TRACE OBSERVATIONS OF PROPAGATING SLOW MAGNETO-AcouSTIC DISTURBANCES IN CORONAL LOOPS

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ABSTRACT

We study propagating disturbances in 38 coronal loops and give an overview of their properties using high cadence, 171 Å, TRACE data (JOP 83 & JOP 144). The majority of these outward propagating oscillations are found in the footpoints of large diffuse coronal loop structures, close to active regions. The disturbances travel outward with a propagation speed of the order of \(v \approx 119 \pm 30\) km/s. The variations in intensity are estimated to be roughly 4.1\( \pm \)1.6\% of the background brightness and the propagating disturbances are found to be damped very quickly, within 8.6\( \pm \)3.8 Mm along the loop. Using a wavelet analysis, periods of the order of 282\( \pm \)93 seconds are found and the energy flux was estimated as 346\( \pm \)132 ergs/cm\(^2\)/s. It is suggested that these oscillations are slow magneto-acoustic waves propagating along the lower part of large, quiescent, coronal loops.

Key words: Sun; Corona; Oscillations.

1. INTRODUCTION

The detection of oscillations in coronal loops is crucial to determine the presence and relevance of coronal heating mechanisms based on the dissipation of MHD waves and to improve existing estimates of coronal properties and dissipation coefficients. Recently, the high spatial and temporal resolution of SOHO and TRACE have drastically increased the number of observations of both transversal and longitudinal oscillations in the solar corona. For example, signatures of compressional waves in plumes were first detected by the White Light Channel of the UVCS instrument on SOHO high above the limb by Ofman et al. (1997). DeForest & Gurman (1998) reported on quasi-periodic compressive waves in solar polar plumes which Ofman et al. (1999) interpret as slow magneto-acoustic waves. De Moortel et al. (2000) reported on the detection of similar propagating oscillations observed in coronal loops on 23rd March 1999 in the TRACE 171 Å passband, which they suggest to be propagating slow magneto-acoustic waves. Robbrecht et al. (2001) compare propagating disturbances in coronal loops, observed on 13th May 1998, in the TRACE 171 Å and EIT (SOHO) 195 Å passbands. A totally different class of oscillatory phenomena, namely flare-excited, transversal oscillations of coronal loops were first discussed by Schrijver et al. (1999), and subsequently by Aschwanden et al. (1999), Nakariakov et al. (1999) and Schrijver & Brown (2000). An extensive overview and analysis of transversal coronal loop oscillations was presented by Schrijver et al. (2002) and Aschwanden et al. (2002).

In this paper we give an overview of both geometric and physical properties of propagating disturbances that were observed by TRACE, in the footpoints of large, quiescent coronal loops. In Section 2 we describe the observations and the preparation of the data. An explanation of the analysis and an overview of the results is given in Section 3, followed by a discussion in Section 4 and summary in Section 5.

2. OBSERVATIONS

The analysis in this paper uses high-cadence, 171 Å TRACE data that was taken as part of JOP 83 (23 March 1999 and 04-19 April 2000) and JOP 144 (05-13 June 2001). The observed active regions during these campaigns are AR 8496 (23/03/99), AR 8939 (04-09/04/00), AR 8948 (11-13/04/00), AR 8954 (17/04/00), AR 8955 (18-19/04/00), AR 9484 (05-07/06/01), AR 9487 (08-09/06/01), AR 9491 (11/06/01) and AR 9493 (12-13/06/01). At the time of observing, these were generally large, quiescent active regions, with the exception of AR 8948 (3 GOES class M1 flares and 7 C flares) and AR 9484 (3 GOES class C flares). All data have been corrected for dark current and cosmic ray hits using the standard TRACE procedures. For a detailed analysis, we extracted subchords of roughly 25-30 minutes, with a constant cadence of typically 10 seconds for the JOP 83 data and 30 seconds for the JOP 144 data.
The selected subcubes are the longest sequences with identical exposure times and a roughly constant cadence, which are uninterrupted by the South Atlantic Anomaly (SAA) and radiation belt transits. We note here that this implies that the duration of the analysed data sequences is limited by instrumental restrictions. To increase the signal-to-noise in the JOP 83 data, we summed over consecutive images, thus reducing the cadence to roughly 20 seconds. All JOP 83 data and the JOP 144 data taken on 05 June 2001 have a pixel size of 1", whereas the remaining JOP 144 data have a pixel size of 0.5".

3. ANALYSIS AND RESULTS

To analyse the data subcubes, we follow the method described by De Moortel et al. (2000); we use a running difference to identify propagating disturbances and a wavelet analysis, with a 99.0 % confidence level, to determine an oscillation timescale. We divided the tube-like area that outlines the lower part of the loop (see Fig. 1) into cross-sections and added all the unique datacounts along 2 or 4 cross-sections, for 1" and 0.5" pixel sizes respectively. This implies that a cross-section now corresponds to roughly 2'. Finally, we divided by the number of pixels to obtain a uniform normalisation. To extract the time-variable behaviour of the loop, a running difference was created by subtracting an earlier timestep from each frame. An example of such a running difference is shown in Fig. 1 (right). The clear, diagonal ridges of higher (bright) and lower (dark) intensity indicate that a disturbance is travelling along the coronal structure.

We examined a total of 51 TRACE 171 Å subcubes, in which we identified 105 loop footpoints that supported some oscillatory signal. We note that, in this context, the term footpoint does not refer to the actual photospheric/magnetic footpoint of the loops, but to what appears to be the lower coronal part of the loops. In this paper, we present the 38 best examples and in Fig. 2, we give an overview of the distribution of some physical properties of these propagating oscillations. The more statistical information of the averages and ranges of the different parameters can be found in Table 1. The length of the examined loop footpoints is found to be 26.3±9.3 Mm, covering a range of 10.2−49.4 Mm, whereas the average width of the footpoints is found to be 8.2 ± 2.7 Mm, with a range of 3.9 − 14.1 Mm. Obviously, this is only a 2D width, rather than a 3D diameter. All loop footpoints are slightly diverging, with the gradient of the divergence (|(top cross-section-bottom cross-section)/L|) $D = 0.28 ± 0.15$, ranging from 0.07−0.71.

Secondly, propagation speeds were calculated from the slopes in the running differences. In all analysed examples we only found positive gradients, i.e. we only found outward propagating disturbances and there seems to be no evidence indicating downward propagation. When the signal can be observed (above a 99.0 % confidence level) for a sufficient number of consecutive positions along the structure, we are able to give a reliable range of values for the propagation speed but in other cases, we can only give an estimate of the order of the propagation speed. Velocities are found with a mean and standard deviation of 119 ± 39 km/s, covering a range of 65−205 km/s. Taking into account line-of-sight effects, the quoted values are only a lower limit for the true propagation speed. In most cases, no noticeable deceleration or acceleration was observed as the signals travel along the structures.
The amplitude of the intensity disturbances is of the order of $4.1 \pm 1.6\%$ (ranging from $0.7\%$ to $14.6\%$) compared with the background intensity and generally gets weaker as the signal propagates along the structure. We can get an idea of how far the disturbances travel along the footpoint by examining the number of consecutive positions where wavelet power above the 99.0 \% confidence level, at a similar period, is detected. This procedure yields values $L_d = 8.6 \pm 3.8 \text{ Mm}$, covering a range of $2.9 - 18.9 \text{ Mm}$. Calculating this damping length as a percentage of the footpoint length, we find $L_d = 36.0 \pm 18.2 \%$. We remind the reader that this is not a true damping length, as it only indicates where the intensity changes vanish into the data noise. However, $L_d$ can be considered to be a lower limit to the true physical damping length. A final parameter that can be obtained from the wavelet analysis is the oscillation period. As we here concentrate on propagating disturbances, we only take into account those periods that are consistent in a significant number of consecutive positions, from which the estimate of the damping length $L_d$ is calculated. We found values for the oscillatory period with a mean and standard deviation of $P = 282 \pm 93$ seconds, ranging from 145 s to 525 s. All periods are well above the acoustic cutoff and hence the waves are propagating into the corona.

4. DISCUSSION

We presented an overview of physical parameters of 38 observed propagating disturbances in the lower part of large coronal loops. All loops were found to be quiescent, with their overall structure and appearance remaining stable and unchanged for long
Table 1. Statistical overview of the averages and ranges of the physical properties of the 38 oscillations found in the footpoints of large coronal loops.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average</th>
<th>Range</th>
</tr>
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<tbody>
<tr>
<td>Footpoint length $L$</td>
<td>$26.3 \pm 9.3$ Mm</td>
<td>$10.2 - 49.4$ Mm</td>
</tr>
<tr>
<td>Average footpoint width $w$</td>
<td>$8.2 \pm 2.7$ Mm</td>
<td>$3.9 - 14.1$ Mm</td>
</tr>
<tr>
<td>Footpoint divergence $D$</td>
<td>$0.28 \pm 0.15$</td>
<td>$0.07 - 0.71$</td>
</tr>
<tr>
<td>Oscillation period $P$</td>
<td>$282 \pm 93$ s</td>
<td>$145 - 525$ s</td>
</tr>
<tr>
<td>Propagation speed $v$</td>
<td>$119 \pm 39$ km/s</td>
<td>$65 - 205$ km/s</td>
</tr>
<tr>
<td>Relative Amplitude $A$</td>
<td>$4.1 \pm 1.6$ %</td>
<td>$0.7 - 14.6$ %</td>
</tr>
<tr>
<td>Damping length $L_d$ (as % of $L$)</td>
<td>$8.6 \pm 3.8$ Mm</td>
<td>$2.9 - 18.9$ Mm</td>
</tr>
<tr>
<td>$36.0 \pm 18.2$ %</td>
<td>$8.0 - 81.4$ %</td>
<td></td>
</tr>
<tr>
<td>Energy flux $F$</td>
<td>$346 \pm 132$ ergs/cm$^2$/s</td>
<td>$194 - 705$ ergs/cm$^2$/s</td>
</tr>
</tbody>
</table>

periods of time. On large scales, the oscillatory signals have no noticeable effect on the loops. Most loops were situated at the edges of active regions, and no oscillations have been found in actual active region loops. However, it is not clear whether these shorter, more active loops do not support such oscillatory signals, or whether the signals are just obscured by other transient events.

As the data clearly displays variations in intensity, and thus in density, which propagate with a roughly constant speed of the order of the coronal sound speed, $c_s$, we interpret the propagating disturbances as slow magneto-acoustic waves. Assuming the loops to be linear and homogeneous, we can estimate the energy flux carried by the oscillatory signals as $\rho ((\delta v)^2/2) v_s$, where $\delta v$ is the wave velocity amplitude and $v_s \approx c_s = 150$ km s$^{-1}$ in the corona. Setting $\rho = 5 \times 10^{-16}$ g cm$^{-3}$ and $\delta v = 3.0 \pm 0.5$ km s$^{-1}$, we get an estimate for the wave energy flux $\sim 346 \pm 132$ ergs cm$^{-2}$ s$^{-1}$. This energy is only a very small fraction of the total energy required to heat coronal loops. As was pointed out by Tsiklauri et al. (2001), this estimate is a lower limit for the energy flux. However, the wide spectrum needed by their model to fulfill the heating requirements of the average coronal loop has not been observed in this study, as the clear bands seen in the running differences indicate the presence of a dominant harmonic.

Without a detailed study of the magnetic footpoints of the coronal loop supporting these oscillations, it is impossible to determine how these pulses are excited. The range of observed periods makes it very hard to exclude or confirm some form of coupling with the photospheric 5-minute period.

5. CONCLUSIONS

From the analysis of a substantial amount of high cadence, 171 Å TRACE data, we identified 38 large coronal loops that support clear, periodic intensity variations. These small-amplitude ($A \approx 4.0 \pm 1.5$ %), propagating intensity disturbances were interpreted as slow magneto-acoustic waves, travelling at a speed of the order of $v \approx 120 \pm 40$ km/s. We found peri-