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DOPPLER OSCILLATIONS OF ACTIVE REGION LOOPS: STEPS TOWARDS CORONAL SEISMOLOGY

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Abstract. Oscillations of coronal loops – subject of theoretical work for a long time – can help to determine coronal plasma parameters not otherwise accessible. Therefore, the Doppler oscillations recently observed by the SUMER spectrometer on SOHO are of extreme interest and constitute a significant contribution to the old, but rejuvenated field of coronal seismology. High-velocity oscillation events in hot EUV flare lines are seen almost every time these lines brighten. Such events seem to be a common feature of active region loops. The oscillations always have an impulsive trigger and are strongly damped while they cool down. Lines formed at normal coronal temperatures do not show any signature of these oscillations.

Key words: solar flares - coronal loops - oscillations

1. Introduction

Any elastic system can oscillate in its specific eigenmodes. This basic rule applies for anything including the Sun itself, for the solar interior as well as for the solar corona. While helioseismology is a well-established scientific field, which in the last decade has brought new insight into the physics of the solar interior, this was not the case for the dynamics of the solar corona: coronal seismology never reached the importance of helioseismology, although the theoretical background was prepared 30 years ago (Aschwanden 1987, Roberts *et al.* 1984) by applying similar physical laws. However, observational evidence was scarce. There have been numerous radio observations in the 1 s domain and isolated observations of oscillatory motions in prominence loops (Vršnak *et al.* 1990), but it was not possible to observe periods longer than 60 s in a systematic manner. Since 1999, however, TRACE has been observing transverse loop oscillations with periods of several minutes (Aschwanden *et al.* 1999), and the SUMER spectrometer on SOHO (Wilhelm *et al.* 1995) has found strong Doppler-oscillations in emission lines of highly-ionized iron with even longer periods. This communication will describe the recent SUMER results and the interpretation in the light of existing models. We will also compare the TRACE events to the SUMER events.

2. The observations

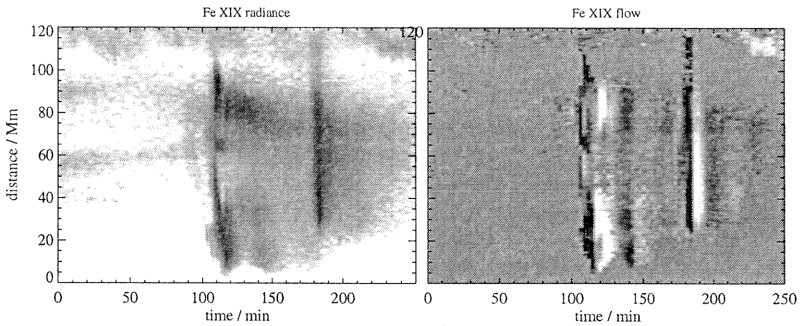

Figure 1: Intensity map and velocity map (scaled to ± 50 km/s, red shifts are dark) of a typical recurring oscillation event, observed in the 1118 Å Fe XIX line.

The first SUMER oscillation event was described by Kliem *et al.* (2002) as a strongly damped oscillatory Doppler flow in Fe XXI emission. Since then, more than 100 events have been observed during four campaigns, suggesting that oscillations in hot coronal loops are frequently occurring events. Typically, the spectrometer slit was positioned at a fixed-slit position 50"–100" off-disk above a near-limb active region and segments of the spectral window from 1100 to 1150 Å were telemetered to the ground. This spectral range provides emission lines covering the wide temperature range from 4000 K to 10 MK (Feldman *et al.* 1999, Curdt *et al.* 2001). A typical example of an oscillation event observed in Fe XIX – a species normally not found in solar spectra – is shown in Fig. 1. After a sharp rise from zero, the radiance of Fe XIX falls off gradually. In the Doppler map, however,

Table I: Physical parameters of 54 SUMER Doppler-oscillation events

Parameter	Average	Range
Oscillation period P	17.6 ± 5.4 min	7.1–31.1 min
Decay time $\mathcal{T}_d$	14.6 ± 6.9 min	5.5–37.3 min
Doppler-oscillation amplitude V_m	98 ± 75 km/s	13.3–315 km/s
Derived displacement amplitude A	16.4 ± 14.1 Mm	1.8–54.1 Mm
Ratio of decay time to period $\mathcal{T}_d/P$	0.84 ± 0.34	0.33–2.13
Number of periods observed N_p	2.3 ± 0.7	1.5–5
Time lag of radiance peak ΔT_{IV}	8.5 ± 13.1 min	-2.5–52.5 min
Radiance peak duration ΔT_I	36.2 ± 27.0 min	10–141 min
Number of radiance peaks N_I	1.5 ± 0.7	1–3
Speed of phase propagation c	43 ± 25 km/s	8–102 km/s

three periods of a strongly damped oscillation are seen, re-triggered after ≈80 min. We determined a period of ≈28 min for both oscillations. From the fact that a loop can be triggered several times, we conclude that the events normally do not change the overall structure of the loop system. The oscillatory Doppler flows are exclusively observed in lines formed at temperatures >6 MK. However, a few observations exist, where signatures are also seen in transition region lines like Si III (Kliem *et al.* 2001). Some events are related to C-class flares, but the majority of the SUMER events is invisible elsewhere, i.e. below the detection limit of any other instrument like EIT, TRACE or GOES. However, in cases when context images reveal the loop geometry, a more detailed analysis of the event can be done (Wang *et al.* 2002 a). The physical parameters derived from 54 selected oscillation instances are summarized in Table I (cf., Wang *et al.* 2003 b).

3. Interpretation

Three immediate questions arise: How does the trigger work? What is the physical nature of the oscillation? Which process is responsible for the strong damping? The first two questions will be discussed here. For this analysis we have studied the light curves in emission formed at different temperatures throughout typical oscillation events.

3.1. The trigger

The trigger is obviously impulsive. Almost instantaneously, highly-ionized species dominate the coronal spectrum at a well-defined slit position, sometimes spatially and temporally correlated with bremsstrahlung. This suggests an impulsive energy release in the active region loop, which is often recurring. While the 'heating' curve is too steep to be resolved, the cooling of the plasma, which can be observed in the decreasing ionization stages for more than an hour (cf., Fig. 2). Some events are correlated to activities observed by EIT, SXT or TRACE. These context images show that the trigger is released at the sunward side and probably evolves at the footpoints from where it rises as a bright emission front. The cooling curve starts to fall exponentially, but finally falls off very rapidly. This may support models predicting a run-away cooling process ('coronal rain').

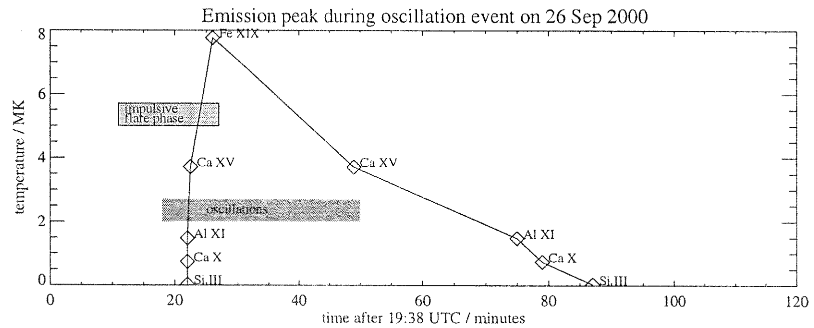

Figure 2: Cooling curve of the Sep 26 event

3.2. The loop model

On April 16, 2002, an oscillation event with reduced damping was observed. The event was clearly seen over six periods in the velocity curve. In this case, a ripple of 15 % was also visible in the light curve. And after subtraction of the general background trend for darkening, the intensity oscillation became obvious, as depicted in Fig. 3. The intensity curve has a phase shift of exactly 90° relative to the Doppler flow. This new result from recent work of Wang *et al.* (2003 a) is a convincing indication for a compressive

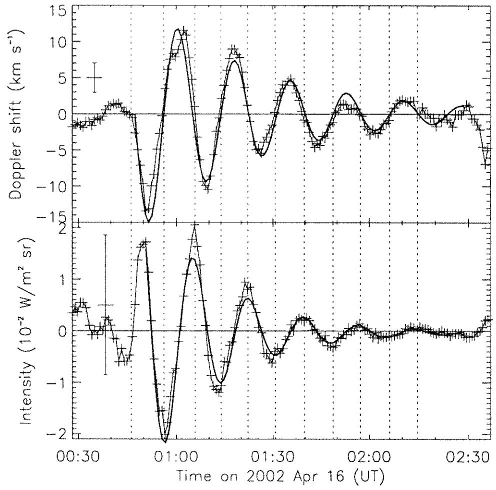

Figure 3: Light curve and velocity curve of the April 16 event

wave. Together with other evidence (Wang *et al.* 2003 b), this suggests that compressive waves are causing the majority, if not all of the Doppler-oscillation events, although the periodic radiance fluctuation is difficult to observe in cases of strong damping. We now assume that the SUMER events are standing magneto-acoustic waves in slow mode. The propagation speed c, which can be derived from the loop length L and the period P by

$$c = 2L/P \tag{1}$$

is related to the density and the magnetic field B (Roberts 2002) via

$$1/c^2 = 1/c_A^2 + 1/c_s^2 \tag{2}$$

where the speed of sound, c_s and the Alfvén speed, c_A depend on

$$c_s^2 = \kappa p_0/\rho_0 \text{ (Laplace) and} \tag{3}$$

$$c_A = B/\sqrt{4\pi\rho}\ , \tag{4}$$

κ denoting the compressibility.

Using this model, we have access to physical parameters of the oscillating loops, and this is what makes our observations so interesting (Nakariakov & Ofman 2001, Schmelz 2002).

4. TRACE oscillations and SUMER oscillations

We have compared the physical parameters of the TRACE events compiled by Schrijver *et al.* (2002) to our results (Wang *et al.* 2002 b,c). The histograms in Fig. 4 showing oscillation period, damping time, max-

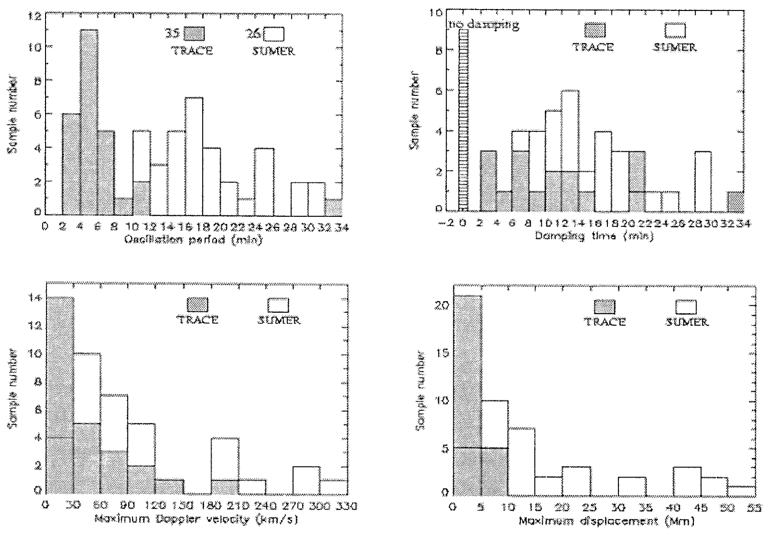

Figure 4: Statistical overview of TRACE results and SUMER results

imum Doppler velocity, and maximum displacements of both instruments (Curdt*et al.* 2002) do not look very different at first glance.

This and the as-we-thought missing brightness oscillation led to the idea, that both instruments are seeing the same phenomenon. However there are three strong arguments in favour of a different interpretation: the SUMER results show that the oscillations occur exclusively at temperatures >6 MK, a temperature range not accessible to TRACE, secondly, SUMER sees most oscillations during minor, hardly detectable subflare events, while TRACE needs M- or C-class flares, and finally SUMER observes axial Doppler-oscillations, while TRACE observes transverse intensity variations.

Since February 2002, the HESSI probe is in orbit. Lin *et al.* (2002)

report that HESSI sees a sea of microbursts stemming from 5 keV electrons. These could be perfect candidates for the trigger of the SUMER events. However, joint observations with HESSI are still to come. We have also started to look for signatures in radio data.

5. Summary

Doppler oscillations in hot coronal loops have never been observed before. We do not know yet, whether this phenomenon is of any relevance for the transport of energy into the solar corona. It certainly provides a new method for the measurement of physical parameters in the solar corona and thus has the potential to re-open the field of coronal seismology.

We have demonstrated that coronal loops exist, which are only temporarily visible, namely when being filled and activated. To the ongoing debate whether heating is a steady or an impulsive process, SUMER observations suggest a scenario, where pulses occur continuously, but randomly and at a low level. Finally, this result is a clear demonstration of the importance to fly high-resolution spectroscopes on board of future solar missions.

Acknowledgements

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References

Aschwanden, M. J.: 1987, *Solar Phys.* **111**, 113.

Aschwanden, M. J. *et al.*: 1999, *Astrophys. J.* **520**, 880.

Curdt, W. *et al.*: 2001, *Astron. Astrophys.* **375**, 591.

Curdt, W. *et al.*: 2002, in A. Wilson (ed) Proc. 10^{th} European Solar Physics Meeting, Prague, *ESA SP*-**506**, in press.

Feldman, U. *et al.*: 1997, *Astrophys. J. Suppl.* **113**, 195.

Kliem, B. *et al.*: 2002, *Astrophys. J.* **568**, L61.

Lin, R. *et al.*: 2002, in A. Wilson (ed) Proc. 10^{th} European Solar Physics Meeting, Prague, *ESA SP*-**506**, in press.

Nakariakov, V. M., and Ofman, L.: 2001, *A&A*, **372**, L53.

Roberts, B., Edwin, P. M., and Benz, A. O.: 1984, *Astrophys. J.* **279**, 857.

Roberts, B.: 2002, in A. Wilson (ed) Proc. 10^{th} European Solar Physics Meeting, Prague, *ESA SP*-**506**, in press.

Schmelz, J.: 2002, *Astrophys. J.* **578**, L161.

Schrijver, C. J. *et al.*: 2002, *Solar Phys.* **206**, 69.

Vršnak, B., Ruždjak, V., Brajša, R., and Zloch, F.: 1990, *Solar Phys.* **127**, 119.

Wang, T. J. *et al.*: 2002 a, *Astrophys. J.* **574**, L104.

Wang, T. J. *et al.*: 2002 b, in A. Wilson (ed) Proc. 11^{th} SOHO Workshop, Davos, *ESA SP*-**508**, 465.

Wang, T. J. *et al.*: 2002 c, in H. Sawaya-Lacoste (ed) Proc. IAU Colloquium 188, Santorini, *ESA SP*-**505**, in press.

Wang, T. J. *et al.*: 2003 a, *Astrophys. J.*, submitted as letter.

Wang, T. J. *et al.*: 2003 b, *Astron. Astrophys.*, submitted.

Wilhelm, K. *et al.*: 1995, *Solar Phys.* **162**, 189.

DOPPLEROVE OSCILACIJE PETLJI AKTIVNIH PODRUČJA: KORACI PREMA SEIZMOLOGIJI KORONE

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Izlaganje sa znanstvenog skupa

Sažetak. Oscilacije petlji u koroni su već duže vrijeme predmet teorijskih razmatranja i mogu pomoći u određivanju parametara plazme korone koji se ne mogu drugačije odrediti. Stoga su nedavno opažane Dopplerove oscilacije pomoću SUMER spektrografa na sondi SOHO izuzetno važne te predstavljaju značajan doprinos starom, ali i pomlađenom području seizmologije korone. Oscilacije s velikim brzinama opažaju se skoro uvijek kada zasvijetle EUV linije bljeskova. Izgleda da je takvo ponašanje uobičajena značajka petlji aktivnih područja. Oscilacije uvijek imaju impulzivni pokretač i snažno su prigušene tijekom hlađenja. Linije koje nastaju na normalnim koroninim temperaturama ne pokazuju naznake takvih oscilacija.

Ključne riječi: Sunčevi bljeskovi - koronine petlje - oscilacije