OSCILLATING HOT LOOPS OBSERVED BY SUMER

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ABSTRACT

We report observations of Doppler shift oscillations in hot flare lines emitted from active region loops. The Solar Ultraviolet Measurements of Emitted Radiation (SUMER) spectrometer on SOHO recorded spectra of limb active regions loops in several emission lines with formation temperatures from $\sim 10^4$ to 10^7 K. The events were only detected in the hot flare lines, without any signature in lines formed around 2×10^6 K. There is a large shift pulse of up to 190 km s^{-1} during the rising phase of the flux which is followed by two or three periods of strongly damped alternating red and blue shift oscillations with periods in the range 12−31 min. Slow mode standing waves match the observed period. However, the initial large Doppler shift pulse suggests that the waves are impulsively generated. Unlike the oscillating loops seen in the TRACE images, these Doppler shift oscillations are sometimes seen without an associated flare.

Key words: solar flares; coronal oscillations; UV radiation, X-rays.

1. INTRODUCTION

The exploration of oscillations in coronal loops may provide insight into the process of coronal heating. Theoretical aspects of MHD waves and oscillations of coronal loops have been reviewed by Aschwanden (1987) and Roberts (2000). Transverse oscillations of active region loops were first discovered with TRACE in EUV bands (Aschwanden et al., 1999), and more cases have been reported in a recent statistical study by Schrijver, Aschwanden, & Title (2002) and Aschwanden et al. (2002), showing that these loop oscillations are triggered by flares, and have oscillation periods in the range of 2−11 min, decay times of 3−21 min, transverse amplitudes of 100−9000 km, and maximum transverse speeds of 229 km s^{-1}. Nakariakov et al. (1999) propose that the oscillations are standing waves and the rapid damping is a sign of anomalously high dissipation. On the other hand, Aschwanden et al. (2002) suggest that flare-induced impulsively generated MHD waves propagate back and forth in the loops, and decay quickly due to wave leakage at the footpoints.

In order to study time variations and dynamics of active region loops, a number of spectral observations were made by the Solar Ultraviolet Measurements of Emitted Radiation (SUMER) spectrometer (Wilhelm et al., 1995). A preliminary investigation led to the discovery of Doppler shift oscillations in hot flare lines (e.g. Kliem et al., 2002; Wang et al., 2002). In this study, we report physical parameters of the Doppler oscillations, explore the relationship between Doppler oscillations and coronal loops using Yohkoh/SXT images, and discuss the possible excitation mechanism in terms of loop oscillations and waves.

2. OBSERVATIONS AND DATA REDUCTION

In this paper, we describe several examples of loop oscillations. In each case the SUMER spectrometer slit was placed at a fixed position in the corona about $100''$ above an active region at the limb. The observations of AR 9371 on 9 March 2001 and AR 9176 on 29 September 2000 were made in a spectral window 1098−1138 Å, on detector A with a 162 s exposure time, and the $300'' \times 4''$ slit. The observations of AR 8758 on 6 November 1999 are described in detail by Kliem et al. (2002). They covered 8 lines in the range 1320−1360 Å with the $300'' \times 1''$ slit and used an exposure time 120 s.

After processing the raw data by standard procedures, the lines were fit to a single Gaussian to obtain a Doppler shift time series at each spatial pixel. Examples are shown in Figures 1,3,4,5. These show distinct regions of coherent oscillations along the slit. For each region, we average over a width of 11 pixels ($\sim 1''$/pix) to get its average time profile. The function

$$V(t) = V_0 + V_m sin(\omega t + \phi) e^{-\lambda t}, \qquad (1)$$

is then fit to the oscillation, where V_0 is the post-event Doppler shift, V_m is the shift amplitude and ω, ϕ, and λ are the frequency, phase, and decay rate of the oscillations. The time series parameters are listed in Table 1.

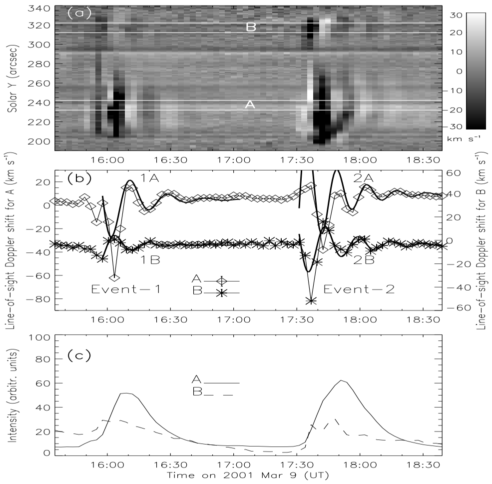

Figure 1. (a) Doppler shift time series in the Fe XIX line on 9 Mar 2001. (b) Average time profile of Doppler shifts along cuts A and B. The thick solid curves are the best fit functions (1). (c) Average time profile of line-integrated intensities for cuts A and B. For a clear comparison, the time profile for B is scaled by a factor ×10.

3. DOPPLER OSCILLATION EVENTS

3.1. Case 1: 9 March 2001

This example (Figs. 1 and 2) is probably the clearest example of loop oscillations. SUMER observed two hot plasma events occurring in AR 9371 at the west limb on 9 March 2001. Wang et al. (2002) showed that the flux enhancements were only manifested in hot flare lines (strong emission in Fe XIX and weak emission in Fe XX), without any signatures in lines with formation temperature below 2 × 10^6 K. No GOES flares were related to these two SUMER events.

The two oscillation events occurred within an interval of less than 2 hours and showed very similar double components in anti-phase. During the second event, when simultaneous SXT observations were available, a SXR loop was seen at the position of the loop oscillation (Fig. 2). The length of the SXR loop, calculated in a 3-D geometry, is $L = 140$ Mm, the sound speed of the Fe XIX, 6×10^6 K plasma is $c_s = 295$ km s^{-1}. So a standing slow mode wave would have a period, $2L/c_s = 15.8$ min which well agrees with the observed 14−18 min periods. Wang et al. (2002) showed that the Alfvén and kink mode periods for the loop were around 3-4 min.

3.2. Case 2: 6 November 1999

In this case the oscillations are even better defined than in the March 9 events (Fig. 3). Unfortunately there were no simultaneous SXT observations so we are unable to pinpoint the oscillating loop. This time the event is associated with a C4.6 flare that occurred in AR 8758 at the north-east limb. More details of the event and associated 10^4 K line emission are given in Kliem et al. (2002). A damped sine-function provides a good fit (Fig. 3b) and gives a period of 11.7 min.

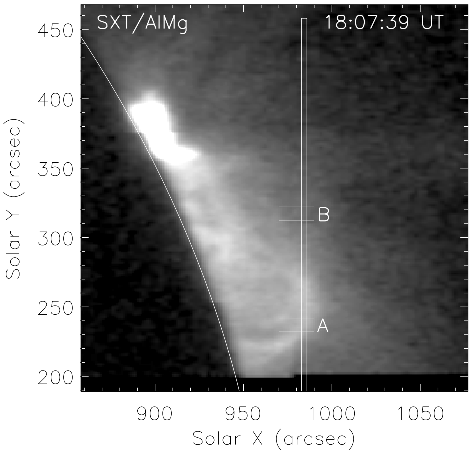

Figure 2. The SUMER spectrometer slit position drawn against the oscillating soft X-ray loop during the event on 9 Mar 2001. The positions A and B from Figure 1 are indicated.

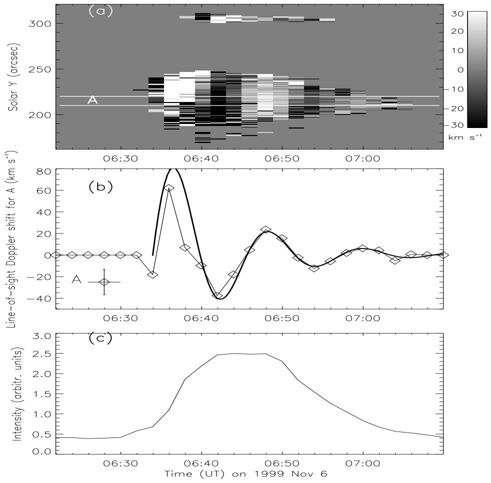

Figure 3. Doppler shift oscillation event in the Fe XXI line on 6 Nov 1999.

3.3. Case 3: 29 September 2000

This example is described for the first time here. The SUMER time series revealed 4 hot plasma events, all in the Fe XIX line, without signatures in the lines formed below 2 × 10^6 K. Figure 4 shows the two earlier events. The first at about 02:30 UT and the second about an hour later at 03:50 UT. Neither were detected by GOES. The later two events (Fig. 5) were both associated with GOES C-class flares. The earlier ones are about a factor five fainter (c.f. Figs. 4c and 5c), and have well defined oscillations whereas the flare events are much more complex with several non-periodic components.

Interestingly, all 4 events began with strong red shifts. We notice that the flares, as indicated by a brightening

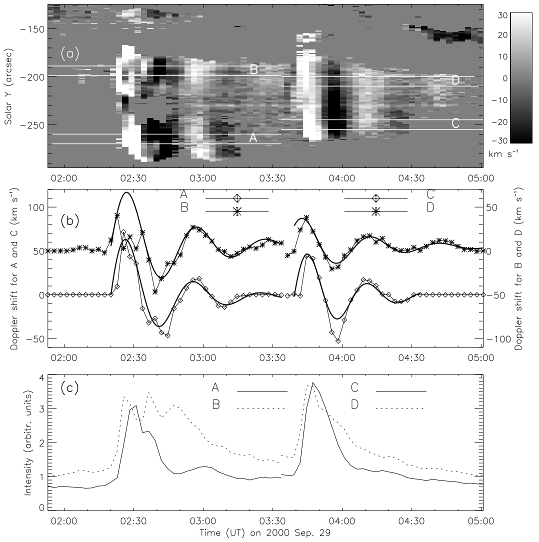

Figure 4. Doppler shift oscillation event in the Fe XIX line on 29 Sep 2000, during 02:00–05:00 UT.

in SXT images, initiated at the southern side of the W footpoint of the large loop system (Fig. 6). So the initial red shift was probably produced by an outward-pushing force generated in the flares (e.g. reconnection outflows or shocks). Propagating MHD waves will result if a disturbance is generated impulsively at one end of a loop (Roberts & Edwin, 1984). The observed cases seem to support such a trigger mechanism for loop oscillations.

The SXT images (Fig. 6) show that the SUMER slit was near the top of a large SXR loop system. During the fainter earlier events, the SXR loops brightened but there were no major changes in the loops' structure. Both flare events were associated with X-ray plasma ejections (see Fig. 6a-d) and this is probably why the shifts are confused. Nevertheless there are two regions in the second flare event (around 13:00) with in-phase oscillations. These may correspond to the intersection of the slit with two legs of an oscillating loop. The period of the oscillation is very close to the periods of the earlier fainter events, with a mean of 28.0±2.3 min, covering a range of 25−31 min (Table 1). This is also close to 43 min, the slow mode standing wave period, assuming a sound speed of $c_s = 295$ km s^{-1}, for a loop length of $L \approx 383$ Mm, which is the length of the large loop system as measured from Figure 6a. If the coronal loop contains some components hotter than Fe XIX, the estimated period will be more close to the observed value, e.g. $P \sim 30$ min, when take T=13 MK.

4. DISCUSSION AND CONCLUSION

From the analyses of three sets of SUMER spectral observations of limb active region loops, we find Doppler shift oscillations in 7 hot plasma events; 3 of which were associated with C-class flares. All events were only detected in the hot flare lines. For all cases, variations of line-integrated flux have impulsive profiles. Moreover, all cases show that the shift began to increase at the same

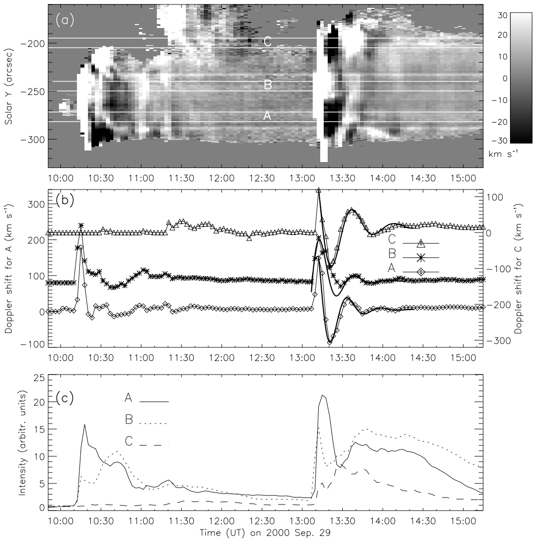

Figure 5. Doppler shift oscillation event in the Fe XIX line on 29 Sep 2000, during 10:00–15:00 UT. In (b) the curve B is plotted to left y-axis with a shift of 80 km s^{-1}.

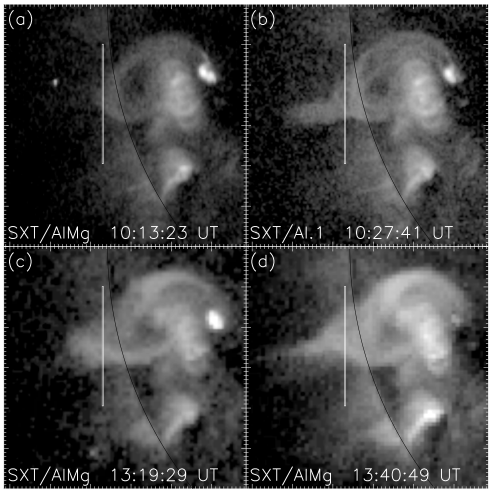

Figure 6. Overlay of the $4'' \times 300''$ SUMER slit on Yohkoh/SXT images obtained at different times (given at the bottom of each image). A GOES C3.0 flare occurred at 10:17 UT, and a C4.5 flare at 13:13 UT.

Table 1. Time series analysis of Doppler shift oscillations. t_0 is the start time of the modeled time series. T is the oscillation period, $T = 2\pi/\omega$. τ_λ is the decay time, $\tau_\lambda = 1/\lambda$. A is the displacement amplitude, calculated from $A = V_m/(\omega^2 + \lambda^2)^{1/2}$. N_P is the number of periods during the total duration of a detected oscillation.

Osci. Components	t_0 (UT)	V_0 (km s^{-1})	V_m (km s^{-1})	T (min)	ϕ (rad)	τ_λ (min)	A (km)	N_P
A	06:33:56 06-Nov-99	0.5	110.2	11.7	−0.01	8.8	12045	2
A	02:20:09 29-Sep-00	−2.4	88.7	29.1	0.03	22.0	24155	2
B	02:20:09 29-Sep-00	5.7	78.2	30.0	−0.01	28.9	22118	2
C	03:39:13 29-Sep-00	−1.5	63.7	25.7	−0.01	21.2	15374	2
D	03:39:13 29-Sep-00	4.9	36.9	29.6	0.70	28.0	10294	2
A	13:12:14 29-Sep-00	5.3	191	25.1	2.25	12.5	43650	2
B	13:06:49 29-Sep-00	4.9	191.7	25.7	-0.16	12.6	44704	2
C	13:12:14 29-Sep-00	15.8	188.7	31.1	2.55	18.7	54106	2
1A	15:57:45 09-Mar-01	4.8	43.8	17.9	3.07	13.7	7330	2
1B	15:57:45 09-Mar-01	−4.0	13.6	15.7	−0.92	11.9	1995	2
2A	17:31:07 09-Mar-01	9.5	69.9	14.2	−0.17	15.0	9373	3
2B	17:31:07 09-Mar-01	−3.7	29.7	15.7	2.83	19.0	4415	3

time as the flux, but the shift peaked earlier than the flux. These events often repeat at the same place and manifest similar oscillation features such as identical periods and the fact that separated spatial components remain in anti-phase or in-phase (see the case 1 and case 3). These features suggest that the re-occurring Doppler oscillations were related to the same magnetic structures. The fact that the events did not cause substantial changes to the loop system, as indicated by Yohkoh SXT time series, supports this assumption. Comparing to the loop oscillation observed in TRACE, we find some consistent properties, such as the maximum velocity, the damping time, and displacement amplitude. However, a distinct difference is that the SUMER Doppler oscillations are not seen in lines formed around 10^6 K in which TRACE loop oscillations are detected. Moreover, about 70% of the TRACE events were triggered by strong flares with M or X class (Schrijver, Aschwanden, & Title, 2002). On the other hand, more than half the Doppler oscillation events, showed no associated GOES flare. This implies that the hot loop oscillation is excited by even weak flare-like disturbances, and is likely to be a more general phenomena than the TRACE loop oscillations. We cannot rule out, however, that flares occurring at the loop footpoint behind the limb triggered some of the events studied here.

The other difference to TRACE loop oscillations is that the SUMER events have periods in the range of 12−31 min, distinctly larger than those observed by TRACE, which lie in a range of 2−11 min. We find that the observed periods of Doppler oscillations are consistent with that of slow mode standing waves. One problem with this interpretation is, however, that the intensity fluctuations, with the same period as the Doppler shifts, are not readily visible in the data, pointing to an incompressible wave. The initial large shift pulse is in good agreement with an initial large displacement often seen in TRACE loop oscillations (Aschwanden et al., 2002), and suggests flare-induced impulsively generated MHD waves. But it is not clear why only long-period oscillations are detected in the SUMER events. It may be because the fast-mode wave is damped extremely quickly in these hotter loops, while the slow-mode wave can establish the resonance via reflection at the ends of the loop. To solve these puzzles, we need to develop, on the one hand, theory and simulation to understand the properties of impulsively generated MHD propagating waves in coronal loops, and to explore, on the other hand, high frequency oscillations by improving the observing cadence.

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