MULTI-FREQUENCY OBSERVATIONS OF
THE FEBRUARY 6, 1992 FLARE

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Abstract. Observations of the two-ribbon flare of February 6, 1992 which occurred in
the active region NOAA 7042 involving a sigmoidal soft X-ray loop pattern, are
described. YOHKOH SXT images, Hα filtergrams and coronal magnetic field
extrapolations are used to reveal details of the preflare coronal magnetic field
configuration. The development of the flare in SXR, Hα and dm-m radio wavelength
range is followed in detail to disclose the basic stages of the energy release process.

Key words: solar flares, energy release, sigmoid

1. Introduction

Observations of the solar corona with the soft X-ray telescope (SXT) on-
board YOHKOH revealed that solar active regions are sometimes overlaid
by magnetoplasma structures showing a “sigmoid” shaped loop pattern
(Acton \textit{et al.}, 1992; Rust, 1996). Several papers focused on the analysis
of the possible magnetic field evolution and current distribution around
sigmoid-shaped patterns (e.g. Sakurai \textit{et al.}, 1992; Sakurai 1993; Pevtsov,
V. RUŽĐIJAČ ET AL.: MULTI-FREQUENCY OBSERVATIONS OF A FLARE

Canfield and Zirin, 1996; Démoulin, Priest and Lonie, 1996; Pevtsov, Canfield and McClymont, 1997; Canfield, Hudson and McKenzie, 1999).

In this paper we study Hα filtergrams, X-ray and radio observations, magnetograms and extrapolated field line maps of one flare event characterized by a sigmoidal preflare soft X-ray pattern (further on S-pattern). The morphology and evolution of the loop system will be investigated and the energy release signatures analysed.

The studied event occurred in NOAA 7042 on February 6, 1992 at the location S13 W09. A two-ribbon 2B/M4.4 flare began at 09:28 UT, and attained the Hα maximum at about 10:05 UT. Various aspects of the event were studied by Sakurai et al. (1992), Sakurai (1993) and Aurass et al. (1999).

2. The Data

The event is studied using following data:
- Hα image sequences with a four minutes time cadence (SO Kanzelhöhe);
- YOHKOH SXT observations (gap between 09:48 UT and 13:37 UT);
- magnetic field maps (Kitt Peak Obs. and Okayama Obs.);
- sunspot magnetic field strengths (Solnechnye Dannye Byulleten – SDB);
- GOES soft X-ray flux curves (Goddard SDAC);
- hard X-ray (HXR) curves till 10:22 UT by BATSE/CGRO (Goddard SDAC) and YOHKOH HXR detectors;
- single frequency decimetric/metric radio flux records (AI Potsdam 40–800 MHz);
- radio dynamic spectrum (Obs. Paris-Meudon 100–500 MHz (courtesy M. Poquérusse).

In Figure 1 the SXT full disc image is exhibited showing that the preflare S-pattern has a normal orientation according to the hemispheric segregation rule (Rust, 1996). In Figure 2, a composite drawing of the active region is presented. The Hα flare and the dominant soft X-ray loops (further on SXR loops) are sketched on the magnetogram showing the main features of the longitudinal photospheric field.
Fig. 1. The preflare full disc YOHKOH SXT Al-Mg image taken at 01:23 UT.

Fig. 2. Composite drawing showing the flare morphology. Thin full (dashed) lines are north (south) polarity photospheric 20 and 160 G isogauss contours. Black areas – sunspots; gray areas – the flare ribbons at 09:47 UT and various Hα bright patches (HB) whose timing can be found in the text; thick gray lines represent the flare ribbon silhouettes at 11:30 UT; thick black lines – the SXR loops.
Fig. 3. Kitt Peak longitudinal magnetogram measured on February 5, 1992 (17:13 UT). Superposed: a) force-free field extrapolation ($\alpha = +0.016 \text{ Mm}^{-1}$); b) potential field extrapolation ($\alpha=0$).

3. Magnetic Field Topology

3.1. Photospheric Magnetic Field

The Kitt Peak magnetogram measured on February 5, 1992 (Figure 3), exposes a rather complex structure of the photospheric magnetic field in AR NOAA 7042 (further on AR), revealing a number of opposite polarity islands and intrusions in a general bipolar pattern. However, the main part of the Hα flare covered mainly an area characterized by a rather simple bipolar magnetic field configuration dominated by several large spots of the leading northern polarity and a number of small spots grouped in a horse-shoe pattern (SH in Figure 2) within the following southern polarity region. At the beginning of the flare the ribbons were lying at the 320 G isogauss level, and during the evolution of the flare the maximum isogauss level covered by the ribbons was 640 G on the Kitt Peak magnetogram. During the flare, the Hα ribbons protruded over one of the large leading polarity spots (N2 in Figure 2) and the main following polarity spot S1. According to the sunspot magnetic field measurements reported in the SDB for February 5, 6 and 7, 1992, the magnetic field of the sunspots in the AR
was fastly decaying: the magnetic filed strengths changed from February 5 to February 7, 1992 from 0.25 T to 0.18 T in N2, and from 0.22 T to 0.15 T in S2, respectively.

The highest measured value of the gradient of the line of sight magnetic field component at the magnetic inversion line amounted to about 100 G/Mm. The overall magnetic field gradient of the whole AR could be estimated as about \((B_N - B_S)/d = 20 \text{ - } 30 \text{ G/Mm}\). Here, \(B_N\) and \(B_S\) are the highest values of the longitudinal magnetic field measured on the Kitt Peak magnetograms in the leading and the following polarity regions, respectively, and \(d\) is the corresponding distance. The gradient between the inversion line and the ribbons (i.e., in the direction of the lateral expansion of ribbon fronts) was about 10 G/Mm.

Two large sunspots of northern magnetic polarity in the leading part of the AR were involved in the flaring process (denoted as N1 and N2 in Figure 2). The H\(\alpha\) brightening HB\(_{N1}\) was attached to the sunspot N1 from the very beginning of the flare, and the northern polarity flare ribbon (NPFR) protruded over the umbra of the sunspot N2 at 09:55 UT. Similarly, the southern polarity flare ribbon (SPFR) approached the horse-shoe grouped spots of the following polarity (SH in Figure 2) slowing down the SPFR advancement. The SPFR protruded over the main sunspot in the pattern S1 at 09:56 UT. The magnetic field concentration S2 located in the area of the following polarity at the end of the horse shoe-pattern, is of special importance, as it was the footpoint of the largest visible SXR S-shaped loop (LS in Figure 2) seen also as a weak H\(\alpha\) brightening denoted as HB\(_{S2}\).

The H\(\alpha\) flare ribbons formed at a rather large distance from the magnetic inversion line: the centre of the NPFR was located 40 Mm from the inversion line and the SPFR was at a distance of 30 Mm. The ribbons exposed a comparatively small shear: the line connecting the centres of the NPFR and the SPFR was inclined to the neutral line at an angle of about 45°.

The preflare electric currents inferred from the Okayama vector magnetograms taken around 01:00 UT on February 6, were concentrated in the region of the spot N1 in the leading polarity area, and in the region of the spot S2 in the area of the following polarity (see Sakurai, 1993). Electric
current concentrations can also be recognized at the remote sites where the Hα brightenings HB_{E1,2,3} and HB_{W} appeared (compare Figure 2 with Figure 1 in Sakurai, 1993). The directions of the magnetic field vectors and the electric currents at N1 and S2 have the same orientation as the legs of the large S-shaped soft X-ray loop LS at their footpoints in the magnetic field concentrations associated with N1 and S2. The magnetogram taken after the flare (at about 01:00 UT on February 7) reveals that the transverse component of the magnetic field and the electric current decreased in the area of N1 and S2 with respect to the preflare situation (Sakurai, 1993).

3.2. Coronal magnetic field topology inferred from SXT images

The SXT preflare images taken at about 03:00 UT reveal a sheared and very active soft X-ray loop system connecting the leading and the following polarity regions over the inversion line (Figures 4a-4c). Apart from this sheared loop system, several S-shaped loops can be seen, with the southern polarity legs converging towards the region of S2, while the northern polarity legs of the S-shaped loops were anchored in the region of the spot N1.

The loop system was gradually transforming towards an unstable preflare configuration (Figures 4a-4d). SXT images taken at the beginning of the powerful nonthermal energy release phase (Figure 4e) reveal an overall S-shaped pattern dominated by the loop LS. The other two loops in the central part of the system (LS1, LS2) were also S-shaped. The two northern loops of the system (L3, L4) were apparently unkinked and were less sheared than in the preflare images. The northern polarity legs of all loops were anchored in the region of N1 coinciding with the Hα emission patch HB_{N1}. The southern polarity footpoints of the loops were located along the southern polarity Hα flare ribbon, except the footpoint of the dominant S-shaped loop LS which was located at the remote southern polarity field concentration S2, coinciding with the Hα brightening HB_{S2}. The northern polarity legs of all loops involved in the energy release process (including L3 and L4) overlapped in the projection, having the footpoint in the region of N1 (Figure 2). The loop system revealed by SXT after the flare (13:40 UT) was fully relaxed, crossing the magnetic inversion line at approximately 90°.
The distance between the footpoints of the loop LS (i.e., the distance from the spot N1 and the field concentration at S2) was 160 Mm, whereas the footpoint separations of the loops LS1 and LS2 were 135 Mm and 100 Mm, respectively. The total projected length of the S-pattern LS was almost 450 Mm.

Fig. 4. Full resolution SXT images. a) – d) The formation of the unstable preflare configuration. e) The onset of the powerful nonthermal energy release. f) The relaxed postflare loop system.

3.3. Extrapolation of the Photospheric Magnetic Field

The linear force free magnetic field extrapolation ($\alpha = +0.016 \text{ Mm}^{-1}$) reproduces the preflare situation well (Figure 3a). The field lines corresponding to the loops LS, LS1, LS2, L3 and L4 can be identified. The strongly kinked field line connecting N1 and the distant region of the following polarity, where the dislocated Hα bright kernels HB_{E1} and HB_{E2} were situated, can also be notified. According to the extrapolation shown in Figure 3b the SXT loop pattern LS may be a superposition of two loops: the one connecting N1 and S2, and the other one protruding from N1 to HB_{E1,2}. The postflare soft X-ray patterns are reproduced well by the configuration obtained using the potential field extrapolation (Figure 3b).
Fig. 5. The Hα filtergrams (SO Kanzelhöhe). N1, N2 and S1 – the dominant spots; HB – the dominant Hα remote kernel (denoted as HBE in the text; OPI – opposite polarity islands; PFL – postflare loops; FA, FB and FC – filaments.

Fig. 6. a) The HXR flux; the sensitivity is reduced between 10:02 and 10:16 UT. The times of contacts of Hα ribbons with N1 and S1 are denoted by arrows. b) The lateral expansion of the south polarity ribbon front. \( \Delta t=0 \) corresponds to 09:42:40 UT.
4. Flare Evolution

The selected set of Hα filtergrams is shown in Figure 5. The HXR flux (YOHKOH channel 14-23 keV) and the lateral expansion of Hα flare ribbons are shown in Figure 6.

The flare evolution can be divided in several phases:

i) preflare phase before 09:30 UT
ii) precursor phase 09:30 – 09:45 UT
iii) powerful nonthermal energy release 09:45 – 10:15 UT
iv) prolonged nonthermal energy release 10:15 – 10:50 UT
v) late phase after 10:50 UT
vi) large scale magnetic field restructuration

4.1. Preflare Phase

Several days before the flare an emerging flux region at the western edge of the leading polarity area was developing. The flux emergence led to the formation of the arc shaped opposite polarity region (Figure 3). YOHKOH SXT observations reveal that this region was the site of a permanent SXR jet activity.

In the hours before the main event the dominant loop system overlying the magnetic inversion line was gradually developing (Figure 4a-4d) to form the preflare pattern shown in Figure 4e. The transformation was accompanied by a series of subflares, SXR brightenings and SXR plasma flows. The most prominent SXR flux enhancement occurred at about 09:20 UT. The brightness of the entire SXR structure was gradually increasing.

During this period a number of impulsive HXR bursts was recorded, achieving maxima at 01:41 UT, 01:48 UT, 03:22 UT, 06:22 UT, 08:01 UT, 09:08 UT and 09:40 UT, respectively (BATSE).

In the preflare phase several Hα brightenings (HB) were also observed: HB_W south-west from N1 (08:38 - 09:42 UT); HB_L at the location where the northern part of the SPFR will be formed, i.e., in the vicinity of the southern polarity footpoints of the SXR loops L3 and L4 (08:46 - 08:55 UT); HB_N1 attached to the spot N1 (09:10 - 09:18 UT).
4.2. Precursor Phase

The early phase of the flare was characterized by the soft X-ray precursor (maximum at 09:31 UT), an activation of the magnetic inversion line filament FB and the appearance of the Hα brightening (HB_{N1}) at 09:34 UT close to the spot N1. At the same time the formation of the SPFR began, and the distant Hα brightening HB_{E1} occurred eastward from the main flare site in the southern polarity region separated from the main following polarity area by a northern polarity 'bridge' protruding in the north-south direction (compare Figures 3 and 5).

In the time period between 09:36 UT and 09:43 UT a series of isolated short-duration bursts was observed in the metric wavelength range. At 09:42 UT the formation of the NPFR began.

4.3. Powerful Nonthermal Energy Release

The nonthermal energy release phase started between 09:45 UT and 09:50 UT when the main soft X-ray flux increase started. At the same time the filament FB disappeared and the microwave and HXR bursts started.

The NPFR and SPFR were fully formed at 09:49 UT and started to expand. Whereas the SPFR showed a regular expansion away from the magnetic inversion line, the expansion of NPFR was nonuniform, obviously determined by the locations of several large spots (see Figure 2). Simultaneously, the HXR burst began. Approximately at the same time an ejection of a loop shaped pattern was observed by SXT. One footpoint of the erupting structure was at N1. The ejection was possibly a signature of the LS eruption.

At 09:54 UT a moving type IV burst in the dm/m wavelength range started. The onset of the burst was accompanied by a fast lateral expansion of the SPFR attaining the maximal velocity of 25 km/s. At 09:55 UT the NPFR front reached the border of the umbra of the spot N2, and the SPFR front 'contacted' the umbra of the spot S1 at 09:56 UT. The time of the contact approximately coincided with a distinct HXR peak superposed on the growing main HXR event (Figure 6a). At 09:58 UT the distant Hα kernel HB_{E2} appeared in the vicinity of the remote brightening HB_{E1}.
At 10:02 UT another distant Hα brightening HB₅ was observed in the northern polarity island southward from the following polarity area. The occurrence of HB₅ and HB₆ was associated with the disappearance of the filament FA at 10:00 UT. The period between 09:54 UT and 10:02 UT was characterized by the fastest lateral expansion of NPFR and SPFR. In the same time interval the fastest growth of the 3 GHz microwave burst was registered, reaching its maximum at 10:02 UT. The first maximum of the dm/m burst occurred at 10:04 UT. The soft X-ray flux attained the fastest growth rate approximately at 10:05 UT. The HXR burst was characterized by a long lasting maximum between 10:00 UT and 10:15 UT.

4.4. Prolonged Nonthermal Energy Release Phase

At 10:14 UT the filament FA reappeared. At 10:20 UT another maximum was registered in the dm/m wavelength range, as well as in the microwave range at 10:22 UT. At 10:22 UT the distant Hα brightening HB₆ was observed eastwards from the main flare site. HXR observations are available till 10:22 UT, showing a weak decrease of the count rate.

At 10:38 UT the third maximum of the dm/m burst was registered, simultaneously with the appearance of another remote Hα brightening HB₇. At 10:48 UT a Hα surge-like event was observed originating from the spot N1 and spreading in the northward direction.

4.5. Late Phase

The soft X-ray burst attained maximum at 10:48 UT, slowly decaying afterwards. At 10:50 UT an isolated impulsive burst was registered at 638 MHz, marking the end of the nonthermal energy release phase. The relaxed postflare SXR loop system (Figure 4f) was gradually growing. The Hα postflare loop system (PFL in Figure 5d) appeared at 10:51 UT. The flare development during the late phase was of a thermal character typical for two-ribbon flares.

4.6. Large Scale Magnetic Field Restructuration

The preflare full disc SXT images reveal two coronal holes on the solar disc (Figure 1). One was extending from the northern hemisphere towards...
the AR and the other one was extending from the southern polar regions towards the AR. In the hours after the flare the coronal hole areas elongated and protruded into the active region towards the locations of the preflare S-pattern endpoints: the first one towards the leading edge footpoint and the second one towards the following one (Figure 4f). Such a transformation discloses a restructuring of the solar global magnetic field structure.

5. Discussion and Conclusion

The preflare magnetic field structure can be described as a sheared arcade with a core consisting of a large sigmoidal loop. One footpoint of the sigmoid was anchored at the remote area outside the arcade. The structure was built up gradually through a series of small scale restructurizations which caused a number of individual energy releases revealed by a permanent subflare and jet activity. The formation of the structure was completed several hours before the flare. During the further slow evolution, the structure lost equilibrium and an eruptive instability (Vršnak, 1990) set on, driving the arcade eruption.

The flare developed in several stages, following a typical two-ribbon flare scenario. It started by an activation of the neutral line filament, accompanied by the first Hα brightenings and the soft X-ray precursor. The nonthermal energy release was revealed by the dm/m burst, microwave burst and HXR burst. It was associated with the reconnection of the magnetic field lines below the erupting arcade core as revealed by the lateral expansion of the ribbons and the relaxed postflare SXR and Hα loops. The nonthermal energy release lasted until the induced electric field associated with the reconnection was sufficiently high to accelerate electrons. Afterwards the energy was released only in the form of the bulk plasma heating.

The large scale restructuration of the solar magnetic field structures was probably caused by an interaction of the erupting arcade with the global field. The process of reconnection between the magnetic field lines belonging to the arcade and the overlying fields was driven by the arcade core eruption as in the scenario proposed by Vršnak et al. (1987).
References


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