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# HOT CORONAL LOOP OSCILLATIONS OBSERVED BY SUMER: SLOW MAGNETOSONIC WAVE DAMPING BY THERMAL CONDUCTION

L. Ofman[1] and Tongjiang Wang[2]
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## ABSTRACT

Recently, strongly damped Doppler shift oscillations of hot ($T > 6$ MK) coronal loops were observed with the Solar Ultraviolet Measurement of Emitted Radiation (SUMER) spectrometer on board the *Solar and Heliospheric Observatory*. The oscillations are interpreted as signatures of slow-mode magnetosonic waves excited impulsively in the loops. Using a one-dimensional MHD code, we model the oscillations and the damping of slow magnetosonic waves in a model coronal loop. We find that because of the high temperature of the loops, the large thermal conduction, which depends on temperature as $T^{2.5}$, leads to rapid damping of the slow waves on a timescale comparable to observations (5.5–29 minutes). The scaling of the dissipation time with period agrees well with SUMER observations of 35 cases in 17 events. We also find that the decay time due to compressive viscosity alone is an order of magnitude longer than the observed decay times.

*Subject headings:* MHD — Sun: activity — Sun: corona — waves

## 1. INTRODUCTION

Coronal loop oscillations have been observed for decades in radio (e.g., Aschwanden 1987), visible, EUV, and soft X-rays. The waves have been suggested as a source of heating of coronal loops by Ionson (1978) and were extensively studied since then (see Narain et al. 2001 and references therein). The waves were also proposed as a means to obtain the physical parameters of the coronal plasma (Roberts, Edwin, & Benz 1984; Nakariakov & Ofman 2001), hence, the importance of observation and analysis of waves in the coronal loops. Temporally and spatially resolved longitudinal waves in coronal loops were first detected by the *Solar and Heliospheric Observatory* (*SOHO*) EUV Imaging Telescope (EIT; Berghmans & Clette 1999). The first resolved imaging observations of transverse oscillations in coronal loops were obtained recently in EUV by the *Transition Region and Coronal Explorer* (*TRACE*; Aschwanden et al. 1999; Nakariakov et al. 1999).

The impulsive heating of coronal plasma to temperatures of ~10 MK was recently observed by the Solar Ultraviolet Measurements of Emitted Radiation (SUMER) spectrometer (Wilhelm et al. 1995) on board the *SOHO* spacecraft. The far-ultraviolet observations of a solar limb flare revealed large Doppler shift velocities (up to 200 km $s^{-1}$), which exhibit oscillatory damping (Kliem et al. 2002; Wang et al. 2002a, 2002b, 2002c). Observations of 17 flarelike events show that the oscillation periods are in the range 11–31 minutes, and the decay time is in the range 5.5–29 minutes. The oscillations were interpreted in terms of standing slow or kink magnetosonic modes. However, the source of the wave dissipation was not established in these studies.

The oscillation periods of the cool loops observed by *TRACE* (Aschwanden et al. 2002) have much shorter periods and smaller amplitudes than the Doppler shift oscillations of the hot loops observed by SUMER. This suggests that the phase speed of the waves in cool loops is larger than the phase speed of the waves in hot loops. Also, the scaling of the decay time with the period is different in the cool and hot loops (Ofman & Aschwanden 2002; Wang et al. 2002c). These observations suggest a different wave mode and a different damping mechanism in the cool and hot loops. Since the dominant dissipation mechanisms for slow-mode MHD waves (thermal conduction or compressive viscosity) are different from the main dissipation mechanism acting on Alfvén waves (resistivity or shear viscosity), the identification of the wave mode is important for the modeling and the interpretation of the results.

Slow magnetosonic waves were observed in coronal plumes (Ofman et al. 1997, 1998, 2000) using the *SOHO* Ultraviolet Coronagraph Spectrometer (UVCS) White Light Channel. EIT observations of plumes showed evidence of propagating waves in the EUV iron emission lines (Deforest & Gurman 1998). These waves were identified as slow magnetosonic waves by Ofman, Nakariakov, & Deforest (1999). Signatures of slow magnetosonic waves were also observed in EUV in cool coronal loops (Berghmans & Clette 1999) and identified as propagating slow waves (Nakariakov et al. 2000; De Moortel, Ireland, & Walsh 2000; Robbrecht et al. 2001; De Moortel et al. 2002a, 2002b).

The damping of the slow waves in the solar coronal plasma by compressive viscosity and thermal conduction was investigated analytically and numerically by solving the dispersion relation arising from the linearized one-dimensional MHD equations, including self-consistent heating (Porter, Klimchuk, & Sturrock 1994). Ofman, Nakariakov, & Sehgal (2000) investigated the viscous damping of these waves using one-dimensional and two-dimensional MHD codes. Nakariakov et al. (2000) investigated the damping by viscosity and thermal conduction of linear and nonlinear slow magnetosonic waves in a one-dimensional model of a coronal loop by solving the one-dimensional MHD equations that incorporate viscosity, thermal conduction, and gravity. The solution was obtained in the limit of small dissipation and did not include self-consistent heating. The damping by thermal conduction of the slow waves in *TRACE* loops was considered by De Moortel et al. (2002a).

Here, we present the first one-dimensional MHD study of the oscillatory damping of moderately nonlinear slow magnetosonic waves in a model hot coronal loop, which includes large dissipation (i.e., dissipation time on the order of wave period) by thermal conduction, self-consistent heating, and vis-

[1] Department of Physics, Catholic University of America; and NASA Goddard Space Flight Center, Code 682, Greenbelt, MD 20771; leon.ofman@gsfc.nasa.gov.

[2] Max-Planck-Institut für Aeronomie, Postfach 20, D-37191 Katlenburg-Lindau, Germany.

cosity based on the observed temperature. The goal of this study is to understand the SUMER observations of the damped Doppler oscillations of hot coronal loops associated with small flarelike events.

## 2. SUMMARY OF SUMER OBSERVATIONS

The new kind of damped oscillation of coronal loops that was revealed by SUMER was studied in detail by Wang et al. (2002c). From a statistical study of 17 flarelike events, Wang et al. (2002c) summarized the main properties of the hot loop oscillations. Doppler shift oscillations were detected only in flare lines like Fe XIX, Fe XX, and Fe XXI of $T = 6$–$10$ MK. Most cases belong to recurring events, i.e., they recur 2–3 times within about 2 hr. Most events were not associated with *GOES* flares, unlike loop transverse oscillations seen by *TRACE* that were mostly triggered by strong flares (Aschwanden et al. 2002). There is a large shift pulse with peak velocities up to 200 km $s^{-1}$ during the rising phase of the flux that is followed by two or three periods of strongly damped alternating red- and blueshift oscillations. The periods are about 11–31 minutes, longer than those (2–11 minutes) observed by *TRACE*. The exponential decay time is in the range 5.5–29 minutes, comparable to the *TRACE* loops' damping time. The best-fit power-law scaling of the damping time with the period gives an exponent of $1.07 \pm 0.16$. For more than one-third of oscillations, the intensity profiles have several peaks but show no periodic behavior. The Doppler shift generally peaks earlier than the flux but almost simultaneously with the line width.

For some cases, the oscillating loops and their geometric parameters can be determined using *Yohkoh*/soft X-ray telescope (SXT) observations, therefore allowing us to explore the possible wave mode. Wang et al. (2002b, 2002c) found that the measured period agrees well with that of a slow standing wave. The phase speed of the fundamental mode is $C_s = 2L/P$, where $L$ is the loop length and $P$ is the oscillation period. For the cases in which $L$ was obtained from SXT observations, the phase speed agrees well with the expected sound speed for the observed emission-line temperatures. They also noticed that for the period of the global kink mode to match the observed period, it implies an unusual coronal loop environment of plasma $\beta \geq 1$.

We note that a kink mode wave with a typical amplitude of 100 km $s^{-1}$ and period of 20 minutes is expected to cause the loops' displacements of about 20,000 km or about 25″. This displacement could be resolved but was not observed by SXT in the oscillating loops. No significant displacement of the loops' magnetic field is expected for slow magnetosonic waves, in agreement with SXT observations.

Wang et al. (2002a, 2002b, 2002c) used the following method to analyze SUMER Doppler shift observations. After processing the raw data following standard procedures, a single Gaussian was fitted to the lines to obtain a Doppler shift time series at each spatial pixel. An example is shown in Figure 1. The lines exhibit distinct regions of coherent oscillations along the slit. For each region, we average over a width of 11 pixels (~1″ $\text{pixel}^{-1}$) for the old data sets and 6 pixels for the new data sets to get the average time profile. The function $V(t) = V_D + V_m \sin(\omega t + \phi)e^{-\lambda t}$ was then fitted to the oscillation, where $V_D$ is the postevent Doppler shift, $V_m$ is the shift amplitude, and $\omega$, $\phi$, and $\lambda$ are the frequency, phase, and decay rate of the oscillations. The parameters of the time series for 35 oscillations in 17 events were derived and are given by Wang et al. (2002c).

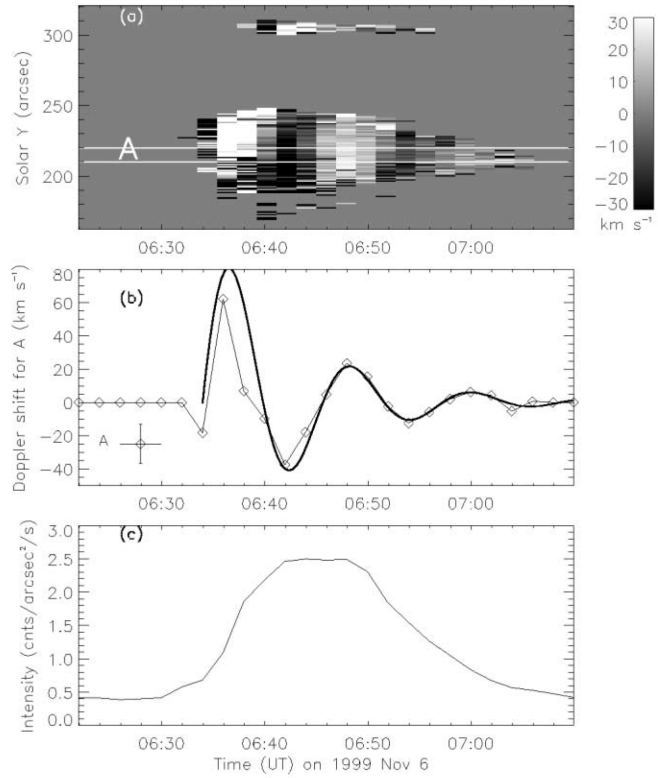


FIG. 1.—(*a*) Doppler shift oscillation event in the Fe XXI line on 1999 November 6. (*b*) Average time profile of Doppler shifts along the cut A. The thick solid curve is the best-fit damped sine function. (*c*) Average time profile of line-integrated intensity for the cut A (adapted from Wang et al. 2002a).

In the typical case shown in Figure 1, the oscillations are well defined. Unfortunately, there were no simultaneous SXT observations for this case, so we are unable to pinpoint the oscillating loop. This event is associated with a C4.6 flare that occurred in AR 8758 at the northeast limb. More details on the event and associated cool line emission are given in Kliem et al. (2002). The damped sine function provides a good fit and gives a period of 11.7 minutes and a damping time of 8.8 minutes.

## 3. ONE-DIMENSIONAL LOOP MODEL

The magnetic field of the loop is taken to be along the $x$-direction, and it enters into the model only as a guide to the slow magnetosonic waves. The nonlinear one-dimensional MHD equations in Cartesian geometry, neglecting gravity (this is justified, since the hot coronal loop height is much less than the scale height of 0.9 $R_\odot$ for $T \sim 10$ MK plasma), with usual notations for the variables are

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho V_x) = 0, \tag{1}$$

$$\rho\left(\frac{\partial V_x}{\partial t} + V_x \frac{\partial}{\partial x} V_x\right) = -\frac{\partial p}{\partial x} + F_v, \tag{2}$$

$$\frac{\partial T}{\partial t} + (\gamma - 1)T\frac{\partial V_x}{\partial x} + V_x\frac{\partial T}{\partial x} = \frac{(\gamma-1)}{\rho}\frac{m_p}{2k_b}(S_v + H_c). \tag{3}$$

The viscous force due to compressive viscosity is $F_v = (4/3)\,\eta_0\,(\partial^2 V_x/\partial x^2)$, the heating term is $S_v = (4/3)\,\eta_0(\partial V_x/\partial x)^2$, and $\gamma = 5/3$. We have neglected radiative losses in the energy

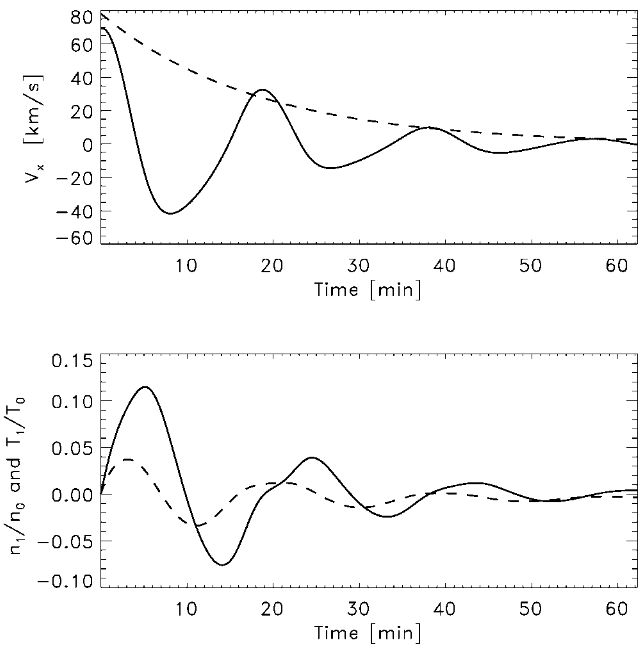


FIG. 2.—Temporal evolution of the $V_x$ (*top panel*) at $x = 0.20\ R_\odot$ (*solid line*) due to the dissipation of the slow wave with $k = 1$, $T = 8$ MK, and loop length $L = 4 \times 10^{10}$ cm $= 0.571\ R_\odot$. The exponential decay time fit is shown with the dashed line. The temporal evolution of the perturbed $n$ (*solid line*) and $T$ (*dashed line*) at the same location (*bottom panel*).

equation, which occur on a timescale that is long compared to the observed damping time. The coefficient of compressive viscosity is given by (Braginskii 1965)

$$\eta_0 = 0.96 n k_B T_p \tau_p, \tag{4}$$

where $n$ is the number density, $T_p$ is the proton temperature, and the proton collision time given by $\tau_p = (3/4)\,(m_p)^{1/2}\,(k_B T_p)^{3/2}/(\pi^{1/2} n \ln \lambda e^4)$, where $m_p$ is the proton mass, $e$ is the electron charge, and $\ln \lambda$ is the Coulomb logarithm. For typical conditions in the hot coronal loops $T_p = 10^7$ K and $n = 10^9$ cm$^{-3}$, we get $\ln \lambda \approx 23$ and $\tau_p \approx 23$ s. The collision time is 2 orders of magnitude shorter than the typical slow wave period observed by SUMER. Note that the compressive viscosity scales with temperature as $\eta_0 \sim T_p^{2.5}$.

The heat conduction term along the magnetic field ($x$-direction) is $H_c = \partial/\partial x\,[\kappa_\parallel\,(\partial T_e/\partial x)]$, where $T_e$ is the electron temperature and $\kappa_\parallel$ is the thermal conductivity parallel to the magnetic field given by (Spitzer 1962)

$$\kappa_\parallel = 7.8 \times 10^{-7} T_e^{5/2} \text{ ergs cm}^{-1}\text{ s}^{-1}\text{ K}^{-1}. \tag{5}$$

In the single-fluid MHD model, it is assumed that $T = T_e = T_p$. The loop density and temperature are assumed to be initially uniform. The initial velocity profile is given by $V_x = V_0 \sin(2\pi x k/L)$, where $V_0$ is the amplitude of the wave at $t = 0$, $L$ is the length of the loop, and $k$ is the wavenumber. The MHD equations are solved using the fourth-order Runge-Kutta method in time and fourth-order derivatives in space using 256 grid points. The boundary conditions at both ends of the loop were $V_x = 0$ and zero-order extrapolation for the rest of the variables.

## 4. NUMERICAL RESULTS

In the numerical simulations discussed below, we use the following loop parameters motivated by SUMER and *Yohkoh*/SXT observations of hot coronal loops: the loop length $L = 0.571\ R_\odot$, the density $n_0 = 5 \times 10^8$ cm$^{-3}$, the temperature $T = 6.3$ or 8 MK, with the corresponding sound speeds $C_s = 416$ or 469 km s$^{-1}$. With these parameters, the compressive viscosity is $\eta_0 = 9.8$ g cm$^{-1}$ s$^{-1}$ ($T = 6.3$ MK) or 17.6 g cm$^{-1}$ s$^{-1}$ ($T = 8$ MK), and the corresponding heat conduction $\kappa_\parallel = 7.77 \times 10^{10}$ ergs cm$^{-1}$ s$^{-1}$ K$^{-1}$ or $1.41 \times 10^{11}$ ergs cm$^{-1}$ s$^{-1}$ K$^{-1}$.

In Figure 2, we show the temporal evolution of the slow magnetosonic wave velocity $V_x$ at $x = 0.2\ R_\odot$, with $T = 8$ MK (*top panel*). The wave with a period of 17.9 minutes is dissipating rapidly with an exponential decay time of about 17.7 minutes, in agreement with the typical decay time comparable to the period obtained with SUMER observations. By comparing the effects of the dissipation terms in separate runs, we find that thermal conduction is the dominant dissipation mechanism. The fit of the exponential damping of the wave amplitude is shown with the dashed line. When the wave amplitude is 84 km s$^{-1}$ and the dissipation is artificially decreased by 2 orders of magnitude, we have found numerically that the slow wave steepens nonlinearly to form shocks. However, with solar values of $\eta_0$ and $\kappa_\parallel$ in hot loops, the steepening is suppressed, in agreement with observations. The temporal evolution of the perturbed density ($n_1$) and temperature ($T_1$) is shown in the bottom panel. It is evident that $n_1$ and $T_1$ are dissipating on the same timescale and that there is a phase shift of about a quarter period between $n_1$ and $V_x$. Higher harmonics are present because of the nonlinearity and viscous heating.

The linear theory of slow wave dissipation predicts that $t_{\rm decay} \sim P^2$ (e.g., Porter, Klimchuk, & Sturrock 1994; Nakariakov et al. 2000). We were able to recover the linear scaling, as predicted by theory, when we used $V_0/C_s = 0.0018$, decreased the dissipation by an order of magnitude, and eliminated the viscous heating term in our model. However, for the parameter range relevant to the hot loops observed by SUMER ($V_0/C_s = 0.18$), the scaling is less steep. The observational scaling of the data for 35 hot loops with a range of temperatures $T > 6$ MK is $t_{\rm decay} = 0.61^{+0.37}_{-0.23} P^{1.07 \pm 0.16}$ (Wang et al. 2002c). In Figure 3, we show the decay time with the period for $T =$

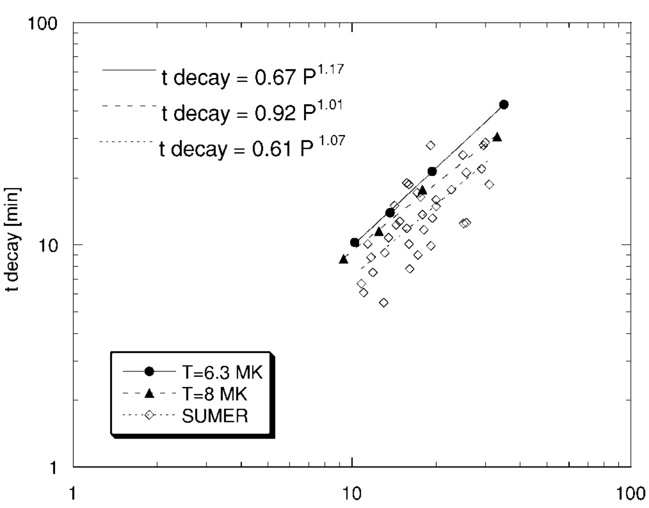


FIG. 3.—Scaling of the dissipation time of the slow waves with the wave period for $T = 6.3$ and 8 MK. SUMER observations are shown for comparison.

6.3 and 8 MK obtained with our model and the best-fit scaling for both temperatures. The SUMER data for the 35 loops are shown for comparison. We find that the power of the scaling is 1.17 for the lower temperature and 1.01 for the higher temperature, in agreement with the expected effects on the thermal conduction and viscosity (i.e., increased $\eta_0$ and $\kappa_\parallel$ results in higher dissipation rate for the same wave period). The simulation results are in good agreement with observations, and the spread can be justified by the expected range of temperatures 6 MK $< T <$ 10 MK, loop densities, and wave amplitudes in the observational data set.

## 5. DISCUSSION AND CONCLUSIONS

Motivated by SUMER observations of damped Doppler shift oscillations of hot coronal loops associated with flares or microflares, we use a one-dimensional nonlinear dissipative MHD model to study the damping of slow magnetosonic waves. We find that for typical observational parameters of the hot loops, the period and the decay time of the Doppler shift oscillations are in good agreement with the model. Moreover, we find that the scaling of the decay time of the oscillations with period is in good agreement with the model. These findings strongly suggest that the observed Doppler shift oscillations are signatures of damped slow magnetosonic waves.

The high temperature of the hot coronal loops leads to high thermal conduction and compressive viscosity, since both depend on temperature as $T^{2.5}$ (Spitzer 1962; Braginskii 1965). We find that for the typical observational solar parameters of these loops, the dominant wave damping mechanism is thermal conduction, with less significant contribution by compressive viscosity. The transverse Alfvénic oscillations observed in *TRACE* loops require enhanced resistivity or enhanced viscosity in order to dissipate on the observed timescale (Nakariakov et al. 1999; Ofman & Aschwanden 2002). In contrast, the dissipation of slow magnetosonic waves in the model of hot coronal loops occurs because of the classical thermal conduction calculated using Spitzer's (1962) expression, and the damping rate agrees with the observed timescale.

In our simplified model, we did not include the effects of gravity, loop structure, cross-sectional variations of the magnetic field (e.g., Edwin & Roberts 1983), and the coupling of the loop with the chromosphere. However, these effects are secondary for the long-period oscillations observed by SUMER, and we do not expect them to significantly affect the results of our model. The large temperature gradient and the corresponding sound speed gradient at the loops' footpoints prevent significant slow wave leakage from the coronal parts of the loop, similar to the nearly total Alfvén wave reflection by the steep Alfvén speed gradient at the loops' footpoints (e.g., Ofman 2002).

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