EVIDENCE FOR IN SITU HEATING IN ACTIVE REGION LOOPS

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ABSTRACT

We report new observational results and insights in the energy release during transient events on sub-flare level, which seem to be a common feature of active region loops. Our work is based on multi-temperature observations obtained high above the limb by SOHO/ SUMER. We conclude that the energy input into the loop system is initiated at one and only one foot point by an asymmetric impulsive mechanism. This trigger does not seem to be connected with any bulk flow and there is no indication that the plasma in the loop is replenished or replaced. These observational facts rule out some of the heating models under discussion. The electron density, N_e however, increases significantly during such events. If no new material is added to the local plasma, then the N_e increase can only be explained by a rapid volume decrease, i.e., by an in-situ pinch effect, compressing and heating the affected plasma.

1. INTRODUCTION

Since 1999 SUMER has run several off-disk flare-watch campaigns. In all studies the spectrometer slit was pointed to a limb target at a position 50'' – 100'' off the disk and spectral scans were taken in sit-and-stare mode including (among others) simultaneously the emission lines

Fe XIX 1118 Å	(6.7 MK)	
Fe XVII 1154 Å	(2.9 MK)	
Ca XIII 1133 Å	(2.0 MK)	and
Ca X 1116 Å /2	(0.7MK) .	

Another window around the Fe XXI 1354 Å line was also used. Context images from EIT, *TRACE* and/or *YOHKOH*/SXT helped to understand the loop geometry.

As a surprising new result it came out that Doppler oscillation events (DOE), an example of which is shown in Fig. 1, seem to be a common feature in hot active region loops (Kliem et al., 2002, Curdt et al., 2003, Wang et al. 2003a). Using these oscillation events, Wang et al. (2003b) have reopened the field of coronal seismology. While many details are known now about the oscillations, little is known about the trigger. From recent work we now suggest that the oscillation is just a by-product of the impulsive start of isolated heating events.

Here we combine some of the results reported by Wang et al. (2005, paper I), Feldman et al. (2004, paper II) and Curdt et al. (2005, paper III) and discuss their implications on heating and cooling processes.

2. OBSERVATIONS

As a primary result multi-temperature $L_\lambda(x,t)$ and $v(x,t)$ maps were obtained (spectral radiance L_λ and Doppler shift v along the slit versus time) from all the observations. As an example we show in Fig. 1 a typical event observed on 8 May 2001. Fe XIX emission is normally not observed anywhere on the Sun except for flaring plasmas, which also originate soft X-rays (SXR), and it can be taken as SXR proxy. DOEs have a sudden impulsive start.

2.1 The organ pipe model

The initial Doppler shift, which is typically 50 km/s, is the starting point of a strongly damped oscillation about a zero position corresponding to the rest wave-length. The linear extent of some tens of an arcsec is still growing, while the event goes on.

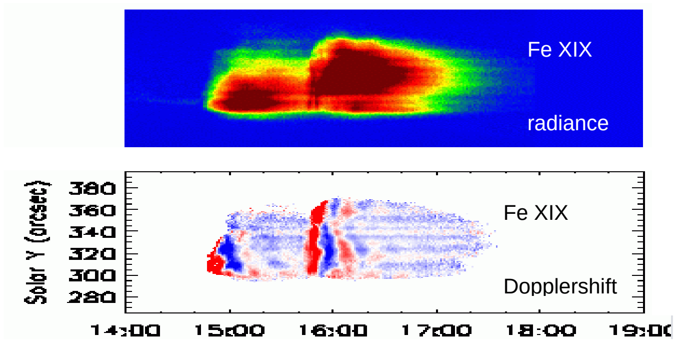

Figure 1. A recurring event observed in Fe XIX 1118 Å (6.7 MK). DOEs have a signature on both spectral radiance (top) and Doppler flow (bottom). The oscillatory nature is best seen in the velocity map v(x,t).

The oscillation is difficult to see in the spectral radiance. In some cases with lesser damping, however, we were able to subtract the strong background trend. Such an example is given in Fig.2, showing for a DOE observed at 00:45 UT on 16 April 2002 the radiance *L(t)* and velocity *v(t)* curves at a selected position *x*. In this case the oscillation is seen in both the *L(t)* and the *v(t)* curve. The phase shift between velocity and spectral radiance is exactly 90°. This is a strong argument in favour of an axial slow mode standing wave (Wang 2003b). In such a case the maximum deflection, x_0, can be calculated from the period, T, and the maximum velocity, v_0, by Eq. 1.

$$x_0 = v_0\, T / 2\pi \qquad (1)$$

In those cases, where the loop geometry is known from context images, we have an estimate of the actual loop length, l. We found comparable values for x_0 and l thus supporting a model where an initial impulsive trigger excites the first axial compressional eigenmode.

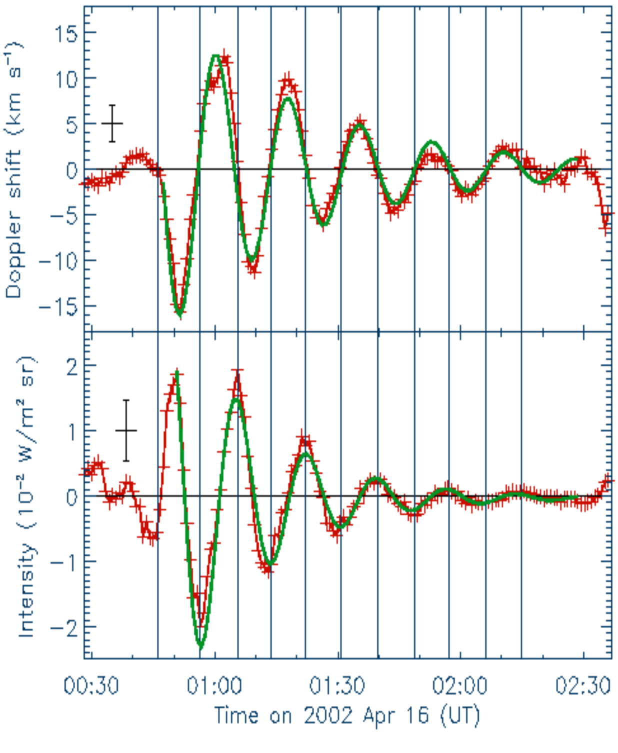

Figure 2. Doppler shift and spectral radiance (background trend removed) of the Fe XIX emission during a DOE. After a sudden start, the loops oscillate about a zero position corresponding to the rest wavelength. The phase shift is exactly 90° (Wang 2003b). This is a strong argument in favour of an axial slow mode standing wave.

2.2 The rule of unidirectionality

40% of the DOEs are multiple events like in the Doppler maps shown in Figs. 1 and 3. It seems as if a follow-up event is just a repetition, identical to its predecessor and it is most remarkable that multiple events show initial Doppler shifts always into the same direction (colour). This is a strong argument for asymmetric energy input and proves that the activity comes from one and only one foot point.

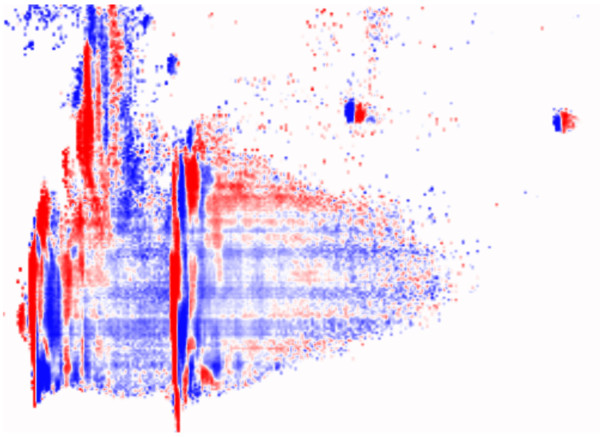

Figure 3. Doppler map of two double events. The loop, which has been hit by a DOE is unchanged and still in place, when another homologeous trigger occurs. It seems to be a common feature that multiple events always start in the same direction, which implies that it is always the same foot point that generates the trigger.

2.3 Diagnostic results

Diagnostic methods have been used in paper II and by Feldman et al. (2003) for several cases to derive the electron density, N_e, the electron temperature, T_e, and the elemental composition of the flaring plasma.

The elemental abundances of low-FIP calcium and iron are enhanced by a factor of 8 – 10 relative to photospheric values.

A typical value of $N_e = 1.2\ 10^{10}$ cm^{-3} has been found as lower limit. This is at least two orders of magnitude higher than in a quiescent coronal loop.

T_e peak values vary between 4.9 10^6 K and 9.0 10^6 K. Similar values have also been reported in papers I & III. The maximum is reached within minutes (cf., Curdt et al., 2004 for details).

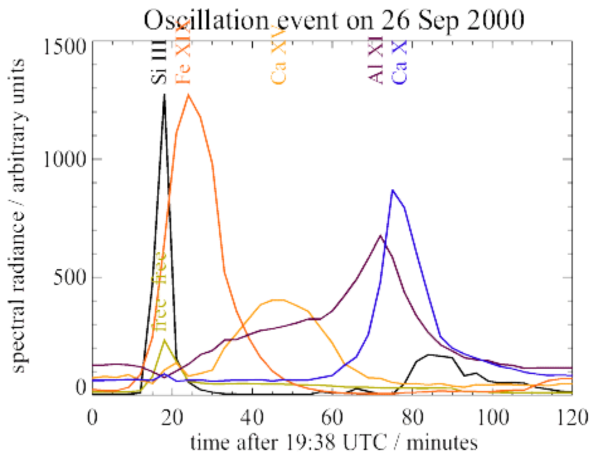

Figure 4. Multi-temperature light curves. During the initial phase emission is seen in all temperatures, peak temperatures are reached within minutes. The cooling lasts over 1 hour and comes to a sudden end. During the cooling the plasma is isothermal, i.e. at one temperature at a given time.

3. DISCUSSION

Here we summarize key arguments described in section 2.

(1) No systematic bulk flow > 2 km/s is observed during DOEs (papers I & II & III).

(2) The foot points behave differently, there is only one active foot point. DOEs have an asymmetric impulsive start from this active foot point.

(3) Abundances are coronal, not photospheric.

(4) Double events can only have identical nature, if nothing has changed.

(5) The cooling takes much longer than expected from radiative losses. This suggests that moderate heating continues for a while.

Each of these arguments is in conflict with the popular model of chromospheric evaporation, which assumes that chromospheric plasma fills the loops and repleni-shes the coronal plasma. Our observations, however, imply that no new material is added to the local plasma.

The observed increase in N_e can only be explained by a substantial decrease in volume. Therefore an in-situ compressive mechanism is required.

4. THE EMPIRICAL MODEL

Following the argumentation of Feldman et al. (2004) we assume that the loop is being compressed by an azimuthal magnetic field, ***H***, which is based on an axial current, ***j***,as denoted in Eq. 2

$$\boldsymbol{j} = c/4\pi \, \nabla \times \boldsymbol{H}. \qquad (2)$$

Such a magnetic field exerts pressure on the coronal plasma and consequently compresses and heats it. In this picture, a discharge front starts suddenly at the foot point with negative polarity and runs with a speed of 50 to 100 km/s along the loop as derived from the initial peak Doppler flow and from the timing in those cases, where both loop legs are imaged by the slit. This impulsive mechanism also imposes a mechanical shock to the elastic system, the starting point of an axial oscillation. A similar mechanism is known as z-pinch and used in tokamaks and high-energy lasers.

Small spikes are often seen in the SXR signal of *GOES* and there is little doubt that DOEs seen by SUMER and *GOES* spikes are identical features. The fact that *GOES* spikes are only observed in 40% of DOE events may have a simple explanation. If the trigger comes from one foot point, then for a limb target there is a 50% chance that the active foot point is behind the limb and not seen by *GOES*. Also, since *GOES* is a disk monitor, spikes may be hidden by disk emission.

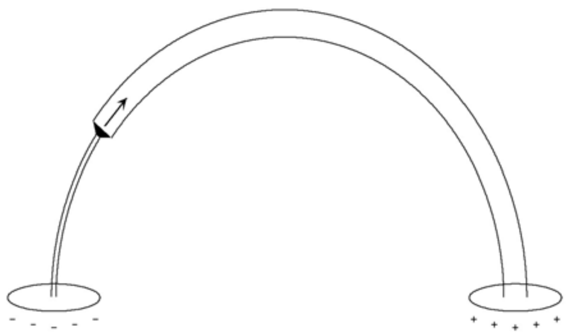

Figure 6. Cartoon of the empirical pinch model. The presented model can explain all observed features, in particular the rule of unidirectionality. It requires a potential difference between the foot points and a dominant polarity of the trigger area. This is also true for the magnetic polarity of the active foot point. More observations are needed to refine and test the presented model.

Likewise the shape of these spikes with a steep in-crease and an almost exponential fall-off resembles the light curves of Fe XIX emission observed by SUMER. The overall behaviour of a DOE resembles somehow to a capacitor which in analogy is continuously charged and which releases the accumulated energy in quasi-periodic discharge events. This pulsating nature is also seen in *GOES* SXR light curves, as reported by Švestka (1994). Since this author does not observe with a spectrometer (cf., arguments in Fig. 2) he does not see the oscillation, and what he denotes as period is in our view the elapsed time between repetitive events.

More recently, Boffetta et al. (1999) have presented the concept of self-organized criticality and established a relation between SXR recurrence time, τ, and SXR power. The probability for minor events peaks at ~1 h, which is consistent with our observations.

Our observations clearly suggest that the energy input is asymmetric and that the trigger starts at one of the foot points of the loop. The energy source may be conversion of magnetic flux by reconnection. Reconnection is a process which produces a new magnetic topology and a new magnetic field orientation. The multiple event argument implies that this does not seem to be the case anywhere along the loop. If the trigger is related to reconnection, this would imply that reconnection takes place at or below the foot point.

According to Švestka (1994) 'electron streams were apparently accelerated at the primary site'. He also assumes that the source regions are at the foot of, or below, large-scale coronal loops. We assume that emerging flux near the active foot point is the driver of DOEs.

5. SUMMARY

Doppler oscillation events (DOE) seem to be a common feature in coronal loop systems. DOEs often trigger slow-mode loop oscillations. Because of the strong damping the oscillation can only be observed at the beginning of the event, when the plasma is at very high temperatures. This may be the reason, why they have not been observed before.

DOEs are impulsive and often recurring flare-like events, although occurring mostly at sub-flare level. Sometimes they generate a free-free continuum, which we interpret as the bremsstrahlung originating from an axial beam of energetic electrons, the 'smoking gun' hinting at the violent nature of this process.

It is widely accepted that flares are avalanches of minor instabilities (Abramenko et al. 2003). The fact that, after a sudden start, we normally observe an undisturbed - although strongly damped - sinusoidal oscillation clearly implies that DOEs are induced by one-and-only-one initial trigger.

We claim that the DOEs presented here as distinct and isolated elements, are those candidates, which can make up a compact flare. There is an obvious advantage in analyzing small-scale events, thus avoiding interference and overlap of the various processes going on in a major event.

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