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The effects of radiative cooling on oscillating coronal loops*

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Abstract

Recently, high resolution observations by SOHO and TRACE spacecraft have identified oscillating loops and propagating waves in the solar coronal. These new discoveries established a new discipline that is known as *coronal seismology*. The importance of this lies in the potential for the diagnostics of coronal structures and knowledge of coronal heating. We present a study of the effects of radiative cooling and heating processes on longitudinal waves in coronal loops. We find that radiation and heating results in a modification in the evolution of temperature and pressure perturbations but not in the decay time of the wave.

Key words: Sun: Corona; hydrodynamics; sun: oscillations.

Efectos del enfriamiento radiativo en lazos coronales oscilantes

Resumen

Recientemente, observaciones de alta resolución por el SOHO y TRACE han identificado lazos oscilando y ondas propagándose en la corona solar. Estos nuevos descubrimientos establecen una nueva disciplina que es conocida como *sismología coronal*. La importancia de esto consiste en el potencial para los diagnósticos de estructuras coronales y el conocimiento del calentamiento coronal. En este trabajo, presentamos un estudio de los efectos de los procesos de calentamiento y enfriamiento radiativo sobre ondas longitudinales en lazos coronales. Encontramos que la radiación y el calentamiento causan una modificación en la evolución de las perturbaciones en temperatura y presión pero no en el tiempo de decaimiento de la onda.

Palabras clave: hidrodinámica; Sol: corona; Sol: oscilaciones.

Introduction

Recent observations by high-resolution space imaging telescopes and spectrometers have revealed a variety of coronal oscillation modes. Such oscillations are important because of their potential for the diagnostics of coronal structures (magnetic field strength, gas density, etc.) through coronal seismology and their poten-

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tial for heating the corona (1, 2). Standing slow magnetoacoustic waves have been detected in hot (T > 6 MK) loops using the SUMER spectrometer on board the SOHO satellite (3-5). These oscillations are excited impulsively, as evidenced by the presence of large initial Doppler shifts and impulsive profiles of intensity and line width. However, unlike the transverse loop oscillations observed by the TRACE, the SUMER hot loop oscillations are usually not associated with large flares. They are believed to be excited in the lower parts of the atmosphere near one of the footpoints.

Ofman & Wang (6) found that thermal conduction is the primary dissipation mechanism of slow waves in hot coronal loops. Mendoza-Briceño et al. (7) showed that the inclusion of gravitational stratification results in a further 10-20 percent reduction of the damping time.

The isothermal loop models used in the above mentioned studies explained the rapid damping of the slow standing mode oscillations and showed that the decay time is mainly governed by the thermal conduction timescale. However, the excitation mechanism still remains unclear.

In the present work a 1D loop model for the study of the nonlinear oscillations in hot loops is proposed. We extend the model calculations of Mendoza-Briceño et al. (7) to include the effects of radiative cooling and heating processes on damping of longitudinal waves in hot coronal loops.

Hydrodynamical Modeling

Since the plasma dynamics in a coronal loop is dominated by the magnetic field, we make the usual assumption that the plasma motion takes place primarily along the magnetic field lines which in turn determine the loop geometry. Heat conduction due to the electron diffusion also occurs along the field lines rather than across them. In this way, each plasma loop can be treated almost independently from the neighboring ones implying that the thermodynamical evolution of the coronal plasma along the field lines is essentially one-dimensional (1D). Under these conditions, the energy conservation equation, including the effects of thermal conduction and radiative cooling and heating reads.

$$\frac{\partial(\rho T)}{\partial t}+\frac{\partial(\rho v T)}{\partial s}=-\frac{\mu(\gamma-1)}{R_g}\left[p\frac{\partial v}{\partial s}+\rho^2 Q(T)-H(s,t)-\frac{\partial}{\partial s}\left(k\frac{\partial T}{\partial s}\right)\right], \qquad [1]$$

In this equation, s denotes the position along a loop of constant cross-section, is the plasma mass density, is the fluid velocity, T is the plasma temperature, p is the gas pressure, $Q(T)$ is the optically thin radiation-loss function (8), $H(s,t)$ is the coronal heating function, (=5/3) is the ratio of specific heats, μ is the mean molecular weight, and k $^{-6}T^{5/2}$ ergs cm^{-1} s^{-1} K^{-1} is the coefficient of thermal conductivity parallel to the magnetic field (9). Equation [1] together with continuity and momentum equations are closed by assuming a pressure relation of the form $p = R_g \rho T / \mu$, where R_g is the gas constant.

The set of governing equations are solved numerically using a 1D, finite-difference (FD) hydrodynamics code based on a temporally and spatially second-order accurate Lagrangian remap technique (10).

Results and Discussion

The aim of the present model calculations is to quantify the effects of cooling and heating processes on damping of longitudinal waves observed by SUMER in hot (T > 6 MK) coronal loops. To do so, we start from the same loop parameters used by Mendoza-Briceño et al. (7), who performed similar calculations of the damping of slow MHD waves in hot loops, by neglecting the effects of cooling and heating. In particular, we choose a one-dimensional loop configuration of semicircular shape, constant cross-sectional area, and total length L=400

Mm (0.575 $R_\odot$), with an initial uniform temperature (T = 6.3 or 8.0 MK) and density (=5.0 x 10^8 cm^{-3}) distributions, and the initial velocity is of the form $v = v_0 \sin(2\pi s / L)$, where v_0 is the amplitude of the wave at t=0. As outlined by Mendoza-Briceño et al. (7), these initial parameters are motivated by *SUMER* and *Yohkoh SXT* observations of hot loops in the upper solar atmosphere.

In Figure 1, we display the cooling and heating processes as a function of time for an initial temperatures of T = 6.3 MK (a) and T = 8.0 MK (b). The solid line in this figure depicts the evolution optically thin radiation loss, while the dashed line shows the constant coronal heating function. The radiation loss oscillates around the constant value of the heating H in time, as a consequence of the time dependence of temperature and density, as given by $\rho^2 \chi T^{\alpha}$ where

and are temperature dependent. After a time of 3000 s, the radiation is still oscillating, but below the heating value, which is now greater than the cooling.

Figure 2 shows the resulting time evolution of the wave density (Figure 2a), temperature (Figure 2b), velocity (Figure 2c) and pressure (Figure 2d) at a fixed distance l_0 = 0.35L (0.20 $R_\odot$), from the left footpoint at s=0 for the particular case in which T = 6.3 MK and v_0= 87 km s^{-1}. In the above plot we indicated with a solid line the wave evolution including the cooling and heating processes, the dashed line shows the same evolution without heating, while the dotted line depicts the same wave evolution without including cooling and heating processes. The effects of cooling and heating can only be observed for the temperature and pressure perturbations. The temperature perturbation (Figure 2b) increases in time when these two effects are considered. Instead when only the cooling process is included the temperature perturbation decreases because the plasma is cooling during the evolution. By looking Figure 1a where the cooling and heating evolution is plotted, the heating is

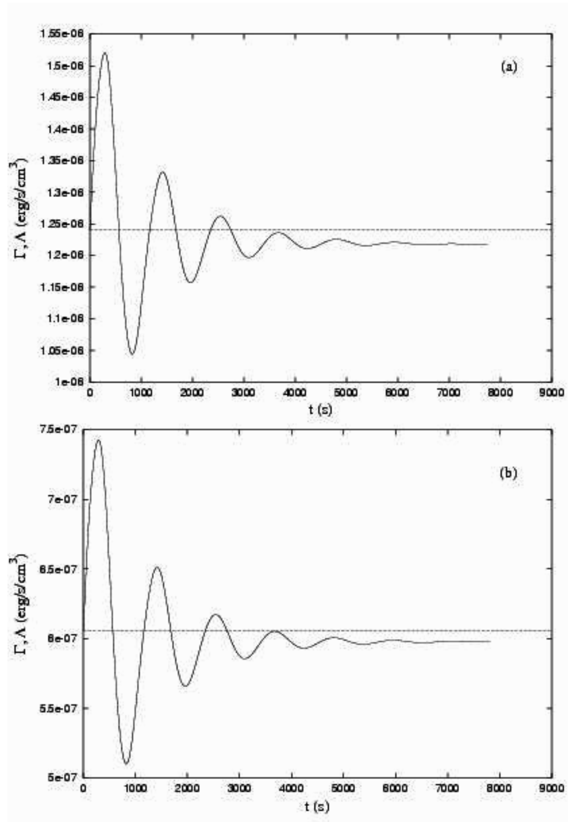

Figure 1. Time evolution of the cooling and heating processes for a loop model with (a) T = 6.3 MK and (b) T = 8.0 MK. The solid line is the radiative cooling and the dashed line is the constant heating.

dominant when t > 3000s, this makes the temperature perturbation to increase in time. The pressure perturbation (Figure 2d) shows slightly variation when different effects are taken in to account.

When we increase the temperature to T = 8.0 MK, the density, temperature, velocity and pressure can be seen in Figure 3. Again it is found the radiative cooling and heating processes only affect the temperature and pressure perturbations. The evolution of the temperature perturbation shows no variations when the cooling and heating processes are included or neglected. In this case in contrast with T = 6.3 MK the cooling

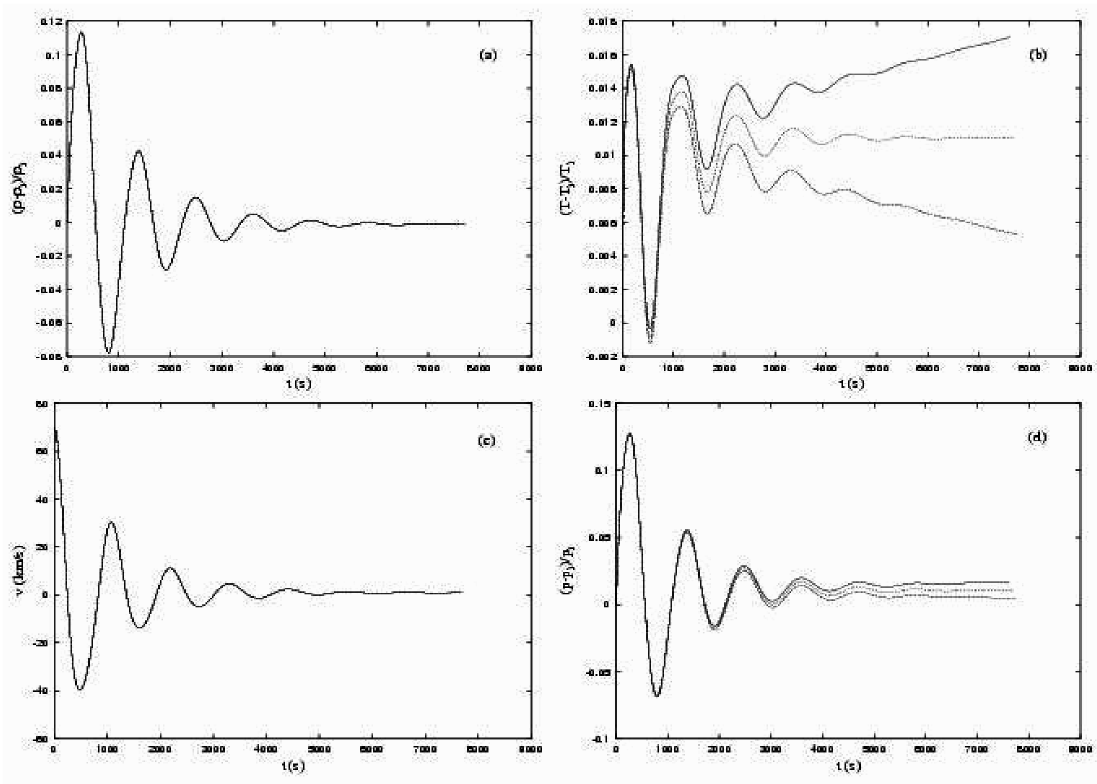

Figure 2. Time evolution of the (a) wave density, (b) temperature, (c) velocity and (d) pressure at $s = l_0 = 0.35L$ for a loop model with $T = 6.3$ MK and $L = 400$ Mm. In all panels, the wave evolution including cooling and heating (solid line) is compared with the same evolution with only cooling (dashed line) and with cooling and heating neglected (dotted line).

and heating are reduced in a factor of two, which makes the loop plasma to evolve as this effect were not considered. When only the cooling process is considered we see the temperature evolution decrease in time as expected.

It is noticeable that the cooling and heating processes have not effect on the velocity and density perturbations, which implies that the damping time is not modified by this new effect.

Conclusions

We have investigated the behaviour of longitudinal waves in hot ($T > 6.0$ MK) coronal loops, starting with loop parameters motivated by *SUMER* and *Yohkoh SXT* observations and taking in to account the effects of radiative cooling and constant heating.

We find that including only radiative loss makes the temperature and pressure perturbations to cool even further in time. For the case of $T = 6.3$ MK the temperature perturbation increases in time when both the radiative loss and heating are considered, as well as the pressure perturbation. This is caused by the heating that is slightly higher that the cooling after two periods. When the initial temperature is increased to $T = 8.0$ MK, the evolution of the temperature and pressure perturbations shows no variations when both the heating and cooling processes are include or neglected. It is probably due to the value of the heating decreases

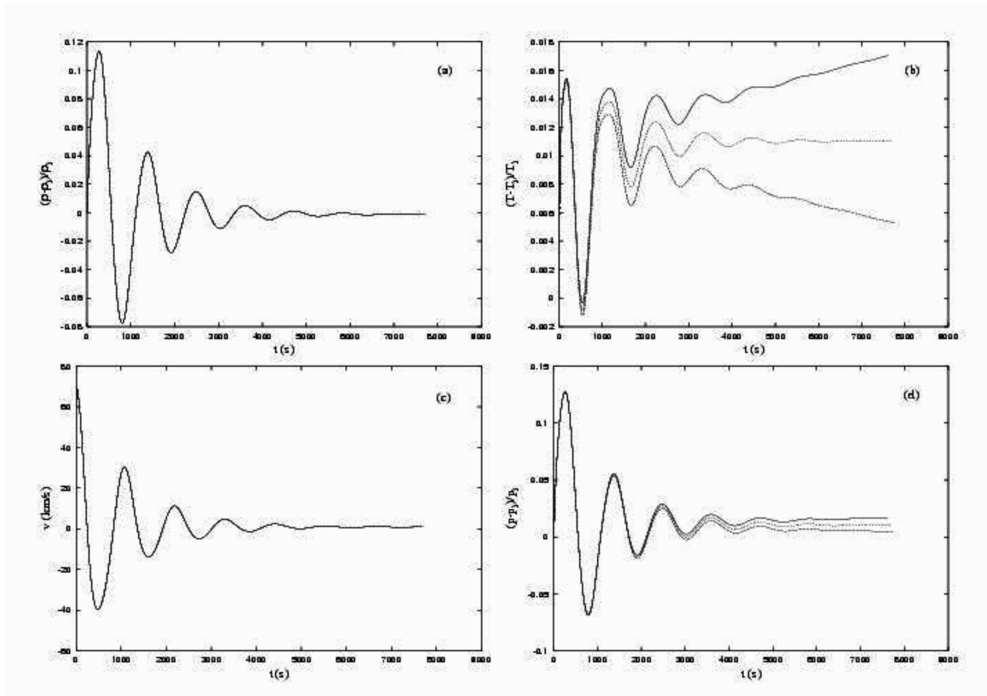

Figure 3. Time evolution of the (a) wave density, (b) temperature, (c) velocity and (d) pressure at $s = l_0 = 0.35L$ for the same model as in Fig. 2 but with $T = 8.0$ MK.

to half of the value for the case when $T = 6.3$ MK, and as consequence the system is kept in equilibrium.

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