ON THE TOPOLOGY OF MAGNETIC RECONNECTION IN FLARES – CONSTRAINTS FROM MULTIWAVELENGTH OBSERVATIONS

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ABSTRACT

Theoreticians modelling magnetic reconnection are divided in their opinion on the subject whether the coronal loops we observe to brighten in a flare connect the bipoles which are interacting or they represent the reconnected loops. Flare observers can not tell from X-ray images alone whether the flare loops represent pre- or post-reconnection magnetic connectivities. However, multi-wavelength (magnetic field, white-light, H\textalpha, soft- and hard X-ray) observations combined with magnetic modelling are able to provide additional clues and improve our understanding of the topology of magnetic reconnection. I show such analysis of several solar flares ranging from small X-bright point brightenings to M- and X-flares, in order to test how well we understand this intriguing physical process.

Key words: flares, magnetic reconnection

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1. INTRODUCTION

Under the weight of evidence amounting from space observations as well as from theoretical developments, the idea that free magnetic energy released during magnetic reconnection is heating coronal plasmas up to several (tens of) million degrees is more and more generally accepted, though due to open questions some remain skeptical (i.e. Feldman & Seely, 1995; Hudson & Khan, 1996; Feldman, 1996). According to the theory, magnetic reconnection occurs along current sheets, where it accelerates particles creating bi-directional particle beams. The beams directed towards the dense lower layers will get absorbed leading to chromospheric evaporation, which increases the density and temperature, thus the brightness, in the related coronal loops. Such brightening loops are called flare loops. The question, which usually does not get an explicit discussion in theoretical papers, is whether we can definitely say along which field lines would the particles be injected, thus that the consequently brightening loops are the original (pre-reconnection) interacting loops, or they represent the new magnetic connectivities created during the reconnection process?

When reconnection occurs inside a (braided, somewhat chaotic) magnetic loop, there is no way distinguishing between pre- and post-reconnection magnetic connectivities. Thus, in this paper the simple-loop flares (which may or may not exist) will not be discussed, but I will rather focus on the so-called macroscopic reconnection occurring between at least two bipoles. In most of the discussed cases at least one of the bipoles represent emerging flux, thus I also discuss the role of flux emergence in the reconnection process. The scope of such a short paper is limited, thus I will not try to review the extremely rich reconnection literature, just list a few cases, when the multi-wavelength analysis and/or modelling provided some clues to answer this simple but fundamental question.

2. A CLASSICAL MODEL

Heyvaerts, Priest, & Rust (1977) proposed a widely quoted emerging flux mechanism for a small flare. In their model the emerging flux impacts on overlying open (or far-reaching) magnetic field lines (Figure 1). The particles accelerated at their interface, in the reconnection current sheet, are injected into the open field lines, leading to Type-III burst and jet formation, as well as along the field lines of the emerging flux, creating H\textalpha footpoint brightenings and heating up the emerging loop itself. When one looks at their figure more carefully we can notice that magnetic reconnection plays a very limited role in this model: the new (reconnected) field line connectivities appear only in the pre-flare heating phase (Figure 1a).

During the last two decades and mainly since Yokoh has been in operation, this classical picture has been transformed and the new observations supported by 2-D simulations clearly show that the heated loops are in fact the reconnected loops (e.g. Shibata et al, 1996 and references therein; also Figure 2).
3. SMM HXIS RESULTS

Another classical paper, which has important implications to the main question posed here, was a synthesis of more than twenty flares observed with the HXIS instrument on board of SMM (Machado et al., 1988). In their paper the X-ray data was supplemented with Marshall vector magnetograms. The picture which emerged from their analysis was that magnetic reconnection just serves as a trigger for the impulsive energy release, but the main energy release is occurring inside the interacting loops. They propose that the flare loop brightness was proportional to the internal free magnetic energy content of the interacting loops (Figure 3). Note that the resolution of SMM HXIS was 8 arcsec/pixel in the small and 32 arcsec/pixel in the large FOV, so it was not easy to identify the loops. However, when one looks at the magnetograms published in their paper, one can realize that the X-ray brightenings they show, in fact, appeared between the opposite polarity spots of a large older and a small younger bipole, thus they had to be formed by magnetic reconnection!

4. A CLEAR CASE FOR RECONNECTED LOOPS: LONG-DURATION EVENTS

Long Duration Events (LDEs) are generally associated with an arcade of loops called post-flare loops which are observed at different temperatures ranging from $10^4$ to more than $10^6$ K. These post-flare loops expand, lasting up to 10 hours (e.g., Brueck 1964). The velocity of ascent of these loops decreases with time from 10-20 km s$^{-1}$ to less than 1 km s$^{-1}$ (e.g., Bray et al. 1991 and references therein). This process of expansion is believed to be due to ongoing magnetic reconnection and a triangle of hot plasma observed in SXR and HXR at the top of the SXR hot loops is also indicative of a reconnection process (e.g., Forbes & Malherbe 1986; Forbes & Acton, 1996,
Harra-Murnion et al., 1998). The newly formed hot loops cool down to appear eventually as Hα loops (Svestka et al., 1987; Schmieder et al., 1996; van Driel-Gesztelyi et al., 1997).

Post-flare loops clearly represent reconnected loops, i.e., post-reconnection magnetic connectivities. This is supported by:

- Cusped geometry, which appears in 2-D theoretical reconnection models
- Hotter loops/high temperature (HXT L channel) areas above the X-ray loops
- X-ray-Hα relations show fast cooling of loops, therefore the expanding X-ray structure is not one long-lived loop, but a series of new loops forming continuously at an ever-increasing altitude.

5. XBP FLARES MODELLLED IN 3-D

Ground-based optical observations coordinated with Yohkoh/SXT of an old, disintegrating bipolar active region (NOAA 7493) provided a multiwavelength (magnetic fields, Hα and X-rays) data set for the study of a flaring X-ray bright point (XBP) of about 16 hours lifetime (van Driel-Gesztelyi et al., 1996). The XBP was related to the emergence of a minor bipole of about 10^20 Mx. The XBP was tiny loop-like rather than point-like, and it linked the emerging negative polarity to a pre-existing positive polarity facular region. Another, long and faint X-ray loop (FXL in Figure 4) appeared to brighten during the XBP flares. Extrapolating the photospheric magnetic field in a linear force-free approximation, Mandrini et al. (1996) found good agreement with the observations of the emerging flux (Hα arch filament system) and the soft X-ray loops (both the XBP and FXL). The photospheric footpoints of their field lines were found on both sides of the computed quasi-separatrix layers (QLSs), as expected from the 3-D reconnection model (see Figure 4). Mandrini et al. (1996) show that the X-ray flare loops (the XBP and FXL) were created and heated by magnetic reconnection between field lines of the new bipole and the pre-existing plage fields, and that the reconnection was induced by the motion of one of the new magnetic elements towards the old plage with a velocity of 0.2 km s^{-1}. Note, that Parnell, Priest & Golub (1994), who were supposing a similar approaching motion between opposite polarity magnetic elements, have also shown that XBP can be interpreted as tiny reconnected magnetic loops. Mandrini et al. (1996) followed the brightness evolution of the XBP during 16 hours and combined it with a computation of the thickness of the related QLSs. They found that when the thickness of the QLSs decreased, the XBP became brighter, due to increasing reconnection rate, while the decreasing brightness coincided with a growing thickness of the QLSs, which apparently became too large to allow significant magnetic energy release. The above multiwavelength observations combined with 3-D modelling provide a very strong case and arguments for the flare loops being reconnected loops. Similar conclusion was reached by Schmieder et al. (1997) for sub-flares.

6. MULTI-WAVELENGTH FLARE STUDY IN A DELTA-REGION

Nitta, van Driel-Gesztelyi & Leka (1999) analysed seven flares in an fast-growing emerging flux region (EFR) which appeared in the trailing plage area of AR 7920. For each flare spots or magnetic elements were identified (Leka et al., 1994) that were connected by the flare loops seen in soft X-ray images. For a better association of the soft X-ray loops with the photospheric magnetic field, hard X-ray and Hα images were also used, since they indicate the footpoints of SXR loops. This truly multi-wavelength analysis of seven flares shows that most of the observed flare loops were reconnected loops, but within
the uncertainty of the resolution some of the brightest flare loops might correspond to one of the interacting loops, normally to an emerging bipole (Figures 5 & 6).

7. CONCLUSIONS

In flare loop studies and some models in the seventies and eighties the fact that during magnetic reconnection new magnetic loops are created which may get heated by the magnetic energy released during the reconnection process, did not appear to be prominent. According to the classical emerging flux mechanism for flares (Heyvaerts, Priest & Rust, 1977) the particles and heat are injected along the interacting loops, thus the emerging flux loop will appear as flare loop. Also, in the seminal paper by Machado et al (1988) on SMM HXIS flares reconnection was seen as a mere trigger, which releases free energy inside the interacting loops. Thus, according to their results the interacting loops become flare loops, and their brightness is proportional to their free energy content. The new reconnected magnetic loops were not even considered in the above papers.

However, in the early nineties, especially after the launch of Yohkoh, there were more and more multiwavelength analyses combined with modelling which indicated that in flares, in fact, the reconnected loops become heated instead of the interacting loops (e.g. Démoulin et al, 1993, 1994; Shibata et al 1996, Forbes & Acton 1996, van Driel-Gesztelyi et al 1996, Mandrini et al, 1996). However, a recent multiwavelength flare study by Nitta, van Driel-Gesztelyi & Leka (1999) showed that not only reconnected loops, but also some of the interacting loops can become bright in the flares, especially emerging bipoles, which had the strongest hard-x-ray sources at their footpoints in their observations. However, the region studied, AR 7260, was a multiple δ-region with complicated magnetic topology, and the pre- and post-flare connectivities were not easy to define. Analysing flare topology in simple magnetic configurations like the XBP (Mandrini et al, 1996) can give much clearer results. However, we can not exclude the possibility that in flares the interacting loops, thus pre-flare connectivities may indeed become bright. However, it is noteworthy that Leka et al. (1996) found that in AR 7260 the new flux emerged with inherent currents, thus this result may be specific to twisted flux emergence.

We may conclude that in most flares the coronal flare loops seem to correspond to reconnected (newly formed) magnetic connectivities, though at least in some cases, when the interacting loops are highly non-potential, the interacting loops may brighten besides the reconnected loops.

ACKNOWLEDGEMENTS

The author wishes to thank the organisers of the conference for local financial support and acknowledges the Hungarian Government grants OTKA T-026165 and ARK 97-58-2/2.

REFERENCES


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Figure 5. Flare of 16 August 1992 13:54 UT. (a)-(e): Soft X-ray images (in negative) taken before, during and after the flare. (f): Hard X-ray (14–23 keV) image in contours (the levels are 10%, 30%, 50%, and 85% of the peak), superimposed on the SXT image replicated from (b). (g)-(i): White-light image showing (in (h)) sunspot identifications.

(i) Magnetogram. The main flare loop appears to connect P10 and F10, which coincide with the double hard X-ray source in panel (f). P10 and F10 represent a bipole which emerged 2-3 hours before the flare. The soft X-ray image shows that flare emission extends to older spots such as F2 (originally connected with P2). Fc (without an obvious partner) and possibly F4 (originally connected with P4), indicating that multiple loops were involved in the flare. However, these secondary loops are not clearly identified, because they are intrinsically diffuse or their footpoints are not widely separated. In fact, this flare could easily be considered to be a simple-loop flare without close examination of the images. Note that the brightest flare loop appears to coincide with an emerging bipole. After Nitta, van Driel-Gesztelyi & Leka, (1999).

Figure 6. Flare of 20 August 1992 03:51 UT. (a)–(c): Soft X-ray images taken about 40 minutes before the flare, one minute after the hard X-ray peak and in the decay. (d): Hard X-ray (25–33 keV) image in contours superimposed on the SXT image replicated (b). (e–f): White-light image showing in (f) sunspot identifications. (g) Magnetogram. (h)–(i): Hα images taken around the hard X-ray peak and in the decay. In this flare the brightest soft X-ray loop connects F50 and the southwestern part of P48. The hard X-ray double sources also coincide with these two locations. Note that it is likely that P48 and F50 formed an emerging bipole (Leka et al., 1994). After Nitta, van Driel-Gesztelyi & Leka, (1999).