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IN-SITU HEATING IN ACTIVE REGION LOOPS

W. CURDT[1], E. LANDI[2], T. WANG[1],
and U. FELDMAN[2]

[1] *Max-Planck-Institut für Sonnensystemforschung*,*
37191 Katlenburg-Lindau, Germany
[2] *E.O. Hulburt Center for Space Research, Naval Research Laboratory,*
Washington DC 20375-5320, USA

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Abstract. We report new observational results and insights in the energy release during transient events on sub-flare level in active region coronal loops. Our work is based on multi-temperature observations obtained high above the limb by the SUMER spectrometer on *SOHO*. We conclude that the energy is impulsively injected into the loop system from one and only one foot point. This asymmetric injection 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. Therefore the chromospheric evaporation model is not applicable for this type of events. The electron density, N_e, however, increases by up to two orders of magnitude 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 a in-situ pinch effect, compressing and heating the affected plasma.

Key words: Sun: flare occurrence, energy release, coronal loops

1. Introduction

Loop oscillations in hot active region loops have first been reported by Kliem et al. (2002) and Wang et al. (2003a). Since then, this phenomenon has been studied in great detail and many more hot loop transient events (HLTE) have been observed by the Solar Ultraviolet Measurements of Emitted Radiation (SUMER) spectrometer on *SOHO*. Wang et al. (2003b) have investigated the oscillatory behaviour and demonstrated their importance

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* Formally known as MPI für Aeronomie

for coronal seismology. In addition to the oscillatory behaviour, these events reveal also a more general aspect of coronal loops, namely the energy deposition triggering these events and the observed heating and cooling processes of the emitting plasma involved in such events.

In the range accessible by SUMER spectral windows can be found, which cover the entire range of formation temperatures from 10^4 K to 10^7 K. A very useful window spans from 1110 Å to 1155 Å in first order of diffraction; among others, a transition region line (Si III λ 1113.2, 0.03 MK), coronal lines (Ca X λ 557.8×2, 0.7 MK or Ca XIII λ 1133.8, 2.3 MK)), flare lines (Fe XVII λ 1153.2, 2.9 MK or Fe XIX λ 1118.1, 6.3 MK) and density sensitive line pairs can simultaneously be recorded in one exposure (Curdt et al. 2004a). Being a high-resolution spectrometer, SUMER can discern bulk motion from apparent motion with a resolution of 1 - 2 $\mathrm{km\,s^{-1}}$ and provides diagnostic capabilities. It is therefore, a powerful tool to study the dynamics of HLTEs. Magnetic dipole transitions in highly ionized species, e.g. Fe XIX λ 1118.1 have the same excitation process as soft X-ray (SXR) lines (Feldman 2003). It has been confirmed in many observations that the Fe XIX emission comes from the same high-temperature plasma that emits soft X-rays and can therefore be taken as a SXR proxy. This allows us to compare SUMER results with *YOHKOH*-SXT observations and to perform X-ray spectroscopy. SUMER is probably the most sensitive instrument in orbit to detect this kind of events. Unfortunately, it was not possible to perform coordinated observations together with *YOHKOH*-SXT for an extended amount of time.

In the next section we add one more HLTE observation to the many already described in the literature (Curdt et al. 2003, Wang et al. 2003b, and Feldman et al. 2004). In following sections we summarize properties that appear to be common to the many HLTEs that SUMER observed and present a preliminary model.

2. Observations

2.1. THE INITIAL TRIGGER AND LOOP DYNAMICS

The observations were taken with a fixed slit position pointing some 50" off the solar limb. We have produced time sequences of the radiance of distinct emission lines along the slit (x-t plots) and of the Doppler shift (v-t plots),

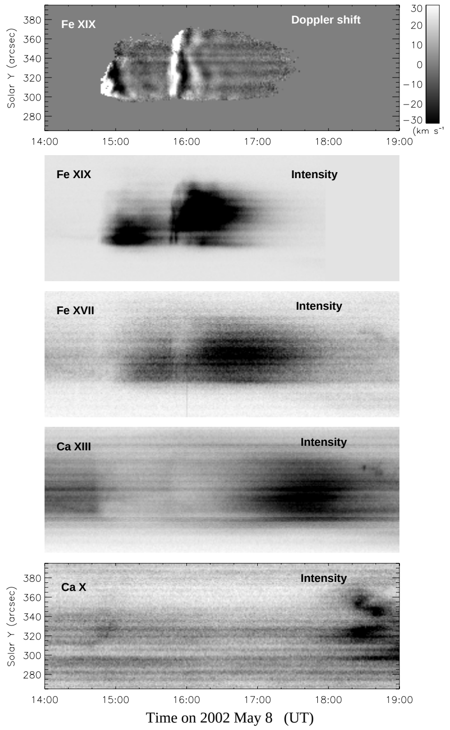

Figure 1: Time sequences of the radiance seen in distinct emission lines along the slit (x - t plots, lower panels) and of the Doppler flow (v - t plot, top panel). The example is a recurring event observed - top to bottom - in the emission of Fe XIX (6.3 MK, both flow and spectral radiance), Fe XVII (2.9 MK), Ca XIII (2.3 MK), and Ca X (0.7 MK) showing the typical HLTE temporal evolution.

as shown in Fig.1. In many cases HLTEs start in a small confined volume as a very short radiance peak seen simultaneously at all wavelengths (c.f., Fig.1 in Curdt et al. 2004b). This feature can, however, only be seen, if the flaring loop contains cold plasma, which does not seem to be the case in the example presented here, where temperatures are already high at the beginning. This initial event is immediately followed by a rapid increase of the temperature up to the Fe XIX formation temperature (6.3 MK). The initial trigger seen in Fe XIX emission also generates large Doppler flows of 100 - 200 $\mathrm{km\,s^{-1}}$, which seems to be the starting point of a strongly damped, but otherwise sinusoidal oscillation (cf., Fig.1). It is well known since many years that the SXR emission in a flare is by several minutes preceded by a short flash of EUV-emission (Rust et al. 1975). Since we exactly observe this behaviour, we assume that also the HLTEs have a flare-like nature. While eruptive flares change the magnetic configuration of coronal loop systems, this does not seem to be the case for HLTEs. They may be comparable to compact flares (e.g., microflares) which are repeatedly triggered, but for some reason do not erupt.

The strongly damped Doppler flow amplitudes normally oscillate in a symmetric manner around the rest wavelength. The lack of background flow $\geq 5\ \mathrm{km\,s^{-1}}$ in most of the cases is not understandable with the chromospheric evaporation model (Shibata 1992). Feldman et al. (2004) have found that the electron density observed during such events increases by two orders of magnitude as compared to quiescent coronal loops.

2.2. Light curves

According to Švestka (1987), a cooling law

$$\dot{T} = 2.9\ 10^4\ T^{-1/2}\ N_e + 2.66\ 10^9\ T^{7/2}\ N_e^{-1} L^{-2} \tag{1}$$

applies to thermalize a heated coronal loop of length L, temperature T and electron density N_e. Since we have simultaneous observations of the light curves in emission lines representative of different temperatures, we can directly measure the cooling of the loop after the occurrence of a HLTE (cf., Fig. 2). The measured cooling time is significantly longer than the cooling time predicted by Equ. 1. Implications of this finding are not discussed here.

2.3. Multiple events

We have noticed that HLTE have a tendency to reoccur within 1 to 2 hours. Approximately 40% of the events are double or multiple events (Wang 2003b, Curdt 2003). This fact is not surprising and fits other observations reported in literature since long (Švestka 1994). There is, however, one important detail, which can only been seen by spectrometers and which is reported here for the first time: During the onset phase of repetitive events the initial Doppler shift is always towards the same direction. If the first

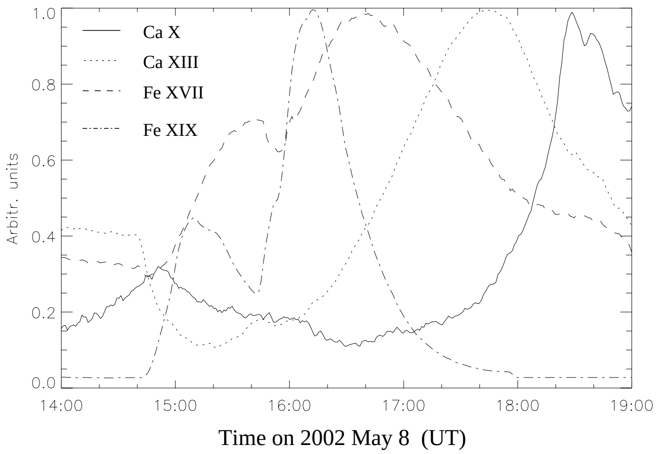

Figure 2: Light curves (spectral radiance integrated along the slit) have been calculated for the event shown in Fig. 1. At 14:40 UTC the Fe XIX emission starts to rise, while dimming occurs in Ca XIII, indicative of the rapid ionization during the trigger. Even the fine structure of this double event is seen with some time delay in cooler lines.

event started with a red (blue) Doppler flow, then the subsequent one will also do so. Until now, we do not have seen any exception to this rule. This is a clear indication for asymmetry and can only be explained through a scenario, where the origin of the energy deposition is located in one and only one foot point of the loop system. Always the same foot point will repeatedly fire and start the activity.

3. Discussion

This strong argument against inflows consequently leads to the concept of in situ heating, as discussed in a recent communication by Feldman et al. (2004). The fact that the second event is co-spatial demonstrates that the magnetic configuration is not affected by this kind of events. One gets the impression that the loop is switched on for a moment, depositing energy into the system. The energy deposition leads to a significant increase of the electron density and at the same time introduces an axial acceleration that causes to loop to oscillate. Kim et al. (1999) reported recurring and homologous X-ray jets observed by SXT. The assumption that this may be a similar phenomenon implies that SXT-jets reflect apparent motion and no bulk motion.

The overall appearance of the events can be compared to switching on an electric device. First there is a short shock-like event going through the loop system. As can be seen from the x - t plots in Fig. 1 and the heating curve in Fig. 2, the passage of this impulsive trigger rapidly changes the ionization equilibrium and the emission measure of the confined plasma. At the same time it introduces high initial bulk Doppler motion. A coronal loop is an elastic system and will consequently start to oscillate. The fact that the oscillation is already sinusoidal after the first stroke tells us that the energy deposition has finished after a very short time, and the attribute 'solitary' may be appropriate for such discrete and isolated heating events. The shock changes the ionization equilibrium towards very high ionization stages within minutes indicative of a rapid temperature increase. This is clearly seen as a dimming of the Ca XIII emission. Fig. 2 depicts, that Ca X and Ca XIII disappear abruptly to make as consequence of the heating room for Fe XVII or Fe XIX (= SXR!) hot emission at the same place and time. The fact that the local plasma is isothermal, i.e. at one temperature at a given time, is another strong argument in favour of in-situ heating and against a scenario, where the existing plasma is being replaced. When in SUMER spectra a small energy packet is sufficient to cause a substantial shift in the fractional ionization equilibrium towards higher temperatures, then we suggest that such an effect may explain the dimming behind propagating waves as seen in EIT and TRACE difference images and reported by Wills-Davey and Thompson (1998).

Our observations and arguments presented above are in conflict with existing loop models. We therefore suggest a new, empirical model as presented on Fig. 3, which seems to be compatible with the observations. We assume that only one foot point is the active foot point. Near this foot point, a flare-like event is triggered and this pulse runs with high velocities of 100 - 200 $\mathrm{km\,s^{-1}}$ along the loop towards the other foot point. Finally and as a by-product, the shocked plasma starts to oscillate. After the impulsive trigger, the electron density has increased significantly. We assume that an axial current $\boldsymbol{j} = c/4\pi\ \nabla\times\boldsymbol{H}$ is responsible for the pulse and its circular magnetic field $\boldsymbol{H}$ is strong enough to compress the plasma. Recently, axial currents have been suggested by Karlický et al. (2004). Such a model

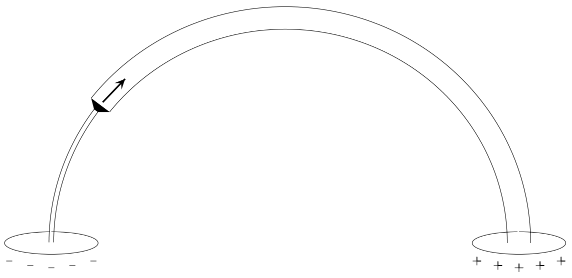

Figure 3: Cartoon of the empirical 'pinch' model used to explain HLTEs

requires a potential difference between the foot points and a predominant polarity of the trigger area, prerequisites which we are unable to confirm with the available observations. The same is true for the magnetic polarity of the active foot point. Any asymmetry could be a strong argument in support of the presented model.

4. Concluding remarks

We have suggested a new, empirical model, which does not seem to be in conflict with any of the observables so far. We will continue to test our model by critical arguments, and since we expect to see a radio signature of HLTEs, we also will include the study of radio data in our future work.

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