TRACE. We cannot claim that the wave dissipation is the only effective process to heat the coronal loops because there are many other agents such as magnetic reconnection, current dissipation, phase mixing, resonant absorption, and so on working with different efficiencies in different regions of the solar corona.

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