THE INTERACTION AND COALESCENCE OF A LOOP-TOP KERNEL WITH A PLASMOID

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Abstract. We study the interaction and coalescence between a downward moving plasmoid and a loop-top source recognized in the 30 Nov 2000 flare. Using observations from Yohkoh, GOES, SOHO and Ondřejov, we performed a multi-wavelength analysis of this event. We found that the interaction and coalescence of the two sources resulted in reconnection of their magnetic fields, particle acceleration and plasma heating. These observations are in agreement with predictions of numerical modelling.

Key words: Sun - corona - flares - X-rays - radio waves

1. Introduction

The most common model of large solar flares is that in which there is an upward moving magnetic rope, below which the reconnecting current sheet, cusp structure and flare loop arcade are formed (e.g. Priest and Forbes, 2000). The observation of plasmoid ejection supports this model (Ohyama and Shibata, 1998). It was found that these plasmoid ejecta are associated with drifting pulsating structures (DPS) observed in the decimetric frequency range (e.g. Khan \textit{et al.}, 2002). Furthermore, there are observations (Karlický, 2004) showing several simultaneous DPSs, which indicate several plasmoids. These observations agree with numerical simulations (Bártá \textit{et al.}, 2007; Karlický and Bártá, 2007), where the interaction of plasmoids are also shown. Some simulations (e.g. Bártá \textit{et al.}, 2007) even show that downward moving plasmoids interact with the flare loop arcade. Using unique observations of the 30 November 2000 flare, this process is studied in detail in this paper.
Figure 1: The upper-left panel: GOES soft X-ray fluxes for the analysed flare. The available observations are marked. The lower-left panel: Temperature for the flare calculated from GOES measurement. Two upper-right panels: The HXR flux of the flare measured by HXT in channels L and M1: total (black lines), impulsive component (after background subtraction; thinner grey line) and smooth component (thicker grey line). The lower-right panel: Integrated radio flux recorded in ONDR in the range 800 – 2000 MHz.

2. Observations and Analysis

In our analysis we utilized observations as follows (see also Figure 1): (1) Images from the Soft X-ray Telescope (SXT) on-board Yohkoh made in three filters: Be119, Al12 and AlMg. However, observations in all three filters are available until 09:06 UT. After that moment, there are only the AlMg images and the SXT diagnostic of the flare can not be performed. (2) The measurement of hard X-ray (HXR) flux from the Hard X-ray Telescope (HXT) on-board Yohkoh. We used HXT light curves and images synthesized with the maximum entropy method (MEM; Sakao, 1994), with modulation patterns computed by Sato et al. (1999). (3) The radio dynamic spectrum
provided by the Ondřejov (ONDR) radiospectrograph for the frequency range from 800 to 2000 MHz. Temporal and frequency resolution is 0.1 s and 4.7 MHz, respectively. (4) Images from the Extreme ultraviolet Imaging Telescope (EIT) on-board SOHO. For the analysed flare, EIT images in 195 Å are available. (5) Solar X-ray light curves from the Space Environment Monitor (SEM) on-board GOES satellites.

The flare occurred at the location N17 W89. It began at 08:55 UT (see Figure 1) and reached the maximum (M1.0) at 09:26 UT. From the GOES data, we calculated the mean temperature of the flare (see Figure 1). We found that the time-profile of $T$ was asymmetric: increase just before maximum was flatter than decrease observed afterwards. This behaviour was similar to the time-profile of HXR (see below).

HXR emission of the flare was recorded by HXT only in channels L and M1 (Figure 1). In both channels, the emission was a superposition of a smooth and impulsive component. The time-profile of the smooth component in channel L was very similar to the temperature time-profile estimated from GOES data. This suggests that the component was emitted by hot plasma. From the ratio $R$ of the fluxes measured in the L and M1 channels, we calculated that the plasma emitting the smooth component was $20 - 30$ MK hot. The impulsive component was weaker than the smooth one. In channel L some periodicity can be noticed. Before 09:04 UT there were five weak, short pulses, which occurred with a period equal to about 1 minute. After that moment, intervals between pulses became longer and less periodic.

The ONDR dynamic spectrum (see Figure 3) shows DPS (e.g. Karlický
Figure 3: The ONDR dynamic spectrum for the analysed flare compared with the predicted frequency of radio emission from the \( S_{DPS} \) (vertical bars). The frequency at each moment was calculated from the minimal and maximal density within the \( S_{DPS} \), assuming the fundamental plasma frequency band.

\textit{et al.}, 2002) with limited frequency bandwidth and with very small global drift of the whole structure (\( \approx 0.4 \) MHz/s). We integrated the observed radio flux over frequency in order to compare it with the HXR impulsive component (see Figure 1). The radio emission was more variable than the impulsive component, nevertheless, three pluses recorded in the L channel at 09:10:10, 09:12:10 and 09:13:20 UT had counterparts in radio flux. This indicates that the impulsive component was emitted by non-thermal electrons in a close location as the radio emission.

Figure 2 presents selected SXT images showing the time evolution of the flare. In the first SXT images, we see the flaring loop with a bright source at the top (LTK - loop-top kernel). The loop had a distinct cusp-shape structure above the LTK. Within the structure there was another source, which moved downwards towards the LTK (MVS - moving source). As time passed, the distance between both sources decreased and finally the MVS merged with the LTK (for LTK, after the merge with the MVS, we use the abbreviation LTK\textsubscript{ac}). The observed interaction and coalescence of the LTK and MVS should be similar to coalescence of two plasmoids. As shown by Karlicky and Bártá (2007), such a process leads to efficient electron acceleration and to radio emission in the form of a pulsating structure with a limited frequency bandwidth. If, in addition, there is a change of density of the coalescing plasmoids, due to e.g. their upward or downward motion, the emitted pulsating structure will show a global frequency drift.

To verify whether the observed DPS might be produced by the LTK-
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Figure 4: The selected temperature maps obtained from the Be/Al diagnostic. The brightness distribution from the AlI2 images is overlaid as isolines.

MVS interaction, we should find the location of the DPS source. From the observed characteristics of the DPS, we can conclude that it was emitted from the region with: (a) a density corresponding to the DPS frequency (plasma waves mechanism) and (b) a nearly constant density during the time of the DPS (09:08.5 - 09:14.2 UT). The main difficulty in finding such an area is the lack of the SXT diagnostic after 09:06 UT. During the time of the DPS we only have the AlMg images. Fortunately, the SXT had higher sensitivity to density variations than to temperature variations, at least in the typical flare temperature range. In the case of the AlMg filter, the signal measured by the SXT (expressed in so-called DN - data number) changed by only a factor of 1.4 in $T$ range 5 - 25 MK (Tsuneta et al., 1991), while the $DN$ is proportional to $N^2$. Using this characteristics, we can roughly estimate from the AlMg images the relative changes of density, or even the absolute value of $N$ by extrapolating the results from the Be/Al diagnostic.

Assuming that all of the observed variations of brightness in the AlMg images were caused by density variations, we analysed the SXT data to find the site from which the DPS could be emitted, i.e., the site where, at least during the radio emission, there was (almost) no significant change of brightness. We found such area located above the LTK$_{ac}$, partially overlapping with the HXR source. Since time-variations of the radio emission were similar to the HXR radiation, we can suppose that the DPS was emitted from the same location as the HXR flux, i.e., from above the LTK$_{ac}$ (see HXT images in Figure 5). Thus, for further analysis, we only took the part of the brightness small-variation site that was in common with the HXR source ($S_{DPS}$; see the second image in Figure 5). To confirm that the $S_{DPS}$
Figure 5: The selected HXT/L images overlaid as contours (thin lines) on corresponding AlMg images. For each HXT/L image, the starting time of integration and its duration are given. The thick contour in the second image shows the area $S_{DPS}$.

was the site where the DPS was produced, we tried to estimate the density in this region and then transform $N$ to radio frequency to compare with the DPS frequency. For each pixel of the $S_{DPS}$, we took the density estimated from the last available pair of Be119/Al12 images (at 09:05:38 UT) and the AlMg brightness at that time and during the DPS, and using the relation $DN \propto N^2$, we calculated the density in these pixels during the DPS time. We then transformed $N$ to plasma frequency and compared the result with the DPS frequency (see Figure 3). The predicted frequency and bandwidth are in good agreement with the DPS characteristics, thus, we can conclude with high probability that the $S_{DPS}$ was the source of the DPS.

The interaction between the LTK and MVS should also be revealed in the thermal structure of the flare, therefore we analysed the temperature distribution on $T$ maps obtained from the Be/Al diagnostic (see Figure 4). In the thermal maps, there were two hot regions on opposite sides of the interacting sources (areas A and B in Figure 4). The areas formed near the brightness depression between the sources, and as time passed they became hotter. Moreover, before the sources coalescence, the highest temperature along the path shown in Figure 4 was observed in this brightness depression. The interaction between the LTK and MVS led to local plasma heating near the interaction site. Heated plasma may then have been ‘squeezed out’ of the site, forming the hot areas A and B.

Only in channel L was the number of counts sufficient to obtain HXT images for the analysed flare (see Figure 5). In all obtained images there is only one HXR source, just above the LTK$_{ac}$. Its position was almost
stable and in good agreement with the position of the hot area B (compare the Figure 4 and Figure 5), thus the HXR source (the smooth component) was probably formed by very hot plasma ‘squeezed out’ of the LTK-MVS interaction site or/and heated by electrons accelerated in the site. Keeping in mind that the radio DPS was also emitted from that location, we can conclude that the impulsive/nonthermal HXR component was also emitted by particles, which, after acceleration, escaped from the LTK-MVS contact site.

3. Discussion and Conclusions

In this paper, we study the unique observations of the 30 November 2000 flare, in which an interaction and coalescence of the loop-top kernel with the plasmoid were recorded. Such a process was predicted by some simulations (e.g. Bártai et al., 2007). Moreover, Karlický and Bártai (2007) showed that interaction and coalescence of two plasmoids leads to effective particle acceleration and plasma heating. The most energetic particles are located in the external parts of the plasmoids and some of them can even escape outside. Although a loop-top kernel can have a different internal magnetic structure than a plasmoid, interaction and coalescence of a loop-top kernel with a plasmoid should be similar to the interaction of two plasmoids. Thus, the increase of X-ray and radio (DPS structure) emissions during the event and the increase of the temperature in the region between the LKT and the MVS are considered here as evidence that the described event was a real interaction process.

The very beginning of the flare was not well observed. However, the formation of the LTK and MVS can be inferred from the EIT images and known numerical simulations (e.g. Bártai et al., 2007). The flare started due to an interaction of two loops in the loop arcade. Between these two loops the current sheet was formed and, due to the tearing-mode instability and loops fixed in the photosphere, the growing flare loop and plasmoid were formed. The tension force in the inverted V-shape magnetic field structure around the plasmoid accelerated the plasmoid (MVS) downwards, and then after some time it interacted with the growing loop, having the X-ray kernel (LTK) at its top. The contact between the sources resulted in reconnection of their magnetic fields, particle acceleration and plasma heating. In the observations these processes manifested themselves as follows: (1) During the LTK-MVS interaction two hot areas A and B developed on opposite
sides of both sources, near the contact site. Moreover, in this site, between the sources, plasma was hotter than inside them. (2) At the end, and just after the sources coalescence, 20 – 30 MK hot plasma appeared in the area B. (3) At the same time nonthermal electrons, which escaped from the LTK-MVS interaction site, emitted impulsive radio and HXR radiation. (4) Periodic HXR pulses were detected during the interaction, and quasi-periodic pulses at the end and after the coalescence.

The location of hot plasma areas observed by the SXT and HXT and the (same) location of the source of impulsive emission in radio and hard X-rays, suggests that they might be formed by electrons, which, after acceleration, escaped from the LTK-MVS interaction site. The coalescence may also have ‘squeezed out’ heated plasma outwards and gave rise to the observed HXR (quasi-)periodic pulses (e.g. Tajima et al., 1982).

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References


