TRANSVERSE OSCILLATIONS IN A CORONAL LOOP ARCADE

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ABSTRACT

TRACE observations from April 15th, 2001 of transverse oscillations in coronal loops of a post-flare loop arcade are investigated. They are considered to be standing fast kink oscillations. Oscillation signatures such as displacement amplitude, period, phase and damping time are deduced from 9 loops as a function of distance along the loop length. Multiple oscillation modes are found with different amplitude profile along the loop length, suggesting the presence of a second harmonic. The damping times are consistent with the hypothesis of phase mixing and resonant absorption, although there is a clear bias towards longer damping times compared with previous studies. The coronal magnetic field strength and coronal shear viscosity in the loop arcade are derived.

Key words: Sun: oscillations; MHD.

1. INTRODUCTION

Transverse oscillations of coronal loops have been discovered by Aschwanden et al. (1999) using TRACE observations of a flaring active region. Aschwanden et al. (1999) and Nakariakov et al. (1999) have interpreted these oscillations as standing fast magnetoacoustic kink body waves, triggered by a passing disturbance that originated from the flare site.

Transverse oscillations are of relevance to the study of coronal heating because the comparison of the observed oscillation characteristics with MHD wave theory allows for the determination of coronal physical parameters crucial for coronal heating studies such as the coronal magnetic field strength (Nakariakov and Ofman, 2001) and (shear) dissipation coefficients. This approach is known as MHD coronal seismology (e.g. Uchida (1970); Roberts, Edwin and Benz (1984)).

Nakariakov et al. (1999) pointed out that the oscillations experience a quick decay, with a typical e-folding damping time of 870 s. Aschwanden et al. (2002) derived from a set of ten loop oscillations an average damping time of 580 ± 385 s. The damping times of these oscillations is too quick to be explained by the classical values of coronal viscosity or resistivity (Braginskii, 1965). It sparked various hypothesis to explain the oscillation damping (see e.g. Verwichte et al. (2004) and references therein).

Two hypothesis, based on small-scale, transverse inhomogeneities, are of special interest: resonant absorption proposes that the wave energy of the global kink oscillation is transferred, not dissipated, to local, torsional oscillations (Ruderman and Roberts, 2002). Alternatively, the hypothesis of phase mixing proposes that the global kink oscillation is damped by shear viscosity due to a build-up of shear velocity gradients by neighbouring loops that oscillate at slightly different periods (Ofman and Aschwanden, 2002). It is argued that the shear viscosity is enhanced by small-scale turbulence or kinetic processes.

Ofman and Aschwanden (2002) and Aschwanden et al. (2003) used 11 events from the gathered collection of observations of Aschwanden et al. (2002) to test observationally these two hypothesis, but the observations do not allow to distinguish between them. Certainly, the results obtained with the use of only 11 or less oscillating loops cannot be considered as statistically significant, especially taking into account the low signal-to-noise ratio. Any improvement of the statistics is therefore welcome.

This paper presents an observational study of the oscillatory behaviour of an ensemble of several loops forming an arcade. The observational data set used in this paper has been analysed by Reeves et al. (2001) and Aschwanden et al. (2002), but the result has not been considered in the context of scaling laws involving oscillation and loop parameters. For a detailed description of this work, the reader is referred to Verwichte et al. (2004).

2. DESCRIPTION OF THE OBSERVATION

The present study focuses on the 171 Å wavelength observations from the TRACE instrument on the 15th of April 2001 between 22:00:43 and 22:27:50 UT. The temporal cadence of the sequence in the first 20 minutes is equal to 26 seconds, but in the last 10 minutes increases to one minute.

The instrument was pointing to the active region NOAA 9415, then on the SW limb. This active region was at the time active and produced an X14.4 flare earlier that day. The flare activity resulted in a postflare loop arcade. Because the active region is close to the solar limb and the arcade axis lies quasi-meridionally, the spacecraft looks along the plane of the arcade loops. The transverse loop oscillations appear as a back and forth motion of the loop plane.
3. ANALYSIS OF OSCILLATION SIGNATURES

Nine paths are constructed using a polynomial fit of a series of points that are selected by eye to follow a loop in one particular image. The loop height for the nine loops lies in the range 65-76 Mm. From each path a uniform grid is built that is fixed in time and has a width which is sufficiently wide to capture the transverse motions of the loop. On each grid point the intensity \( I_p(t, x, y) \) is interpolated, where \((x,y)\) are the coordinates along and across the loop resp. in the plane of the sky. \( x \) is measured from the path top, near the loop top, downwards.

For fixed \( x \) the sets of segment images \( I_{p,x}(t, y) \) are examined. Sets of coordinate pairs \((t_i, y_i)\) that follow the loop profile are captured interactively. A linear trend is subtracted from \( y_i \) to give the loop displacement \( \xi_i \).

Two approaches for examining the displacement coordinates \((t_i, \xi_i)\) have been chosen. Firstly, a wavelet analysis is performed, using the software provided by Torrence and Compo (1998) and the Morlet wavelet. Statistically significant signals are extracted and the period, amplitude and phase of the quasi-periodic oscillation determined. The damping time has not been determined in this fashion because it is not much longer than the oscillation period and therefore the temporal evolution of the amplitude in the wavelet transform is heavily blurred.

Secondly, the displacement coordinates \((t_i, \xi_i)\) are fitted with a single, damped oscillation mode of the form
\[
\xi_n(t) = A e^{-(t/\tau_n)^n} \cos(2\pi t/P + \phi),
\]
where \( A, P, \tau_n \) and \( \phi \) are the amplitude, period, e-folding damping time and phase respectively. The values for \( n \) of 1, 2 and 3 have been applied but no real preference of the observations between the different values of \( n \) has been found.

Overall the results from the wavelet analysis and the curve fitting are consistent. It is clear though, that the wavelet transform has the advantage over the curve fitting method in that it can detect multiple periods and period modulations.

For each segment in the \( x \)-direction along the examined loop of each path, the oscillation parameters are determined. A weighted average across \( x \) is taken. If a clear trend as a function of \( x \) is observed or is expected, then alternatively a weighted linear least-squares fit is calculated. The results are presented in Tables 1 and 2. Results between brackets are uncertain measurements.

For periods and damping times no \( x \)-dependency is seen. In other words, different segments of the analysed loop are observed to oscillate in phase and each loop segment damps at the same rate. The oscillation periods are in the range of 200-450 s, which is typical for transverse loop oscillations. All the measured loop oscillations are damped, with damping times in the range of 800-1800 s. The range of oscillation periods and damping times are consistent with the results of Reeves et al. (2001).

If the observed oscillation is a standing wave, then displacement amplitude, \( A \), should vary with distance while the phase remains constant. If the loops are modeled as circular and homogeneous, the amplitude of the fundamental mode is expected to decrease as a function of \( x \) by a value of the order of \(-5 \text{ km Mm}^{-1}\). On the other hand if the oscillation is a second harmonic standing mode, the displacement has a node at the loop top and is therefore its amplitude is expected to increase as a function of \( x \) near the top. The position of the maximum amplitude

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The loops in paths C and D are different from the other loops as they show multiple modes of oscillation. In loop C there is besides a 250 s oscillation, also an oscillation mode with a period around 450 s. The 450 s period falls within 1 standard deviation of the double of the 250 s period.

The loop central in path D is analysed along a distance of 18 Mm measured from the loop top. The left hand side of Figure 2 shows the displacement as a function of time at four segments along the loop. Two oscillation modes are detected (as illustrated in the right plot of Figure 3) with periods of 240 s and 400 s respectively. The 400 s period falls within 2 standard deviations of the double of the 240 s period. The displacement amplitude profile as a function of distance are shown in Figure 3. The left plot of Figure 3 shows that the 400 s oscillation mode amplitude clearly decreases as a function of x, at a rate of \(-13 \pm 6 \text{ km Mm}^{-1}\). On the other hand, using the wavelet measurements of the 240 s oscillation for x < 8 Mm, the centre plot of Figure 3 shows that the amplitude of this mode increases, at a rate of \(17 \pm 7 \text{ km Mm}^{-1}\).

4. DISCUSSION

For the above observations of paths C and D the following hypothesis is proposed. The long period oscillation is the fundamental mode, with a maximum amplitude at the loop top. The short period oscillation is its second harmonic. It has a node at the loop top and a maximum displacement at approximately 20 Mm from the loop top. A linear phase shift is observed for the 400 s oscillation in loop D. This may indicate transient behaviour, where the phase decrease of -6.6 degrees Mm\(^{-1}\) hints to a downward travelling wave with a wavelength of 55 Mm.

From the measured period, loop length and knowledge that the oscillation is a standing mode, the phase speed of the oscillation is derived. Since the transverse oscillation is considered to be a standing fast magnetoacoustic kink oscillation and the loop width is much smaller than the loop length, the phase speed is approximately equal to the kink speed (Edwin and Roberts, 1983), i.e., \(V_{\text{phase}} = 2L/jP \approx C_k = \sqrt{2/(1 + \rho_0/\rho)} V_A\), where \(j\) is the wave mode. \(\rho_0/\rho\) is ratio of the mass density of the loop and its external surroundings, and is realistically equal to 0.6. \(V_A\) is the Alfvén speed and is, using the previous formula, found to be in the range 700-1300 km s\(^{-1}\). Assuming a realistic number density of 1-6 \times 10^{12} \text{ m}^{-3}, the magnetic field strength in the coronal loop, B, is estimated to be in the range 9-46 Gauss (see Table 3). This is in general agreement with the result from Nakariakov and Ofman (2001).

If it is assumed that phase mixing causes the oscillation damping, then the shear viscosity can be derived from the relation \(\tau^2 = 6L^2\ell^2/\nu\pi^2 V^2 A_j^2\), where \(\nu\) is the kinematic shear viscosity and \(\ell\) is the inhomogeneity length, which is assumed to be 0.01 L. \(\nu\) is found to be in the range 0.3-2.8 \times 10^8 \text{ m}^2\text{s}^{-1} (see Table 3). The corresponding shear Reynolds number is in the range 0.8-7.6 \times 10^6. These values are consistent with those found by Ofman and Aschwanden (2002). There is a discrepancy of eight orders of magnitude between the observational and theoretical values of the Reynolds number.

By combining the dispersion relation with the expression of phase mixing Ofman and Aschwanden (2002) derived...
Figure 3. Left: $A(x)$ for the 400 s oscillation. The crosses, stars, diamonds and circles refer to fits with $n=1, 2, 3$ and wavelet analysis resp. Each dataset is fitted by a straight line (solid: wavelet fit, dashed: $n=1$, dot-dashed: $n=2$, triple dot-dashed: $n=3$). Centre: $A(x)$ for the 240 s oscillation. Only wavelet measurements are available and are shown as circles. The dashed line is a linear fit. The solid curves represent the profile of a second harmonic standing wave for several maximum amplitude values. Left: magnitude of the wavelet transform of the displacement coordinates of $I_{D,x}$ at $x = 11$ Mm from the loop top, showing two detected periods.

Figure 4. Plot of the measured decay times $\tau_1$ with respect to the oscillation period $P$ as solid circles. The diamond symbols show the result of Ofman and Aschwanden (2002). The solid line is a best powerlaw fit of the measurements of this loop arcade. The value of the power index is shown.

the relation $\tau \sim P^{4/3}$. On the other hand, the mechanism of resonant absorption predicts that $\tau \sim P$. The 11 compiled oscillation observations considered by Ofman and Aschwanden (2002) show a dependency of $\tau \sim P^{1.17 \pm 0.35}$ (see the diamond symbols in Figure 4). The predictions of both hypothesis fall within one standard deviation from the observational result, so that none can be ruled out. Figure 4 shows as filled circles the damping times of the measured loop oscillations as a function of period. The solid line represents a best powerlaw fit of $\tau \sim P^{1.18 \pm 0.31}$, with a power index in agreement with the one derived by Ofman and Aschwanden (2002). What is immediately clear from the figure is that the damping times found in this study have a systematic bias towards longer decay times compared with most of those found previously. There are several possible explanations for this bias. Firstly, this study considers an oscillating arcade of post-flare loops, which may be structured differently than the more isolated oscillating active region loops used in the previous measurements. Secondly, the coronal loop arcade oscillation is driven by a prominence eruption in its vicinity, that excites the arcade at several occasions instead of at one single moment.

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