HOT LOOP OSCILLATIONS SEEN BY SUMER: EXAMPLES AND STATISTICS

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ABSTRACT

We measure physical parameters of Doppler-shift oscillations in 17 flare-like events. These events have been recorded by the Solar Ultraviolet Measurements of Emitted Radiation (SUMER) spectrometer on SOHO, along a slit fixed above limb active regions. The selected spectral windows contain emission lines with formation temperatures from ~10^4 to 10^7 K. The events were only detected in hot flare lines, without any signature in lines formed around 2 x 10^6 K. Similarly, the Doppler shift oscillations occur in regions coincident with hot soft X-ray loops, but not with EUV loops. The oscillations have periods of 11–31 min, with an exponential decay time of 5.5–29 min, and show an initial large shift pulse with peak velocities up to 200 km s^{-1}. Several indications suggest that the Doppler oscillations are incompressible coronal loop oscillations, that are usually excited impulsively by weak flare (or microflare) events that also produced a strong emission increase at 5–8 x 10^6 K.

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

1. INTRODUCTION

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). These transverse loop oscillations are excited by flares, and show a very quick decay on time scales of 3–21 min, with oscillation periods of 2–11 min. Aschwanden et al. (1999) and Nakariakov et al. (1999) have interpreted the loop oscillation as a fundamental resonance of the kink mode, and Nakariakov et al. (1999) concluded that the rapid damping is due to anomalously high viscosity, or resistivity in the coronal plasma. Ofman & Aschwanden (2002) investigated the scaling of the oscillation damping time for the TRACE loops, and found that the scaling agrees best with phase mixing as the damping mechanism.

Recently, additional evidence of damped oscillating coronal loops was found by SUMER spectral observations (Kliem et al., 2002; Wang et al., 2002a,b). They show that Doppler shift oscillations in hot coronal loops (T ~ 10^7 K) have a damping time range comparable to that of the TRACE loops, but oscillation periods distinctly longer than those observed by TRACE. This difference is confirmed by new observations with a higher cadence reported in this study. We present three typical case studies and statistical results of hot loop oscillations.

2. OBSERVATIONS AND DATA REDUCTION

In all cases, the SUMER spectrometer slit was placed at a fixed position in the corona about 100" above an active region at the limb. The earlier observations during 1999–2001 were made in a wide spectral window with a 162 s exposure time. The new observations obtained in April 2002 were made in three lines (Si III/S III, Ca X, and Fe XIX) with a high cadence of 50 s.

After processing the raw data following standard procedures, a single Gaussian was fit to the lines to obtain a Doppler shift time series at each spatial pixel. Examples are shown in Figures 1 and 3. These exhibit distinct regions of coherent oscillations along the slit. For each region, we average over a width of 11 pixels (~1"/pix) for the old data sets and 6 pixels for the new data sets to get its average time profile. The function

\[ V(t) = V_0 + V_m \sin(\omega t + \phi) e^{-\lambda t}, \]

is then fit to the oscillation, where \(V_0\) is the post-event Doppler shift, \(V_m\) is the shift amplitude and \(\omega, \phi, \lambda\) are the frequency, phase, and decay rate of the oscillations. The parameters of the time series are listed in Table 1.
3. RESULTS: INDIVIDUAL EVENTS

3.1. Case 1: 9 March 2001

This is probably the clearest example of loop oscillations in our data set. Wang et al. (2002a,b) showed that the two similar Doppler oscillation events occurred within an interval of less than 2 hours, at the place coincident with a SXT loop. They found that the period for a standing slow mode, $2L/c_s = 15.8$ min, in agreement with the observed 14–18 min periods, but the absence of brightness fluctuations with the wave period argue against a compressible wave. On the other hand, an unusual coronal loop environment ($\beta \sim 2$) is implied if we interpret the Doppler oscillation as a standing kink mode.

3.2. Case 2: 29 September 2000

In this case, available coordinated observations between SUMER and Yohkoh/SXT provide convincing evidence that the Doppler oscillation corresponds to hot coronal loop oscillations. Wang et al. (2002a) showed that the SUMER time series revealed 4 hot plasma events. The two earlier events (Fig. 1) have well defined oscillations that coincide with the region where the slit crosses a large SXT loop (Fig. 2). EIT loops differ in position from the SXT loop. The later two events (10:17 UT and 13:13 UT) were both associated with GOES C-class flares, showing X-ray plasma ejections (Fig. 6 in Wang et al., 2002a). Slow mode standing waves have a period $\sim 40$ min, assuming a sound speed of $c_s = 295$ km s$^{-1}$, for a loop length of $L \approx 356$ Mm, which is the length of the large loop system as measured from Figure 2a. This is 1.3–1.6 times the measured periods. We obtain $\beta \sim 1$ when the global kink mode is assumed.

3.3. Case 3: 11 April 2002

This is the best example showing Doppler oscillations in the new observations. Figure 3 shows that three oscillation events occurred within 2 hours, with the periods in the range of 13–18 min, similar to the previous results. The high cadence observations reveal propagation (phase delay) of Doppler disturbances along the slit. The disturbance from C to B (cut 1) and that from C to D (cut 2) have durations of 150 s and 200 s, so that this initial phase delay was not detectable in the previous low-cadence observations. The phase propagating speeds decrease with time. We measure the speed for CB as 96, 49, and 34 km s$^{-1}$ from the slopes of cuts 1, 3 and 5, while the speed for CD is 83, 48, and 13 km s$^{-1}$ from cuts 2, 4 and 6. Figures 3c and e show also distinctly different spatial distributions along the slit (e.g. at B, C, and D) in intensity and line width.

4. STATISTICAL RESULTS

We analyzed the 35 Doppler oscillation components in 17 flux enhancement events of hot plasma (> 6 MK). In each event, we identified several oscillation components along the slit, due to differences in Doppler shift, intensity, or line width. All events show the flux variations of flare-like impulsive profiles, but only 3 of the 17 events were associated with GOES flares. The histograms of physical parameters of the oscillations listed in Table 1 are shown in Figures 4 and 5. Although the new observations...
Figure 3. (a) Doppler-shift time series in the Fe XIX line on 11 Apr 2002. (b) Average time profiles of Doppler shifts for the cuts in (a) and their best fit curves. (c) Line-integrated intensity time series, and (d) the corresponding time profiles for the cuts. (e) Line width time series, and (f) the corresponding time profiles for the cuts.

Figure 4. Histograms of (a) the damping time, (b) the oscillation period, (c) the maximum Doppler shift, and (d) the derived maximum displacement. The solid strips represent the total sample, including the data obtained in 1999-2001 with a low cadence of 169 s and the new data obtained in 2002 with a high cadence of 50 s. The dashed strips represent the new samples.

had a high cadence of 50 s, which allows a detection of short-period oscillations of ~3 min period, no oscillations are found with periods shorter than 10 min. We measure oscillation periods in the range 10.8–31.1 min with a mean of 18.5±5.8 min, damping times of 5.5–28.9 min with a mean of 14.6±6.3 min, maximum Doppler velocities of 14–315 km s\(^{-1}\) with a mean of 102±81 km s\(^{-1}\) and the derived maximum displacements of 2–54 Mm with a mean of 18±15 Mm.

Figures 5a and b indicate that the shift peaked earlier than the flux, but almost simultaneously with the line width. Figure 5c shows that the duration of intensity peak (defined as the time spent at brightness above 1/e of the maximum) is approximately equal to the oscillation period. In 13 of 35 oscillation components, the intensity curves have several peaks showing a non-periodic behavior (Table 1). The best fit power law scaling of the damping time with the period gives an exponent of 1.07±0.16, i.e. a linear relation. In 5 cases (e.g. cases 1, 2 and 3), these events repeat at the same place and manifest similar oscillation features such as identical periods and initial Doppler shifts of the same sign. These features suggest that the recurring Doppler oscillations were related to the same magnetic structures.

Figure 5. Histograms of the time lag of (a) the first intensity peak, and (b) the Doppler line width peak to the Maximum Doppler-shift pulse. (c) Histogram of the duration of the intensity peak above 1/e of the maximum value. The solid and dashed strips have the same meaning as in Fig. 4. (d) Scaling of the oscillation damping time with the period. Diamonds mark the new data sets obtained in 2002, and the crosses mark the old data sets obtained in 1999-2001. The solid line is the best fit scaling.
Table 1. Time series analysis of Doppler shift oscillations. $t_0$ is the start time of the modeled time series. $P$ is the oscillation period, $P = 2\pi/\omega$. $\tau_\lambda$ is the decay time, $\tau_\lambda = 1/\lambda$. $A_m$ is the displacement amplitude, calculated from $A_m = V_m/((\omega^2 + \lambda^2)^{1/2})$. $N_P$ is the number of observed periods. $N_I$ is the number of intensity peaks.

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<th>$V_m$ (km s$^{-1}$)</th>
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<th>$\tau_\lambda$ (min)</th>
<th>$A_m$ (km)</th>
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5. DISCUSSION AND CONCLUSION

The SUMER spectral observations have revealed a new kind of coronal plasma oscillations that were only detected in the hot flare lines of $T > 6$ MK. The Doppler oscillations happened at the region where the slit crossed the SXT loops, indicative of hot loop oscillations. Unlike the loop oscillations seen by TRACE that were mostly triggered by strong flares, these Doppler oscillation events happened mostly without associated GOES flares. We find that Doppler oscillations have periods (11–31 min) distinctly longer than those (2–11 min) observed by TRACE. In two cases we measured the loop length from available coordinated SXT images. Slow standing modes roughly match the observed period. However, the absence of brightness fluctuations with the wave period argues against a compressive wave. But an interpretation in terms of the global kink mode implies $\beta \sim 1$ in hot coronal loops.

REFERENCES


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