AN EVIDENCE OF FLARE ENERGY BUILDUP AND RELEASE RELATED TO MAGNETIC SHEAR AND RECONNECTION

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Abstract. We study series of homologous flares, observed in the active region NOAA 2372 by the HXIS on the Solar Maximum Mission and ground based observatories. Changes in the flare homology, particularly those related to the location of the hard X-ray emission, show clear correlation with the development of magnetic shear within the active region. Following our early study (Machado *et al.*, 1983) we propose that magnetic shear and reconnection are necessary for high power energy release, but the former may not be a sufficient condition in an isolated magnetic loop. These results are discussed within the context of a broader study, in order to explore their generality.

1. Introduction

The active region (AR) NOAA 2372 was one of the most productive and best observed flaring regions of the first Solar Maximum Mission (SMM) observing period (February–November, 1980). From its emergence, 4 April, 1980, until dissapearance over the western limb on 14 April, it produced more than 70 flares. The SMM pointed instruments tracked this region from late on 6 April through the 13th, and part of this period (5 to 10). the time when foreshortening was not a serious drawback, also corresponds to an interval of extremely good coverage by the Marshall Space Flight Center (MSFC) vector magnetograph (Hagyard *et al.*, 1981: Krall *et al.*, 1982).

The region was characterized by the presence of two large spots of opposite polarity and, between them, a small bipolar region of reversed polarity. The AR thus had a magnetic topology reminiscent of flare models which invoke the formation of neutral sheets at the intersecting surface of independent loop systems (Sweet, 1969; Syrovatskii, 1982, and references therein; see Machado *et al.*, 1983, for a detailed description). Figure 1, adapted from the potential field calculations by Wu (see Cheng *et al.*, 1982),

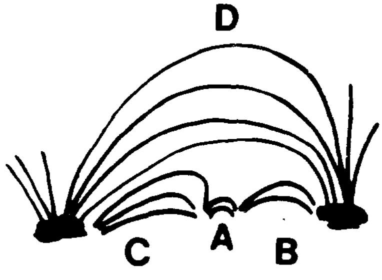

Fig. 1. Schematic representation (based on potential field calculations) of the field configuration in AR 2372, where we label the different magnetic loop structures which take part in the development of the flares.

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shows the distinct magnetic structures **A**, **B**, **C**, and **D**, as labelled by Machado *et al.* (1983, hereafter referred to as Paper I), which took part in the events we shall discuss.

From April 5 to 7 the region underwent what has been defined as its dynamic phase (Strong *et al.*, 1985), with the intermediate bipole moving westward across the region towards the leader spot. This motion is the likely cause of buildup in magnetic shear (Krall *et al.*, 1982; Hagyard *et al.*, 1985) observed in the MSFC vector magnetograms (see below). The main flares which occurred during the SMM coverage through this period and the early hours of 8 April were extremely widespread, both in Hα and X-rays. The flares showed four Hα ribbons or ribbon like structures, two located on each side (polarity) of the intermediate bipole, one behind the leader spot and another in front of the trailer. Soft X-ray emission was observed between each of these (Paper I), so that the combined data set delineates the coronal loop systems and their chromospheric feet.

A final point, of importance in this study, is that many flares showed homologous characteristics (Machado and Somov, 1983; Strong *et al.*, 1985; Woodgate *et al.*, 1985) either spatially or temporally. Furthermore, Machado and Somov (1985, see also Paper I) reported a sudden break in the hard X-ray homology, whose implications on flare energy buildup and release we discuss in the next sections.

2. Flare Homology

In terms of the spatial distribution of chromospheric Hα emission, McCabe (1984) has been able to divide the events observed in AR 2372 into several homologous classes. These will be discussed elsewhere (see Strong *et al.*, 1985, for a preliminary report), but we still point our here the existence of two main groups among those flares appearing within the core of the active region.

Group H I: Seen from April 6 to 8. Show widespread footpoints and four ribbon flares as mentioned above, covering the whole extent of the active region (see Figure 15 of Paper I).

Group H II: From April 10 to 12. Chromospheric as well as transition zone UV emission mainly concentrated towards the leader, extending from the intermediate bipole (see e.g. Machado *et al.*, 1982).

Also from the point of view of combined soft and hard X-ray imaging, as observed by the Hard X-Ray Imaging Spectrometer (HXIS, van Beek *et al.*, 1980) of the SMM, two main homologous groups can be defined.

Group X I: Seen from April 6 to early 7. Widespread flares, obviously comprising several (at least **A**, **B**, and **C**, cf. Paper I) magnetic arcades. As noted, the Hα emission of *Group* H I corresponds to the feet of these X-ray emitting loops. The early soft X-ray brightening appears concentrated over the bipole, and intense hard X-rays appear during the phase in which a strong X-ray increase (large $\mathrm{d}I/\mathrm{d}t$, where I is the X-ray intensity) is seen in magnetic feature **C**, connecting the bipole and trailer. The hard X-ray emission of these flares is long lived (several minutes), gradual (absence of strong short lived spikes) and soft (large spectral index, $\gamma \geq 5$ in most cases). In the HXIS images, the hard X-ray emission has single source appearance concentrated within the trailing region (C) and shifts, during the development of the burst, along a south–east direction following the path of the neutral line ($B_L = 0$). These characteristics are depicted in Figure 2, which corresponds to the 7 April flare at $00^h\ 50^m$ UT. In Paper I we interpreted this shift as evidence of a loop system growing in altitude. However, a more detailed comparison with Hα reveals that it can better represent the sequential brightening of widespread loop arcade along the $B_L = 0$ line.

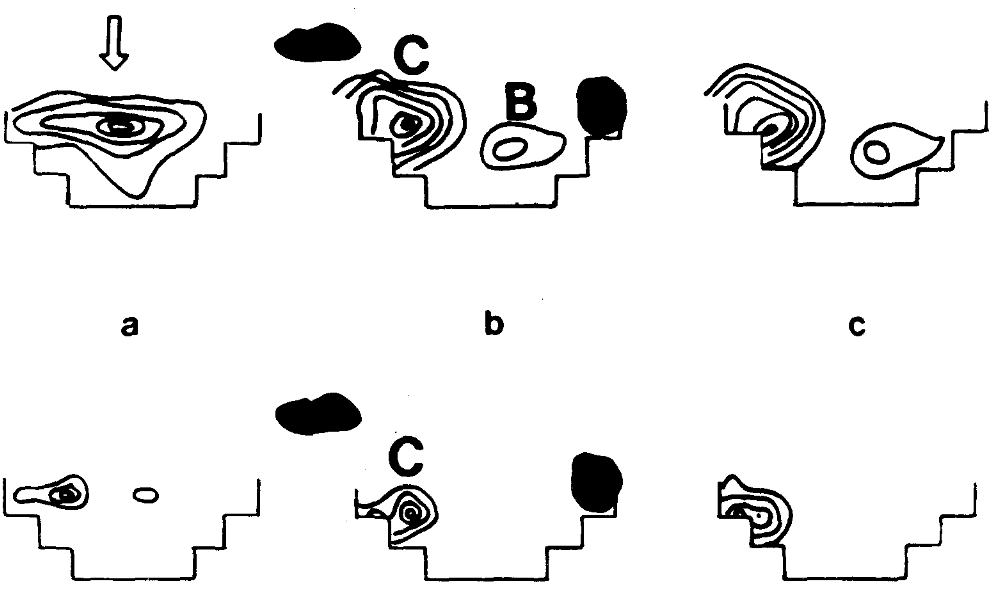

Fig. 2. Development of soft (3.5–8.0 keV, top) and hard (16.0–30.0 keV, bottom) emission in the 7 April flare at approximately 01 UT. The arrow signals the location of the intermediate bipolar feature, where the early flare brightening occurs. Note the strong difference in the X-ray intensity of **C** as compared with **B**, and the fact that the hard X-rays only appear in the loop system **C**, location of the highest magnetic shear region. The images correspond to (a) $00^h\ 50^m\ 40^s$ UT, (b) $00^h\ 52^m\ 47^s$ UT, (c) $01^h\ 07^m\ 23^s$ UT. In (b) we have plotted the location of the two main sunspots. The broken line represents the edge of the HXIS fine field of view.

Group X II: From late 7 to 10 April. The group could be subdivided, including widespread flares in soft X-rays (7 and 8 April), and flares mainly concentrated within the leading portion of the AR. The first subgroup marks the overlap with *Group* H I. Again, the early soft X-ray brightening occurs above the intermediate bipole (Paper I), this characteristic being common to groups X I and X II. In hard X-rays, both integrated and imaging data, this second group is clearly distinguishable. First, the emission becomes more impulsive, generally harder ($\gamma < 5$) and shorter lived (see Paper I and Strong *et al.*, 1985). Secondly, the locus of hard X-ray emission shifts towards the magnetic structure **B**, connecting the bipole and leader (Figure 3, see also Figure 2 of Paper I and Machado *et al.*, 1982), showing chromospheric hard X-ray footpoints during the early impulsive phase in the brightest events. As well as in *Group* XI, strong hard X-ray emission only appears *after* the early bipole brightening, when a large soft X-ray d*I*/d*t* is seen, in these cases, within structure **B**.

We thus adopt the broad scheme that two homologous flares groups were observed in AR 2372 from April 6 to 10. We give more weight to the hard X-ray classification,

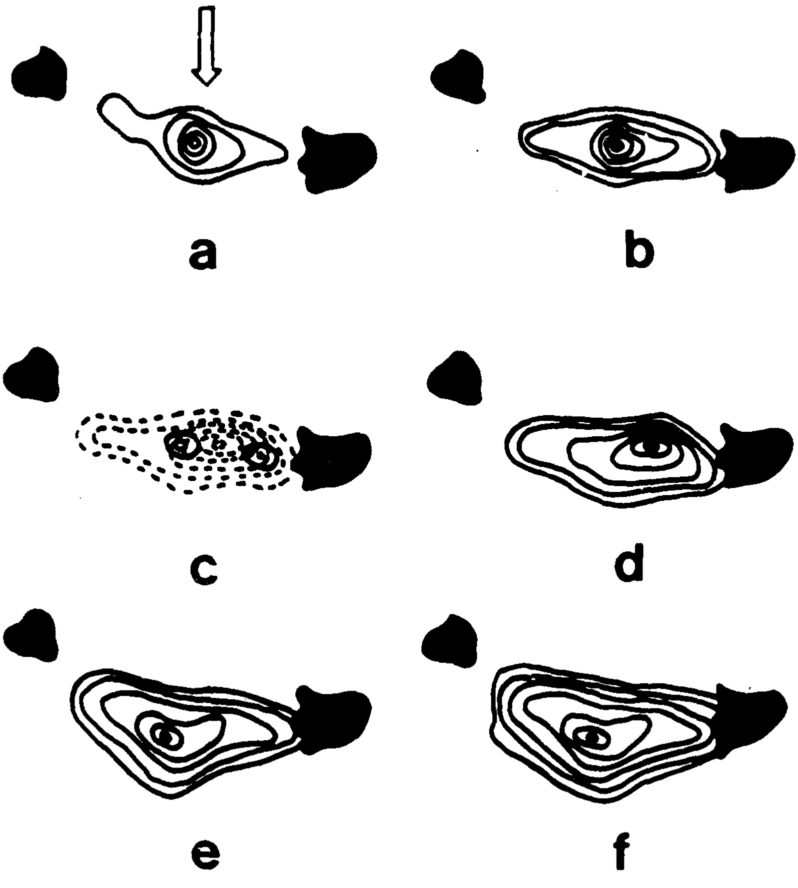

Fig. 3. Development of soft X-ray (3.5–8.0 keV) emission in the 7 April 18 UT event. The arrow again shows the position of the intermediate bipole where the soft X-ray flare starts. In (c) we have plotted (dashed) the soft X-ray contours as well as the location of the two hard X-ray bright points (16–30 keV) which presumably appear at the footpoints of loop **B**. Note that only at this time there is a strong brightening of **B**, connecting the bipole with the leader spot (cf. Figures 1 and 2 and text), such as to make it the brightest flare region, in contrast to the appearance of the 01 UT flare (Figure 2). The contour plots correspond to (a) $18^h\,39^m\,21^s$ UT, (b) $18^h\,43^m\,02^s$ UT, (c) $18^h\,43^m\,14^s$ UT (hard X-ray peak), (d) $18^h\,46^m\,29^s$ UT, (e) $18^h\,55^m\,21^s$ UT, and (f) $18^h\,57^m\,18^s$ UT.

since it reprepresents more closely the high power energy release processes (i.e. primary mechanism) than Hα, which is more related to energy transfer manifestations (Canfield *et al.*, 1980, 1985). We would also like to point out that our homology criteria are less restrictive (but perhaps physically more meaningful) than others applied to Hα and radio data in the past (see Švestka, 1976, and references therein). We do not require strict correspondence in the location of Hα brightenings, neither we take equal peak or integrated brightness at a given frequency as a necessary homology criterium.

3. Vector Magnetic Field Observations

As noted before, the results and implications of the MSFC vector magnetograph observations have been already summarized in several papers (Krall *et al.*, 1982; Wu *et al.*, 1984; Hagyard *et al.*, 1985). We simply point out here some important aspects of these observations, which have bearing on our homology classification and breakup in two X-ray classes.

Figure 4 (adapted from Krall *et al.*, 1982; from data provided by J. B. Smith Jr.) shows a blowup of two MSFC longitudinal and transverse field magnetograms, showing the development and motion of the central bipole as well as the leading and following neutral lines. It is clear from the figure that, during the westward migration of the bipole, strong shear develops, as indicated by the fact that the transverse field component is not orthogonal to the $B_L = 0$ line, as expected in potential field configurations.

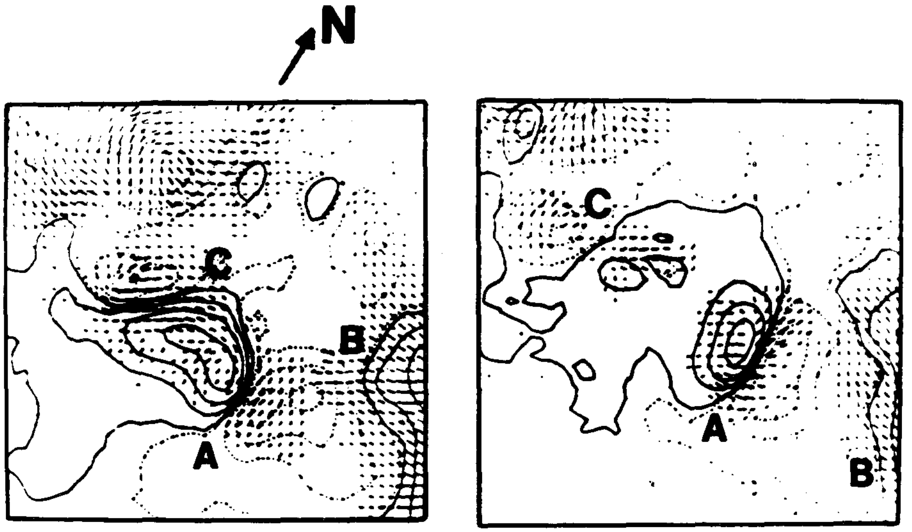

Fig. 4. Longitudinal and transverse field magnetograms of the central portion of AR 2372, where we have marked the location of the three neutral lines corresponding to the magnetic structures **A**, **B** and **C** (cf. Figure 1). Figure 4a corresponds to a MSFC magnetogram obtained at $20^h\,55^m$ UT on 6 April, while 4b was obtained on 7 April at $19^h\,10^m$ UT. Note the high shear level over the central bipole and trailing neutral line in 4a, and the more relaxed configuration, particularly along the **C** neutral line, in Figure 4b. See text for further details. MSFC data courtesy of J. B. Smith Jr.

By $20^h\ 55^m$ UT on 6 April (Figure 4a) strong shear is observed along the bipole's and the trailing neutral lines. This represents the likely magnetic configuration at the time of the late 6 and early 7 April flares, occurring at approximately 01 (Figure 2) and 05 UT (Paper I), i.e. those that belong to *Group* X I. On the other hand, the magnetogram of Figure 4b shows that, by $19^h\ 10^m$ on 7 April, strong changes has occurred in the field configuration. The bipole has come closer to the leading spot and, qualitatively, shows lesser amount of shear which is now stronger along the leading neutral line (note the clear relaxation in the configuration along the trailing $B_L = 0$ line). This situation corresponds to the $18^h\ 40^m$ flare observed by the HXIS, shown in Figure 3, which belongs to *Group* X II. This event had been omitted in our early study (Paper I), and a thorough examination of available data shows that it is the first major event showing X II characteristics.

We thus find good temporal correspondence between homologous groups X I and X II of the X-ray classification and magnetic shear evolution. Moreover, from the point of view of Hα, we note that even though some of the *Group* X II flares, like the one of Figure 3 and the 8 April $03^h\ 03^m$ UT (Paper I) events, fall in the widespread class H I, there are observations (Falciani, private communication) which show a shift, towards the leading portion of the AR, in the location of offband Hα kernels. This also seems to occur at the time of the $18^h\ 40^m$ UT flare. Since offband kernels are related to precipitating high energy particles (Canfield *et al.*, 1985), these data are in excellent agreement with our findings on hard X-ray behavior.

4. Discussion

The results of Section 2 and 3 have shown that the most energetic manifestations of the flares are closely related to the magnetic field configuration and the presence of magnetic shear. The latter seems to be a very important factor in the changing aspect of the flare characteristics, a hardly surprising finding, since it reflects the existence of field motions and energy storage processes.

Yet, we have also stressed that impulsive phase phenomena only occurred after an initial flare brightening, located over the bipole (**A**), and when the emission spread over the neighboring magnetic structures **B** and **C**. Although the soft X-ray yield increased in both (Paper I), the hard X-rays concentrated in either one of these according to the higher shear level. Moreover, even through the time when the bipole had the highest shear (6 and early 7 April) it did never produce concentrated flaring. *Always*, the high energy burst emission appeared when the flare spred over neighboring field structures. These results thus agree with those of Paper I, in which we proposed magnetic reconnection as the primary energy release mechanism, and we now suggest that magnetic shear may be a necessary but sometimes not sufficient condition for high power energy release, which causes the hard X-ray bursts.

It is also worth noticing that the results presented in this paper are not unique. From a comprehensive study of eighteen flares from several active regions (Machado *et al.*, 1985), we have found in all cases that two or more intersecting magnetic structures brightened during the impulsive phase (see also Rust and Somov, 1984; Vlahos *et al.*, 1985), favoring a reconnection model in emerging or evolving fields (Priest, 1981, 1985). In the same study we also found (subject to the availability of magnetic data) a correlation between high shear and the site of hard X-ray emission, in agreement with the more general statistical study of Smith and Hagyard (1984). Therefore, the results obtained from AR 2372 are unique only in the sense that they allowed us to follow the temporal development of flare and magnetic field characteristics and their strong correlation.

Finally, it remains to be explained the difference in impulsivity and spectral hardness of the hard X-ray bursts related to the two groups of flares, X I and X II. The former, softer and less impulsive, seem to occur in more widespread magnetic arcades than those belonging to the second group. This fact may relate to the concentration of electric currents within these structures, which may thus be higher in the X II flares and favor the suprathermal acceleration of a larger number of electrons to higher energies. Still, this speculative relationship may be fortuitous and demands a quantitative analysis, as well as that of a larger sample of events.

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References

Canfield, R. C. *et al.*: 1980, in *Solar Flares – A Monograph from Skylab Workshop II*, Colorado Univ. Press, Boulder.

Canfield, R. C. *et al.*: 1985, in *Proceedings of the SMM Workshop*, in press.

Cheng, C.-C., Bruner, E. C., Tandberg-Hanssen, E., Woodgate, B. E., Shine, R. A., Kenny, P. J., Henze, W., and Poletto, G.: 1982, *Astrophys. J.* **253**, 353.

Hagyard, M. J., Cummings, N. P., and West, E. A.: 1981, NASA TM–82405.

Hagyard, M. J., Moore, R. L., and Emslie, A. G.: 1985, *Adv. Space Res.* **4**, No. 7, 71.

Krall, K. R., Smith Jr., J. B., Hagyard, M. J., West, E. A., and Cummings, N. P.: 1982, *Solar Phys.* **79**, 59.

Machado, M. E. and Somov, B. V.: 1983, *Adv. Space Res.* **2**, No. 11, 101.

Machado, M. E., Duijveman, A., and Dennis, B. R.: 1982, *Solar Phys.* **79**, 85.

Machado, M. E., Somov, B. V., Rovira, M. G., and De Jager, C.: 1983, *Solar Phys.* **85**, 157 (Paper I).

Machado, M. E., Hernandez, A. M., Rovira, M. G., and Sneibrun, C. V.: 1985, *Adv. Space Res.* **4**, No. 7, 91.

McCabe, M.: 1984, report to the FBS Homologous Flares Team.

Priest, E. R.: 1981, in E. R. Priest (ed.), *Solar Flare Magnetohydrodynamics*, Gordon and Breach, New York.

Priest, E. R.: 1985, *Adv. Space Res.* **4**, No. 7, 37.

Rust, D. M. and Somov, B. V.: 1984, *Solar Phys.* **93**, 95.
Smith Jr., J. B. and Hagyard, M. J.: 1984, paper presented at the SMA Symposium, Graz, Austria.
Strong, K. T., Smith Jr., J. B. McCabe, M. R., Machado, M. E., Saba, J., and Simnett, G. M.: 1985, *Adv. Space. Res.* **4**, No. 7, 23.
Švestka, Z.: 1976, *Solar Flares,* D. Reidel Publ. Co, Dordrecht, Holland.
Sweet, P. A.: 1969, *Ann. Rev. Astron. Astrophys.* **7**, 149.
Syrovatskii, S. I.: 1982, *Solar Phys.* **76**, 3.
Vlahos, L., Machado, M. E., Ramaty, R., Murphy, R. J., *et al.*: 1985, in *Proceedings of the SMM Workshop*, in press.
Van Beek, H. F., Hoyng, P., Lafleur, B., and Simnett, G. M.: 1980, *Solar Phys.* **65**, 39.
Woodgate, B. E., Martres, M. J., Smith Jr., J. B., Strong, K. T., McCabe, M., Machado, M. E., Gaizauskas, V., Stewart, R., and Sturrock, P. A.: 1985, *Adv. Space Res.* **4**, No. 7, 11.