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LONG DURATION EVENTS IN MAGNETIC ARCADES AND LARGE LOOPS

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Abstract

A number of long duration flares, with decay time between 1 and 17 hours, have been analysed using the Yohkoh Soft X-ray Telescope images and spectra from the Bragg Crystal Spectrometer. X-ray images suggest that these events typically occur in the following magnetic field configurations: magnetic arcade, expanding arch, or large loops triggered and heated up by a low-lying, compact, impulsive flare located below these high loops. A continued energy release is observed during decay of these events. Single loop flare models should not be indiscriminately applied to analysis of thermodynamics of these flares due to their more complex structure and restructuring of the magnetic field, and often increasing height.

1. Introduction

Long duration flares, decaying for between one and 20 hours, are typically strong events, of GOES class M and X, and occupying a large area - it is therefore possible to study morphology of these events in X-ray emission in great detail. This is an important class of events, allowing us to investigate the energy release, its location within the flare and transport. The main purpose of this paper is to study the X-ray images and spectra of the long duration flares to classify their magnetic field configuration, explain the reasons for the long decay time, and to assess whether a simple, single flare loop model is appropriate for the analysis of thermodynamics of these flares.

We have analysed several long duration flares with the decay time over one hour, including both disk and limb flares, and we will show that there are three main types of configuration leading to a prolonged decay phase: magnetic arcades with X-ray bright filament, expanding arch and large loops heated following a compact, impulsive flare. Knowledge of the magnetic field topology is relevant to study of flare thermodynamics through a comparison with numerical flare models. When only spectroscopic data are available, an assumption is often made that a flare is represented by a single loop and characteristics of this loop are inferred based on this premise. We show that in case of long duration flares more than one magnetic loop structure is involved and the morphology is more complex.

The Yohkoh instruments used here are the Bragg Crystal Spectrometer (BCS, Culhane et al. 1991) and the Soft X-ray Telescope (SXT, Tsuneta et al. 1991). We use SXT images in a Berylium, Al12 and thin aluminum filters. In addition, GOES lightcurves in the 1–8 Å band provide information about the flare duration.

2. Observations

In this section we present characteristics of several flares illustrating different topologies responsible for long duration flares, as seen in SXT images. Where the BCS observations are also available, we calculate the electron temperature and the total emission measure from fitting the Fe XXV and Ca XIX spectra, using a method given by Fludra et al. (1989, 1993).

26 October 1991, 20:46 UT. X1.7, S09 E20, AR 6891. Rise time: 20 minutes, peak: 7 minutes, decay time: 2 hours 20 minutes.
Weak X-ray emitting filament (~2 arc min long). Two side loops dominate the emission (visible length 70 arc seconds), with the most intense emission coming from the intersection of one of these loops with the filament. A gradual restructuring of the magnetic field is seen.

29 October 1991, 19:12 UT. M4.7, S10 W23, AR 6891. Rise: 18 minutes, peak: nearly constant for 10 minutes, decay: 60 minutes.
Long (2 arc min), curved X-ray emitting filament, with brightness increasing towards one end. A perpendicular loop (1 arc min long) is seen at the brightest end of the filament.
BCS Fe XXV temperature is nearly constant at 18.5 – 17.5 MK for 35 minutes (19:20 - 19:54 UT), while the emission measure decreases by a factor seven from 1.5×10^{49} to 2×10^{48} cm^{-3}.

8 May 1992, 15:45 UT. M7.4, S26 E08, AR 7158. Rise: 10 minutes, peak: very flat for 25 minutes, decay: steeper for 30 minutes, very slow for over 3 hours.
Long X-ray filament (2.5 arc min), three loops on one side (70 – 40 arc sec), the brightest emission coming from the intersection of the side loops with the filament. Later one of the side loops dominates the soft X-ray emission.

2 November 1992, 03:07 UT. X9, WS limb. Rise: 30 minutes, peak: 10-15 minutes, decay: 17 hours.
The height of the brightest region increases with time: $H = 28'' = 21000$ km at 03:05 UT; $43'' = 32500$ km at 04:42 UT; $64'' = 48000$ km at 05:22 UT (a bright X-ray filament with length of $98'' = 75000$ km is seen along the top of a magnetic arcade, and it begins to fragment after 05:20 UT); $H = 74'' = 55500$ km at 09:30 UT (round, extended X-ray emitting region seen at the top of the loops, at one end of the filament); $H = 86'' = 64500$ km at 18:35 UT (large loop).
BCS data are available only after 09:30 UT (plus a few earlier spectra near 08:37). Between 09:30 – 10:15 UT the Fe XXV temperature is 15×10^6 K, $EM = 2.5 - 2 \times 10^{48}$ cm^{-3}. The Ca XIX temperature is 12×10^6 K, $EM = 1.4 \times 10^{49}$ cm^{-3}. At about 19:00 UT, the Ca XIX temperature is 9×10^6 K, $EM = 2 \times 10^{48}$ cm^{-3}.

5 November 1992, 06:21 UT. M2.0, WS limb. This event begins as a compact, low located flare with a fast rise (one minute) and decay (four minutes). High loops above the flare are heated up and then decay for 90 minutes. At 07:47 UT the loop height is $H = 50'' = 37500$ km. The height of the brightest point increases to 75"=56000 km after 08:20 UT, when the GOES 1 – 8 Å flux returns to the pre-flare level.
BCS Fe XXV temperature is 19×10^6 K in the impulsive phase, then decreases to 15×10^6 K, and

stays constant after the compact flare ended. The Fe XXV emission measure is $EM = 1.4 \times 10^{49}$ cm^{-3} at flare peak, then it decreases to 3.5×10^{48} at 06:25 UT, and to 1×10^{48} after 06:32 UT. The Ca XIX temperature is 14×10^6 K in the rise phase, then stays constant at $12 - 11 \times 10^6$ K when the emission from the high loops dominates in the decay. The Ca XIX emission measure decreases from 3.5×10^{49} to 5×10^{48} cm^{-3} and stays constant after 06:28 UT.

17 February 1993, 10:39 UT. M6, SW limb. This event begins as a compact, low-lying flare. Rise: three minutes, decay: 25 minutes, the flare loop increases height to $15'' = 11250$ km. Large loops located above the flare heat up almost simultaneously with the flare, and decay for three hours. A large area of emission, increasing its height: $H = 88'' = 66000$ km at 11:38 UT; $112'' - 124'' = 84000 - 93000$ km at 12:12 UT; $H = 130'' = 97500$ km at 13:14 UT.
The BCS Fe XXV temperature is $20 - 22 \times 10^6$ K in the rise phase. The high loops seen in the decay (12:12–12:22 UT) are much cooler: Ca XIX $Te = 8 - 7.5 \times 10^6$ K, $EM = 8 - 6 \times 10^{48}$ cm^{-3}; S XV $Te = 7 - 6.5 \times 10^6$ K, $EM = 1.3 - 1.0 \times 10^{49}$ cm^{-3}.

21 February 1992, 03:00 UT. M3.2, NE limb. Rise: about 20 minutes, peak: one hour, decay: over four hours. The SXT images of this flare have been discussed by Tsuneta et al. (1992). This is an expanding arch, with height increasing from $H = 61'' = 45000$ km at 03:10 UT (the brightest emission extends in height from $60''$ to $120'' = 45000 - 90000$ km at 04:22 UT) to $H = 110'' = 82500$ km (more compact source) at 06:00 UT. Results of fitting the BCS spectra are given in Table 1.

Table 1. BCS results for the 21 February 1992 flare

Time (UT)	Fe XXV Te (K)	EM (cm^{-3})	Ca XIX Te (K)	EM (cm^{-3})
rise phase	18×10^6	4×10^{48}	13×10^6	2.3×10^{49}
04:06 – 05:20	$15 - 14 \times 10^6$	$5 - 2 \times 10^{48}$	$10.5 - 9.5 \times 10^6$	$6 - 4 \times 10^{49}$
05:45 – 06:30	13×10^6	5×10^{47}	9×10^6	$2 - 1.5 \times 10^{49}$

3. Results and Conclusions

SXT images suggest that the long duration flares typically occur in the following different types of magnetic field configuration:
(1) – magnetic arcades, sometimes with a long, X-ray emitting filament along the top of the arcade, with length up to 2 arc minutes. The filament's height above the limb often increases towards one end. These flares have a long rise phase ($>$ 15 minutes), often flat peak of the lightcurve for 10-30 minutes, and a long decay (1–4 hours). Example: 26 October 1991, 20:40 UT; 29 October 1991, 19:00 UT; 8 May 1992, 15:20 UT.
(2) – high loops, forming part of the arcade, expanding due to a partial eruption of a hot ($\sim 10^7$ K) magnetic flux rope at one end. It could be a version of (1). Example: 2 November 1992, 03:07 UT. This case (and possibly some flares of the type 1 above) appear to agree with a scenario proposed by Hirayama (1991).
(3) – expanding arch, with accompanying reconnection. The top reaches altitude over 30 000 km. Example: 21 February 1992, 03:10 UT (Tsuneta et al. 1992).
(4) – large loops (altitude 30 000 - 100 000 km), heated up following a low-lying, compact flare located below these high loops. The impulsive event has a short rise ($<$ 5 min) and decay ($<$ 20 min), but the nearly simultaneously heated high loops cool down for over one hour. Example: 5 November 1992, 06:20 UT; 17 February 1993, 10:35 UT. This class of flares requires a particular care during the analysis, as the BCS or GOES lightcurves alone do not reveal that the emission comes from two spatially different locations: a compact flare in the impulsive phase and high loops above in the decay.

In all these events a continued energy release takes place, as evidenced by a nearly constant or very slowly decreasing temperatures from BCS spectra. For example, the Fe XXV temperature in the 29 October 1992 flare was constant for 35 minutes, while the emission measure decreased by a factor of seven. This shows that while the volume where the energy release took place decreased with time, the heating continued in the smaller core region. The 29 October 1992 flare had the fastest decay time among the flares presented here. The factor seven decrease of the emission measure at a *constant* average temperature from Fe XXV spectra suggests that the emission was coming from many magnetic loops, most of which had a very short length, ensuring a fast cooling time by conduction, while the remaining loops were continuously heated. A scenario where a low-lying, long and hot magnetic flux rope is tied down by a large number of small loops is possible here.

An extreme case of prolonged energy release is seen in the 2 November 1992 flare, where the Ca XIX temperature decreased only by 3 million K over nine hours.

The BCS results also show that the spatial temperature distribution is very non-uniform across the emitting region. The most extreme example is the decay of the 21 February 1992 flare, where the emission measure derived from the Fe XXV spectra at 05:45 – 06:30 UT was 30 times smaller than the emission measure derived from the Ca XIX spectra (the typical ratio of these emission measures is a factor of four to seven). This indicates that the differential emission measure falls off very steeply with temperature and shows that a small region of hotter (13×10^6 K) plasma is surrounded by an extended region of cooler (9×10^6 K) plasma.

All these events involve a complex magnetic field configuration which undergoes restructuring with time. Four of them are limb flares and they all show increasing height of the brightest region above the limb during decay. The energy release region is mostly confined at the top of the structures and appears to be poorly connected to the chromosphere. A single loop flare models do not directly apply to analysis of thermodynamics of these long duration flares.

To fully understand the mechanism of these flares, a number of topics remain to be investigated: a detailed morphology in Hα, location and temporal behaviour of hard X-ray emission, the confinement of hot plasma at the tops of the magnetic structures (Jakimiec 1990), and association of these events with Coronal Mass Ejections.

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