IMPULSE EXCITATION AND DAMPING OF SLOW STANDING MODE OSCILLATIONS IN HOT CORONAL LOOPS

Y. Taroyan\textsuperscript{1}, R. Erdélyi\textsuperscript{2}, and J.G. Doyle\textsuperscript{1}

\textsuperscript{1}Armagh Observatory, College Hill, Armagh BT61 9DG, Northern Ireland, email: yat@arm.ac.uk, jgd@arm.ac.uk

\textsuperscript{2}Department of Applied Mathematics, Sheffield University, Sheffield S3 7RH, England, email: Robertus@sheffield.ac.uk

ABSTRACT

A new theoretical model for the study of slow standing mode oscillations in hot ($T > 6$ MK) active region coronal loops is presented. These oscillations are observed by the SUMER spectrometer on board the SoHO satellite. The model contains the transition region and the upper chromosphere which enables us to study the entire process of hot loop oscillations - from the impulsive footpoint excitation phase to the rapid damping phase. It is shown that the oscillations can be excited by an impulsive heat deposition due to, e.g., nonlinear Alfvén wave energy deposition or magnetic reconnection at the chromospheric footpoint. The existence of the standing mode oscillations is determined by the duration of the heat deposition. The oscillations are excited most efficiently when the duration of the heat deposition is proportional to the fundamental period of the loop. The amount of released energy determines the oscillation amplitude. The combined effects of thermal conduction and compressive viscosity on the damping time in hot gravitationally stratified loops are much stronger than the effect of chromospheric leakage. The dynamic response of the transition region to the impulsive energy release is examined.

Key words: Sun; corona; loop oscillations.

1. INTRODUCTION

Recent observations by high-resolution space imaging telescopes and spectrometers have revealed a variety of coronal oscillation modes. Standing slow magnetoacoustic waves have been detected in hot ($T > 6$ MK) loops using the SUMER (Solar Ultraviolet Measurements of Emitted Radiation) spectrometer on board the SoHO (Solar and Heliospheric Observatory) satellite (Kliem et al., 2002; Wang et al., 2002, 2003). 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 Transition Region and Coronal Explorer 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. The observed periods are between 7-31 min with damping times 5.7-36.8 min. The initial Doppler shifts can reach velocities of up to 200 km/s. The background sound speed in hot loops is $\sim 300 - 400$ km/s and, therefore, the oscillations are nonlinear. The resulting displacement amplitudes are 4-5 times larger than the amplitudes of the transverse loop oscillations. The fact that the intensity oscillation lags behind the Doppler shift oscillation by 1/4 period confirms that the oscillations observed by SUMER are slow standing modes. There is also good agreement between the theoretically predicted (Roberts et al., 1984) and the observed periods.

The slow standing mode oscillations observed by SUMER are characterised by rapid damping proportional to the period. Ofman and Wang (2002) carried out a theoretical study of the damping of the oscillations with typically observed solar parameters. The results showed that the damping is mainly due to the high thermal conduction along the magnetic field lines. Mendoza-Briceno et al. (2004) 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. The footpoint brightenings seen in SXT (Soft X-ray Telescope) images and the upward moving EUV (extreme-ultraviolet) emission along the loop near the brightening footpoint suggest that the slow-standing waves in hot loops seen by SUMER could be excited by pressure disturbances associated with the injection of hot plasma at the oscillating loop’s footpoint. It has been speculated that the brightening and the plasma injection near the footpoint of an oscillating loop could be due to a sudden energy release caused by the process of magnetic reconnection (Wang et al., 2003) or by nonlinear Alfvén waves (Moriyasu et al., 2004). The plasma temperature inside the loop undergoes a steep variation from the footpoint to the apex. Therefore, the isothermal loop models cannot be applied to the theoretical investigation of the excitation process of hot loop oscillations.

In the present work a 1D stratified loop model for the study of the nonlinear oscillations in hot loops

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is proposed. The model contains the upper chromosphere and the transition region which allows us to study the entire oscillation process - from the impulsive footpoint excitation phase to the rapid damping phase. It is shown that fundamental standing slow waves can be excited by an impulsive energy release at the chromospheric footpoint. A crucial parameter for the existence of the oscillations is the duration of the heat deposition. Because of the high temperature inside the loop the combined effects of thermal conduction and compressive viscosity on the damping time are much stronger than the effect of chromospheric leakage. The dynamic response of the transition region to the impulsive energy release is examined.

2. THE LOOP MODEL AND THE GOVERNING EQUATIONS

We consider a one dimensional semicircular loop model in which the only coordinate is the distance $x$ along the loop. The magnetic field does not appear explicitly in the governing equations and the wave motion is governed by the 1D nonlinear hydrodynamic equations which we represent in the following form:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho v}{\partial x} = 0,$$

$$\frac{\partial \rho v}{\partial t} + \frac{\partial \rho v^2}{\partial x} = -\frac{\partial \rho}{\partial x} - \rho g \cos \frac{\pi x}{L} + F_v,$$

$$\frac{\partial e}{\partial t} + \frac{\partial}{\partial x} [(e + pv)v] = -\rho g \cos \frac{\pi x}{L} + L_v + \frac{\partial F_c}{\partial x} - L_v + H,$$

where

$$e = \frac{p}{\gamma - 1} \frac{\rho v^2}{2},$$

$$p = \frac{R}{\mu} \rho T.$$

Eqs. (1)-(3) are solved for density $\rho$, the total energy density $e$ and the momentum density $\rho v$, where $v$ is the $x$ component of the velocity along the loop. $L$ is the total length of the loop, $\gamma$ is the adiabatic index, $g$ is the gravitational acceleration. The magnetic field plays the role of a guide. Only the component of gravity along the magnetic field lines is present in the governing equations. In eqs. (1)-(3)

$$F_v = \frac{4}{3} \frac{\partial}{\partial x} \frac{\partial v}{\partial x},$$

$$L_v = \frac{4}{3} \frac{\partial}{\partial x} \frac{\partial v}{\partial x},$$

represent the force and the heating due to compressive viscosity, respectively. The coefficient of viscosity $\nu$ is defined by (Braginski, 1965)

$$\nu = \frac{0.72(m_p k_B^2)^{1/2}}{\pi^{1/2} \lambda^4 \ln \lambda} T^{5/2},$$

Figure 1. The initial temperature profile along the loop.

where $m_p$ is the proton mass, $k_B$ is the Boltzmann constant, $q$ is the electron charge and $\ln \lambda$ is the Coulomb logarithm. The conductive flux is primarily along the magnetic field and is given by

$$F_c = \kappa \frac{\partial T}{\partial x},$$

where

$$\kappa = 10^{-6} T^{5/2} \text{ergs}^{-1} \text{K}^{-1} \text{cm}^{-1}$$

is the coefficient of thermal conductivity along the field (Spitzer, 1962). The term $L$, corresponds to optically thin radiative losses along the loop. In common with Klimchuk et al. (1987), Bradshaw and Mason (2003) and other authors we smoothly decrease the radiation to zero in regions where the temperature approaches the footpoint temperature. This artificial device helps us to avoid the radiative instability.

The heating function is uniform ($H(t = 0) = \text{const}$) in the corona above the transition region and is smoothly reduced to zero when the chromosphere is reached. In order to make the flow through boundary condition compatible with the equation of hydrostatic pressure balance, we smoothly reduce gravity to zero near the left and right boundaries. The initial loop atmosphere is derived by solving the hydrostatic equations of pressure balance and energy. The resulting temperature profile is shown in Fig. 1. Distance is normalised with respect to the total loop length $L = 145 \text{ Mm}$ and temperature is normalised with respect to the apex temperature $T = 6.3 \text{ MK}$. These typical parameter values are derived from the SUMER observations of oscillating loops by Wang et al. (2003). The temperature in the dense chromospheric footpoints is $20,000 \text{ K} (=0.0032$ in normalised units). The governing equations are solved using a nonuniform grid with a high spatial resolution in the transition region.

Test runs ensure that the initial loop atmosphere is
Figure 2. The evolution of the temperature profile in response to the heat deposition at the left footpoint of the loop.

in hydrostatic equilibrium. The evolution of the initial state develops flows on the order of a few hundred meters per second at the apex. For comparison, the sound speed at the apex is about 380 km/s and, therefore, these flows should have no effect on the behaviour of the plasma inside the loop.

3. FOOTPRINT EXCITATION AND DAMPING OF THE OSCILLATIONS

The intensity oscillations observed by TRACE (Transition region and Coronal Explorer) can be continuously present for several hours (De Moortel et al., 2000), whereas the SUMER hot loop oscillations are excited impulsively and damped very rapidly. The impulsive excitation of these oscillations is evidenced by the presence of an initial large Doppler shift pulse and impulsive profiles of the intensity and line width. Unlike the TRACE transverse oscillations (Aschwanden et al., 1999) the SUMER hot loop oscillations are usually not associated with flares. A more likely mechanism is an energy injection in the chromosphere which could produce a cool mass ejection seen as an upward-moving EUV emission along the loop near the brightening footpoint. The thermal energy release at the loop’s footpoint triggered by the magnetic reconnection is modelled by adding the following term to the right-hand side of the energy equation (3):

$$E = E_0 \exp \left[ - \frac{x-x_0}{2\delta} \right]^2 \exp \left[ - \frac{t-t_0}{2\tau} \right]^2$$

(11)

so that the heating function has the form $H = H_0 + E$, where $H_0$ is the time-independent background heating described in the previous section. In Eq. (11) $\delta$ and $\tau$ are the localisation scale and the duration of the heat deposition, respectively, $E_0$ is the normalised amplitude, $s_0$ and $t_0$ are the location and the time of the heat deposition. We choose $s_0$ to be at the bottom of the transition region and $\delta$ to be highly localised.

The results of the numerical simulations show the response of the plasma inside the hot loop to the impulsive energy release at the loop’s left footpoint. In
Figure 3. The evolution of the velocity profile in response to the heat deposition at the left footpoint of the loop.

Figure 2 several snapshots of the temperature profile during the first few hundred seconds of the plasma evolution are shown. Time is normalised with respect to $L_\gamma^{1/2}/c_s$, where $c_s = 380$ km/s is the sound speed at the apex. The energy release at the footpoint ejects cool dense chromospheric plasma into the corona. Due to the influence of gravity, the initial cool mass ejection does not reach the heights where the SUMER slit is located, so explaining the absence of emission in cool lines in the observations by Wang et al. (2003).

The velocity snapshots plotted in Figure 3 show that the impulsive energy release at the footpoint is indeed able to create a large amplitude standing slow fundamental mode oscillations deformed by nonlinearity. In Figure 3 velocity is normalised with respect to $c_s/\gamma^{1/2}$. The heating and loss functions corresponding to radiation and thermal conduction are switched off so that the damping is mainly due to compressive viscosity. The inclusion of thermal conduction leads to a very rapid damping with a damping time proportional to the oscillation period, which is in agreement with the results by O filament and Wang (2002), Mendoza-Briceno et al. (2004). By switching off all dissipative effects we find that the pure effect of the chromospheric leakage on the damping time of hot loop oscillations is negligible due to the highly reflective transition region. However, this effect can become much more important for cooler loops. In the simulations the results of which are shown in Figures 2, 3 the duration of the heat deposition $\varepsilon$ is proportional to the period ($P \sim 2L/c_s$) of the fundamental slow standing mode. We find that for smaller values of $\varepsilon$ the oscillations become propagating, whereas for higher values of $\varepsilon$ the initial amplitude of the oscillation decreases.

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