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The damping of slow magnetoacustic waves in coronal loops

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It has been recognized long time ago that magnetohydrodynamic (MHD) waves must exist in the solar corona and their presence has a very important implication for the dynamics, heating and stability of the coronal plasma. A new era in the study of this solar region started after the launch of the high resolution SOHO and TRACE satellites which has changed our view of the solar corona in many ways. Using data provided by these space telescopes, scientists were able to discover the existence of waves propagating in the solar corona. High cadence TRACE observations show that outward propagating intensity disturbances are a common feature in large, quiescent coronal loops, close to active regions. One of the basic characteristics of all observed waves is their rapid damping. A model which includes the effect of stratification and thermal damping is used to study the effect of stratification on thermally damped slow and fast magnetoacoustic waves in propagating in coronal loops.

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1. Introduction

The launch of high resolution telescopes (SOHO, TRACE, RHESSI) has marked the beginning of a golden era for solar physics, in particular for magnetohydrodynamic (MHD) wave research in the solar atmosphere. Until very recently, only indirect evidence of the presence of solar coronal MHD waves could be adduced [1]. Now, through the observations made by SOHO and TRACE, waves and oscillations have been observed in various coronal structures such as polar plumes [2]-[5] which are interpreted as slow MHD waves or large scale waves (EIT waves) propagating mainly in the quiet Sun as a result of a sudden energy release [6], [7]. TRACE has seen global vibrations of coronal loops, which are interpreted as MHD kink standing modes of a magnetic flux tubes as predicted by the theory of Edwin and Roberts [8]. Since these waves are strictly localized in the structures in which they propagate they can be labeled local coronal waves or oscillations. On the other hand, there are there are global coronal waves which originate from an impulsive and eruptive sources such as flares or CME and are able to travel over very long distance (comparable to the solar radius). These waves carry information about the average values of the various coronal plasma parameters.

Special attention has been paid to ducted waves in coronal loops for a variety of reasons, including the determination of field structure and plasma transport parameters, i.e. local coronal seismology [9]. The common feature of the observed waves and oscillations in the solar corona is their rapid damping (sometimes the damping length is of the same order as the wavelength). For non-ideal effects, the propagating MHD modes can be damped and there is a minimum damping length that can be obtained by thermal conduction alone [5].

In this paper we investigate the effect of gravitational stratification in 2D model of thermally damped linear compressional waves propagating in coronal loops. The gravitational stratification and thermal conduction increases the length considerably.

2. Basic equations

We suppose that the coronal plasma is a completely ionized gas. The observed wavelengths and periods are large compared to ion Larmor radius and the period of gyration around a magnetic field line, so these waves can be studied within the MHD framework. In order to simplify the model we suppose that we deal only with those waves which have wavelengths of the same order as the size of the loop (waveguide). It was shown by Edwin and Roberts [8] that waves corresponding to this limit (wide tube limit) are very weakly dispersive, i.e. they propagate as in a unbounded plasma. We suppose that the vertical wavelength of the waves is comparable to the gravitational wavelength, so the effect of gravitational stratification must be taken into account (this is assumption is inspired by observational results by De Moortel et al. [5]. In order to describe non-ideal effects which may act to damp the considered modes we consider thermal conduction. Under coronal conditions, thermal conductivity is a tensorial quantity. Since the plasma is inhomogeneous only in the vertical direction, it can be shown that the parallel component to the ambient magnetic field is much larger that the perpendicular one

The dynamics of the plasma is described by the system of magnetohydrodynamics equations he plasma motion is described by the MHD approximation given by the system of equations:

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

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

$$\frac{\partial\vec{B}}{\partial t}=\nabla\times\left(\vec{v}\times\vec{B}\right), \tag{3}$$

$$\frac{\rho^{\gamma}}{\gamma-1}\frac{D}{Dt}\left(\frac{p}{\rho^{\gamma}}\right)=-\nabla\vec{q},\quad \vec{q}=-k_{II}\vec{b}\left(\vec{b}\cdot\nabla T+\frac{b_x}{B_0}\frac{dT_0}{dx}\right),\quad k_{II}=\frac{3\rho_0 k_B^2 T_0\tau_e}{m_p m_e} \tag{4}$$

where v and B are the velocity and magnetic induction vectors, p, ρ and g=-gz are the pressure, density and the gravitational acceleration and γ denote the adiabatic index. The perturbations of the magnetic field and velocity are denoted by b=(bx,0,b_z) and v=(v_x,0,v_z) In eq. (4) q is the heat flux due to thermal conduction (taking into account only the parallel component of the thermal conductivity, the heat flux can be written in the form of Braginskii) , k_{II} is the parallel component of the thermal conductivity, b=B_0 /B_0 is unit vector in the direction of the equilibrium magnetic field, T_0 and T are the equilibrium and perturbed temperature and k_B is the Boltzmann constant, ι_e is the electron collision time, m_p and m_e are the proton and electron mass. For typical coronal conditions, k_{II} approx 5 × 10^4 m s^{-3}kg K^{-1} (Ruderman et al. [10])

3. Results and discussion

Let us consider small but finite amplitude perturbations about the equilibrium, i.e. we write all physical quantities (except the velocity) in the form of: $f=f_0+\widetilde{f}$ where f_0 is the equilibrium quantity and $\widetilde{f}$ is its Eulerian perturbation. Observations show that the amplitudes of te modes is very small [3], therefore we will limit our description to linear waves only. Since the magnetic field is constant with height, the sound speed and the density scale height are both constant, with values determined by the temperature of the atmosphere. In this case the plasa is in hydrostatic equilibrium, which means:

$$\rho_0(z), v_A(z)=\begin{cases}\rho_0 e^{-z/H}\\ v_{A0}e^{z/2H}\end{cases},\quad H=\frac{C_S^2}{\gamma g} \tag{5}$$

where ρ_0 and v_{A0} are the density and Alfven speed at z=0 and h is the isothermal scale-height. We consider a y-independent harmonic solution of the form: $f(x,z,t)=f(z)e^{i(\omega t+k_x x)}$ and in order to make the mathematical approach tractable $k_{II}=\rho_0\widetilde{k}_{II}$. The system of equations (1)-(4) can be reduced to two coupled ODE for v_x and v_z :

$$\left[v_{A0}^2(0)e^{\frac{z}{H}}\frac{d^3}{dz^3}+\left(\omega^2-k_x^2 v_{A0}^2(0)e^{\frac{z}{H}}\right)\frac{d}{dz}+\frac{1}{H}\left(\frac{k_x^2c_S^2}{\gamma}-\omega^2\right)\right]v_x=ik_x\left[\left(\omega^2-\frac{c_S^2}{\gamma H^2}\right)+\frac{c_S^2}{\gamma H}\frac{d}{dz}\right]v_z \tag{6}$$

$$\begin{aligned}&\frac{1}{k_x}\left\{i(\gamma-1)\left(k_x^2c_S^2-\omega^2+k_x^2v_{A0}^2(0)e^{\frac{z}{H}}\right)H\omega+\chi\left(k_x^2c_S^2-\gamma\omega^2-\gamma k_x^2 v_{A0}^2(0)e^{\frac{z}{H}}\right)\frac{d}{dz}+\right.\\ &\left.H\left[\chi\left(\omega^2\gamma-k_x^2c_S^2\right)-v_{A0}^2(0)e^{\frac{z}{H}}\left(\chi\gamma k_x^2-i\omega(\gamma-1)\right)\right]\frac{d^2}{dz^2}+\chi\gamma v_{A0}^2(0)\frac{d^3}{dz^3}+H\chi\gamma v_{A0}^2(0)\frac{d^4}{dz^4}\right\}v_x=\\ &\frac{c_S^2}{H}\left\{\frac{H\omega}{\gamma}(\gamma-1)-\left[H^2\omega(\gamma-1)+i\chi\right]\frac{d}{dz}+2i\chi H\frac{d^2}{dz^2}-i\chi H^2\frac{d^3}{dz^3}\right\}v_z\end{aligned} \tag{7}$$

Introducing the dimensionless quantities

$$: a=k_x H,\ \beta=\frac{H\omega}{C_S},\ \chi=\frac{m_p(\gamma-1)^2\widetilde{k}_{II}}{2k_B\rho_0\gamma},$$

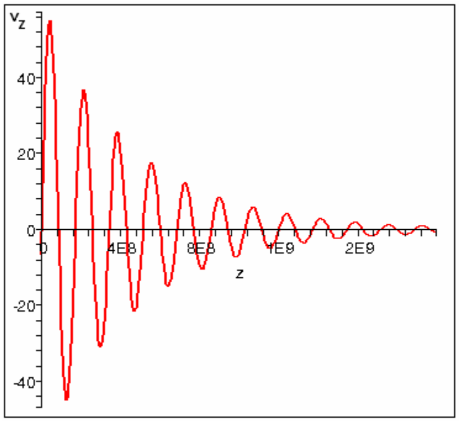
, $\alpha=\dfrac{\chi}{H^2\omega}$ and a new variable $\eta=\dfrac{\omega^2H^2e^{-z/H}}{v_{A0}^2}$ in (6)-(7) the evolution of fast magnetoacustic waves is given by:

$$\sum_{n=0}^{5}a_n(\eta)\frac{d^n v_x}{d\eta^n}=0, \tag{8}$$

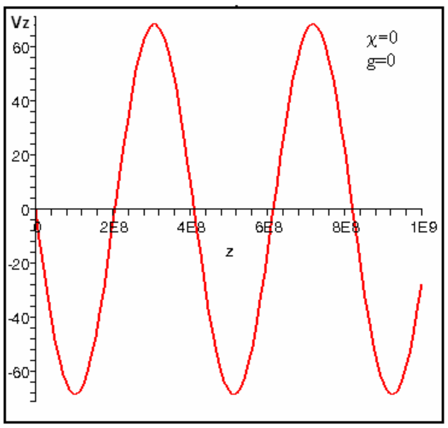
where the coefficients a_n are functions of a, β, α, and χ. We suppose ab ovo that the solution of the equation (8) is of the form:

$$v_x\approx A\eta^d\cos(B\tau) \tag{9}$$

where A describe the amplitude of the propagating fast waves and B is a constant . Since in original coordinates $\eta\propto\exp(-z/H)$, the quantity $l_d=H/d$ describes the damping length of waves, i.e the distance over which the velocity amplitude of waves decay e-fold. The following results are valid for this particular form of decay wave. In (9) the first term describes the damping, while the second is an oscillating term. Introducing this trial solution into (8) and following [11] we can obtain the expression for the coefficient d, i.e. we can obtain the damping length of fast magnetoacustic waves propagating in a gravitationally stratified plasma taking into account the thermal conduction. If we want to study the damping of slow magnetoacustic waves, we must use the damping of fast magnetoacustic waves.



a



b

Fig. 1. (a) Effect of stratification on thermally damped slow magnetoacustic waves, (b) In the absence of stratification and thermal conduction.

4. Conclusions

The high-resolution observation of waves in coronal structures opened a new chapter in solar physics. The rapid damping of modes in coronal loops permts to derive important quantities for magnetic field and transport coefficients. Our theoretical model will extend our research to more realistic configurations. The zoo of possible mechanism which can act (separately or together) on waves in order to provoke their damping is very large. Here we have considered only the combined effect of gravitational stratification and thermal conduction.

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