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Role of equilibrium plasma flow on damping of slow MHD waves

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Abstract : In the solar corona waves and oscillatory activities are observed with modern imaging and spectral instruments. These oscillations are interpreted as slow magneto-acoustic waves excited impulsively in coronal loops. This study explores the effect of steady plasma flow on the dissipation of slow magneto-acoustic waves in the solar coronal loops permeated by uniform magnetic field. We have investigated the damping of slow waves in the coronal plasma taking into account viscosity and thermal conductivity as dissipative processes. On solving the dispersion relation it is found that the presence of plasma flow influences the characteristics of wave propagation and dissipation. We have shown that the time damping of slow waves exhibits varying behavior depending upon the physical parameters of the loop. The wave energy flux associated with slow magneto-acoustic 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.

Keywords : Sun, corona; coronal loops; MHD waves.

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1. Introduction

The existence of 'anomalous' temperature profile of the solar atmosphere and hot corona has puzzled astronomers ever since it was discovered, but it became clear during the 1950s decade that there must be a heating mechanism at work in the corona, which is not connected to radiation. Comparisons of the corona and the Sun's magnetic fields have shown that the corona is hottest where the magnetic fields are strongest. So, we believe that the heat of the corona results from effects of the Sun's magnetic fields instead of radiation from the Sun's core. It is well known that the entire corona is stitched together by thin, bright, magnetized loops of material that constrain the hot, dense gas of the corona and shine brightly at X-ray wavelengths. These loops

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are in a continuous state of change they can rise from inside the Sun, sink back down into it, or expand into space. They often come together, sometimes merging with each other and sometimes destroying each other. When they interact, stored magnetic energy is released into the corona, providing the energy that keeps the corona so hot.

The EUV imaging telescopes on board SOHO (EIT) and TRACE spacecrafts made it possible to directly observe the magnetohydrodynamic (MHD) waves in the solar corona. Solar magnetohydrodynamic (MHD) waves are an important diagnostic tool of the medium through which they propagate. They are responsible for carrying energy and momentum and probably transport some of the energy needed to heat the solar corona, creating instabilities, generating phenomena like magnetic reconnection, phase mixing, *etc*. MHD waves play an important role in the dynamics of the solar corona and are widely considered as a possible source of coronal heating [1,2].

Propagating intensity oscillations have been detected in the corona, firstly in polar plumes using SoHO/UVCS [3] and using SoHO/EIT [4]. These intensity oscillations have been interpreted as propagating slow waves [5–7]. Moortel and Hood [8] have investigated the damping of slow magneto-acoustic waves in homogeneous medium by taking into account thermal conduction and compressive viscosity. They found that the inclusion of thermal conduction results in *'thermal mode'*, which is purely decaying in case of standing waves, but is oscillatory and decaying in the case of driven waves. The excitation and damping of standing slow-mode oscillations has also been studied by several researchers [9–11]. They found that slow standing waves are attenuated within a few wave periods. Nakariakov *et al* [12] showed that in a coronal loop an impulsive thermal energy release excites the first harmonic mode efficiently. This result was confirmed by Selwa *et al* [13], who performed numerical simulations of slow standing waves in the limit of the one-dimensional approximation. This model was extended to a curved slab by Selwa *et al* [14] who measured a reduction in the excitation time of the fundamental mode in a curved structure in comparison with a straight slab.

Ground and space-born satellite observations confirmed the presence of steady flows in the photosphere, chromosphere [15], corona [16] and beyond, in the solar wind [17]. Equilibrium flows are known to introduce a series of new effects such as Kelvin-Helmholtz and resonant instabilities, negative energy waves, *etc*. The effect of steady mass flows on the oscillatory modes of magnetic structures has been theoretically investigated in some works. The most relevant ones for the present investigation are Nakariakov and Roberts [18], who studied the effect of steady flow in coronal and photospheric slabs, and Terra-Homem *et al* [19], who extended the former study to cylindrical geometry. Therefore, theoretical models should include the presence of an equilibrium steady flow.

The main objective of this paper is to study the effect of equilibrium flow on the temporal damping of slow magneto-acoustic waves in homogeneous unbounded coronal plasma.

2. General dispersion relation

For the discussion of propagation and dissipation characteristics of slow MHD waves in coronal loops, we consider an ideal, perfectly conducting plamsa permeated by a uniform magnetic field along the z-axis. We suppose that the wavelengths are much smaller than the gravitational scale-height, *i.e.* gravitational effects are neglected. A field-aligned equilibrium steady flow is present in the system. Thus, the basic MHD equations describing the plasma motion in 1D [8] are:

$$\frac{\partial \rho}{\partial t} = -\frac{\partial}{\partial z}(\rho v) \tag{1}$$

$$\rho\frac{\partial v}{\partial t} + \rho v\frac{\partial v}{\partial z} = -\frac{\partial p}{\partial z} + \frac{4\eta_0}{3}\frac{\partial^2 v}{\partial z^2} \tag{2}$$

$$\frac{\partial p}{\partial t} + v\frac{\partial p}{\partial z} = -\gamma p\frac{\partial v}{\partial z} + (\gamma-1)\frac{\partial}{\partial z}\left(\kappa_P\frac{\partial T}{\partial z}\right) - (\gamma-1)L(\rho,T) \tag{3}$$

$$p = 2nk_BT = \frac{2\rho}{m_p}k_BT. \tag{4}$$

Here v, ρ, p, T and κ_P are the velocity, mass density, pressure, temperature and thermal conductivity of the plasma respectively. η_0 is the compressive viscosity parallel to the magnetic field, k_B is the Boltzman's constant, and m_p is the proton mass. $L(\rho, T)$ is the net heat loss function per unit mass and time having the form

$$L(\rho,\ T) = \rho^2 XT^\alpha - H_0 \tag{5}$$

where χ and α are piecewise continuous functions depending on the temperature. The heating term H_0 is assumed fixed that maintains the equilibrium temperature without contributing to the linearized perturbation equations.

We consider small deviations of the physical quantities of the medium from their equilibrium values as

$$\rho = \rho_0 + \rho_1,\quad p = p_0 + p_1,\ T = T_0 + T_1,\ \text{and}\ v = U_0 + v_1 \tag{6}$$

where the subscripts "0" and "1" refer to the equilibrium and perturbed quantities. Assuming that all disturbances are expressed as Fourier components $\exp(ik.r - i\omega t)$, a general dispersion relation in frequency ω is obtained as

$$\omega^3 + ia_2\omega^2 - a_1\omega + ia_0 = 0 \tag{7}$$

where

$$a_2 = (\gamma - 1)\left(\frac{\alpha\rho_0^2 X T_0^\alpha}{p_0} + \frac{\kappa_P\, k^2 T_0}{p_0}\right) + \frac{4}{3}\frac{\eta_0 k^2}{\rho_0} + 3\, ik\, U_0$$

$$a_1 = (\gamma - 1)\left(\frac{4\,\eta_0\alpha\rho_0 X T_0^\alpha k^2}{3\,p_0} + \frac{4\eta_0\kappa_P k^4 T_0}{3\,p_0\rho_0} + \frac{2\,i\kappa_P k^3 T_0 U_0}{p_0} + \frac{2\alpha\rho_0^2 X T_0^\alpha k U_0}{p_0}\right)$$
$$+ \frac{8}{3}\frac{i\eta_0 k^3 U_0}{\rho_0} + c^2 k^2 - 3k^2 U_0^2$$

$$a_0 = (\gamma - 1)\left(\begin{aligned}&\frac{\kappa_P k^4 T_0 U_0^2}{p_0} + \frac{4}{3}\frac{\eta_0\kappa_P k^5 T_0 U_0}{p_0\rho_0} - i\,\frac{4}{3}\frac{\eta_0\alpha k^3\rho_0 X T_0^\alpha U_0}{p_0}\\ &+ \frac{\alpha\rho_0^2 X\, T_0^\alpha k^2 U_0^2}{p_0} - \frac{\kappa_P k^4 T_0}{\rho_0} + (2-\alpha)\, k^2\rho_0 X T_0^\alpha\end{aligned}\right)$$
$$+ \frac{4}{3}\frac{\eta_0\, k^4 U_0^2}{\rho_0} + ik^3 U_0^3 - ic^2 k^2 U_0$$

$$c^2 = \frac{\gamma\, p_0}{\rho_0}\,\mathrm{cm^2 s^{-2}},\ \gamma = \frac{5}{3},$$
$$\eta_0 = 10^{-16} T_0^{5/2}\ \mathrm{g\,cm^{-1}\,s^{-1}}\ \textit{and}\ \kappa_P = 10^{-6} T_0^{5/2}\mathrm{erg\,cm^{-1}\,s^{-1}K^{-1}}.$$

We have taken $\chi = 10^{29}$ erg cm^{3}s^{-1} and $\alpha = -0.5$ [20]. The wave number k can be approximated in terms of loop length L as $k = \frac{2\pi}{c_s\tau}$ or $k = \frac{2\pi}{L}$ [8]. In the absence of plasma flow, when we solved our dispersion relation Eq. (7) for ω, we get three complex roots namely $\omega_{1r} - i\omega_{1i}$, $-\omega_{1r} - i\omega_{1i}$ and $-i\omega_{2i}$. The root $-i\omega_{2i}$ is purely imaginary corresponding to thermal mode and other two roots are complex corresponding to slow mode waves. But in the presence of steady flow, we get three complex roots in the form $\omega_{1r} + i\omega_{1i}$, $\omega_{1r} - i\omega_{1i}$ and $-\omega_{2r} + i\omega_{2i}$. Thus, we see that in the presence of steady flow thermal mode changes into propagating wave.

3. Results and discussion

The dispersion relation Eq. (7) has been solved numerically for different coronal loops. The behavior of damping rate, ratio τ_D/P (which determines that the damping is either strong or weak) and energy flux associated with slow MHD waves as a function of equilibrium plasma flow is studied and has been shown in Figures 1–3.

Figure 1 shows the variation of damping rate as a function of steady plasma flow. Analysis of observations shows the existence of plasma flow in coronal loops. The magnitude of these motions varies from 5 km/s to 40 km/s [16]. Therefore, we have considered the flow velocities in the range 2 km/s to 40 km/s. From Figure 1 it is clear that in the presence of steady flow slow waves show strong damping. Also it can be seen that the damping is more pronounced in short loops as compared to long loops.

In Figure 2 we have shown the variation of τ_D/P as function of steady plasma flow for different loop lengths including the effect of optically thin radiation, thermal conductivity and viscosity. Wang *et al* [21] have reported that in coronal loops strong

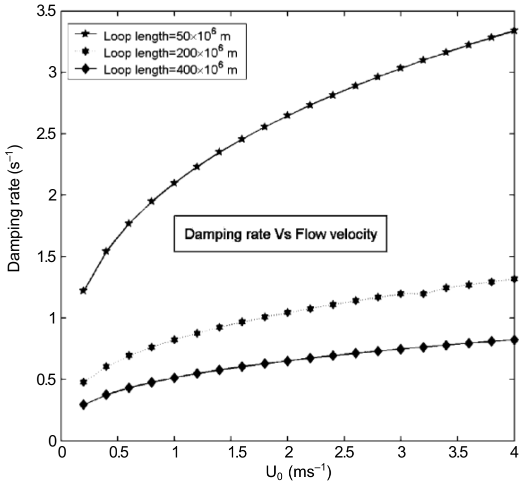

Figure 1. The variation of damping rate as function of steady plasma flow with parameters n_0 = 5.0 × 10^{15} m^3, T_0 = 2.0 × 10^6 K.

damped oscillations take place when $\tau_D / P \leq 1$ and these oscillations were interpreted as weak damped oscillation when $\tau_D / P \geq 2$. From Figure 2, it is evident that the ratio τ_D/P is much smaller than unity at all flow speeds indicating strongly damped

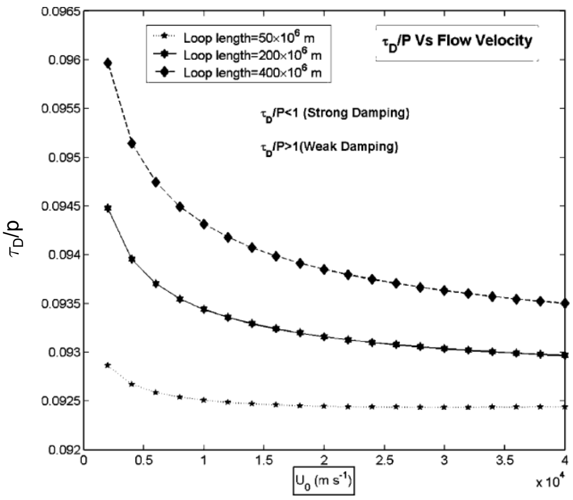

Figure 2. The variation of τ_D/P as function of steady plasma flow with parameters n_0 = 5.0 × 10^{15} m^3, T_0 = 2.0 × 10^6 K.

oscillations. So, in the presence of steady flow loop oscillations are strongly damped irrespective of loop lengths. But, it was found that in the absence of plasma flow the ratio τ_D / P is larger than unity for all coronal loops of any length implying weakly damped oscillations. Figures 1–2 also clearly demonstrate that slow magneto-acoustic waves are strongly damped in short loops.

The energy flux associated with slow waves is given as

$$F = \rho \left\langle \delta v^2 \right\rangle \frac{\partial \omega}{\partial k} \tag{8}$$

where $(\partial\omega / \partial k)$ represents the group velocity of the wave.

Using typical values for a coronal loop n_0 = 5.0 × 10^{15} m^{-3}, T_0 = 2.0 × 10^6 K, $\left\langle \delta v^2 \right\rangle$ = 40 km/s and L = 400 Mm, we study the behavior of energy flux as function of steady flow. The variation of energy flux with steady flow has been shown in Figure 3. It is found that the energy flux associated with slow waves in the presence of flow is of the order of 10^6 erg cm^{-2} s^{-1} which is quite sufficient to heat the solar coronal loops at such high temperatures.

Figure 4 shows the variation of damping rate as function of steady flow for different loop temperatures. From this Figure, we infer that slow waves are strongly damped in hot coronal loops.

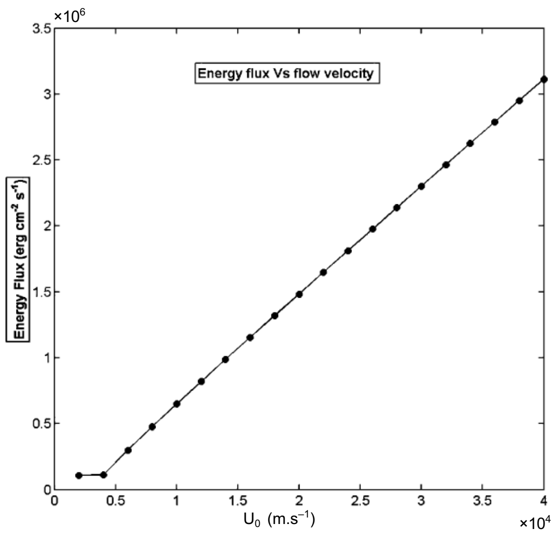

Figure 3. The variation of energy flux as function of steady plasma flow with parameters n_0 = 5.0 × 10^{15} m^3, T_0 = 2.0 × 10^6 K and L = 400 Mm.

4. Conclusions

In this paper we have studied the effect of equilibrium plasma flow on the time damping of slow magneto-acoustic waves in solar coronal loops. The inclusion of equilibrium

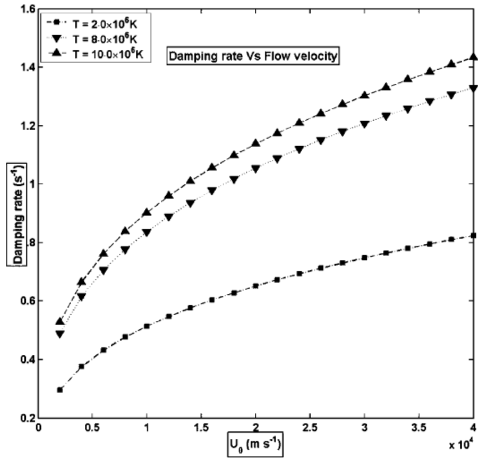

Figure 4. The variation of damping rate as function of steady plasma flow with parameters n_0 = 5.0 × 10^{15} m^3, and L = 400 Mm.

steady flow not only produces a shift in oscillatory frequency but also breaks the symmetry between parallel and anti-parallel wave propagation. The main conclusions of the study are as follows:

(i) The presence of steady flow breaks the symmetry of propagating slow MHD waves.
(ii) Steady plasma flow dramatically influences the propagation and dissipation of slow magneto-acoustic waves in coronal loops.
(iii) In the presence of steady flow slow waves are strongly damped in coronal loops irrespective of temperature and loop length.
(iv) The wave periods are in agreement with the observed period of loop oscillations.
(v) In the presence of flow the energy flux associated with slow waves is of the order of 10^6 erg cm^{-2} s^{-1}.

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