SESSION 6

FLARES AND TRANSIENTS

The Magnetic and Velocity Fields of Solar Active Regions
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FLOWS, EVOLUTION OF MAGNETIC FIELDS, AND FLARES

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ABSTRACT This paper reviews observations on the evolution of magnetic fields and flows in active regions which produce major flares. It includes the following topics: (1) Relationship between magnetic shear and flares; (2) Relationship between electric currents and flares; (3) Flows in active regions, particularly the emergence of new flux inside sheared penumbrae, and the mixed magnetic polarity nature of this kind of flux emergence; and (4) Changes of magnetic structure immediately before and after major solar flares; in particular, I will describe some recent findings that shear may increase after major flares.

1. RELATIONSHIP BETWEEN MAGNETIC SHEAR AND FLARES

Study on this subject has been carried out extensively by the solar group at Marshall Space Flight Center. The magnetic shear is defined as the angular difference between the azimuth of the potential transverse field calculated from the longitudinal magnetic field and the observed transverse magnetic field (Hagyard *et al.*, 1984; Hagyard, Venkatarisknan and Smith, 1990). Hagyard and her colleagues have established that flares occur in areas where the local photospheric magnetic field departs the most from a potential field. These regions are characterized by (1) high shear angle; (2) strong transverse magnetic field along the neutral line and (3) long sheared magnetic neutral line. Discussion of this subject can be found in a number of references: Gary, Hagyard and West, 1990; Hagyard, 1992; Hagyard, Moore and Emslie, 1984; Hagyard *et al.*, 1984; Hagyard 1984, 1987; Hagyard and Rabin, 1986; Moore, Hagyard and Davis, 1987; Machado and Moore, 1991. Figure 1 shows an Hα flare, and the corresponding vector magnetogram by Machado and Moore (1991). The observed vector field is sheared near the neutral line. Gary *et al.* (1990) summarize nonpotential characteristics of flare sites in the Table 1 of their paper. Those flares indeed satisfy the necessary conditions defined above.

However, Tang and Wang (1993) recently found that not all flares occur on sheared neutral lines. If the flare ribbons start near the neutral line, the conditions described above are usually satisfied. If the flare ribbons start further apart, the neutral line may not have large shear. The former situation may represent a reconnection closer to the photosphere, while the latter may

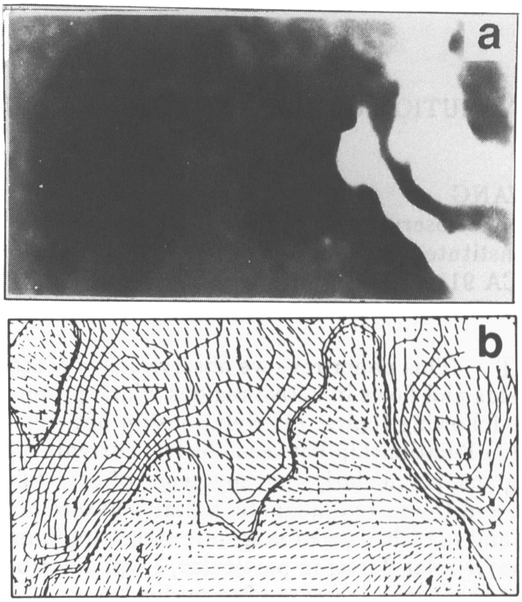

Fig. 1. Nonpotential field in the region of the large flare of April 24, 1984 (courtesy Drs. M. E. Machado and R.L. Moore). (a) Hα picture showing flare ribbons; (b) Observed vector magnetogram. Magnetic shear is high at the neutral line.

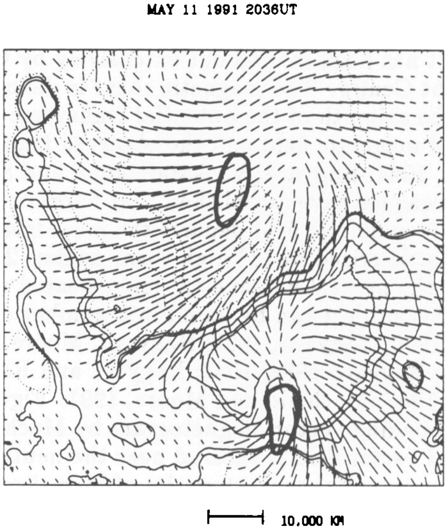

Fig. 2. May 11, 1991 M2.1 flare superposed in a vector magnetogram. Two flare ribbons (thick contour) are widely separated and the shear is not high at the neutral line.

imply a reconnection higher up. An example of the second case is shown in Figure 2, where the flare ribbons of M2 flare on May 11, 1991 are superposed on a vector magnetogram. The maximum shear angle of the neutral line is about 45°.

2. RELATIONSHIP BETWEEN VERTICAL CURRENTS AND FLARES

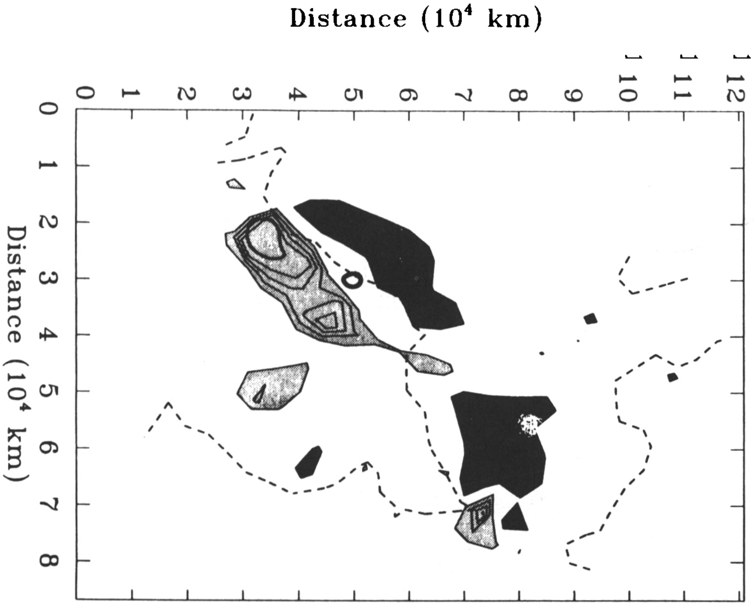

Fig. 3. The sites of non-thermal electron precipitation (thickest contour) and high coronal pressure (medium contour) relative to vertical electric currents (filled contour) and magnetic neutral lines (dashed line) (Courtesy K.D. Leka *et al.*).

Early observations from the Crimean Observatory showed a close morphological relationship between vertical electrical currents in the photosphere, inferred from vector magnetograms, and flare knots (Moreton and Severny, 1968). This correlation has been confirmed by modern observations. Lin and Gaizauskas (1987) and Hagyard (1988) studied the flares and vector magnetograms of AR NOAA #2372 in early April 1980 and found coincidence of flare kernels with maximum shear and peak value of line-of-sight electric current density. In the recent observations of NOAA #5747 in October 1989, done jointly at Big Bear Solar Observatory and Mees Solar Observatory, Canfield *et al.* (1990, also see Canfield *et al.*, 1992; Leka *et al.*, 1992; de La Bearjardiere, Canfield and Leka, 1992) compared the locations of the major current system to sites of nonthermal electron precipitation inferred from $H\alpha$ profiles of three flares. They found that the sites of energetic electron precipitation are at the *edges* of the currents, not at their peaks. Figure 3 is adopted from Leka *et al.* (1992) to demonstrate such a relationship.

More recently, Metcalf *et al.* (1992) compared YOHKOH Hard X-ray images with the electric current map for the November 15, 1991 flare. Hard X-rays provide direct determination of the locations of electron energy loss. The authors found the same relation between hard X- ray emission and vertical electric current as was found between Hα Stokes wing emission and vertical currents: the hard X-ray emission occurs predominantly at the edges of the vertical current sites, and not spatially on the top of these currents.

3. FLOWS AND SHEAR FORMATION IN ACTIVE REGIONS

Big Bear Solar Observatory obtains vector magnetograms, Hα center line and off-band filtergrams, D3 filtergrams and white-light images with a time resolution ranging from 10 sec to 2 min. Many time-lapse movies have been made based on these data. These observations are essential for studying flows, shear formation and flares. Magnetic field evolution and flows are discussed in a number of references (Chou and Wang, 1987; Zirin and Wang, 1989, 1990; Livi *et al.*, 1989; Wang, Zirin and Ai, 1991; Wang *et al.*, 1989, 1991; Wang, 1992a; Wang, 1992b; Wang, 1992c). Here I summarize the results related to the flows in flare producing regions:

3.1 Flux Emergence Inside Sunspot Penumbrae

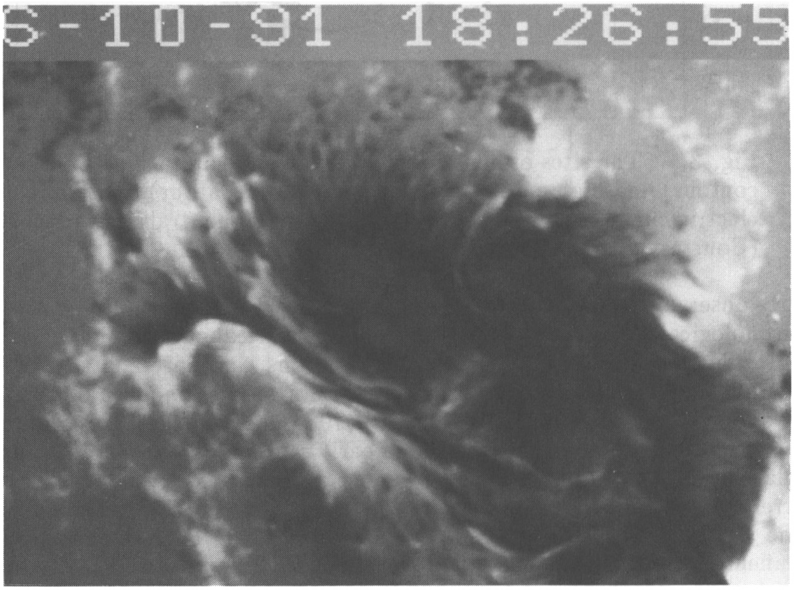

Fig. 4. BBSO magnetogram showing the EFR and channel structure of NOAA region # 6659, on June 10, 1991.

Emerging Flux Regions (EFR) are a well-studied subject. However, Zirin and Wang (1989) have recently discovered that EFRs may originate inside sunspot penumbrae. The first case was observed for the active region NOAA # 5060 on June 28, 1988. They found that in the penumbra where the new fluxes emerged, positive (leading polarity) flux flows along elongated channels immersed in the negative flux. A number of flares were observed in this area and they are associated with the emerging flux.

In addition, EFRs inside existing penumbrae were also observed in the two most flare-productive active regions of this solar cycle (NOAA 5395, March 1989 (Wang *et al.*, 1991) and NOAA 6659, June 1991 (Zirin and Wang, 1992; Wang and Zirin, 1992)). The EFRs were again the sites of many major solar flares. There are two points worth noting: (1) these flares tend to have big surges associated, and (2) regular arch filament systems are not observed for this kind of EFR, probably because the field lines are closely interwined. Figure 3 is a magnetogram observed on June 10, 1991. The elongated negative magnetic flux (channel structure on the left) emersed in the surrounding positive flux is due to new flux emergence inside the penumbrae, starting on June 8, 1991.

3.2 Shear Motion

One obvious cause of magnetic shear is photospheric motion. Low and Nakagawa (1975) studied the evolution of force-free fields as a function of photospheric footpoint motion. Low (1977) obtained analytical solutions to two boundary value problems which demonstrated the association between photospheric shear motion, the alignment of transverse magnetic field with neutral line, and the development toward critical conditions suggestive of flares.

The observations of Krall *et al.* (1982) confirmed the theoretical calculation of Low. They found that rapid spot shear motion coincides with magnetic shear and increased flare activity. Tang and Wang (1992) showed examples of shear motion along penumbral fibrils which may have lead to major flares in several active regions. The X-3 flare on Aug 27, 1990 was associated with of shear motion of active region 6233 (Wang, 1992b).

3.3 Collision of Opposite Magnetic Polarity and Flux Cancellation

Theoretically, magnetic shear also can be produced by head-on collision of two magnetic poles with opposite polarity (Ai *et al.*, 1991). This is confirmed by Hα observations (Kurokawa, 1987) and vector magnetograph observations (Wang, 1992b). However, relatively few cases of this kind of shear formation have been studied.

4. CHANGES OF MAGNETIC SHEAR AFTER FLARES

Observations of Hα fibril structure have been used by several authors (Zirin and Tanaka, 1973; Neidig, 1979; Moore *et al.*, 1984; Sivaraman, Rausaria and

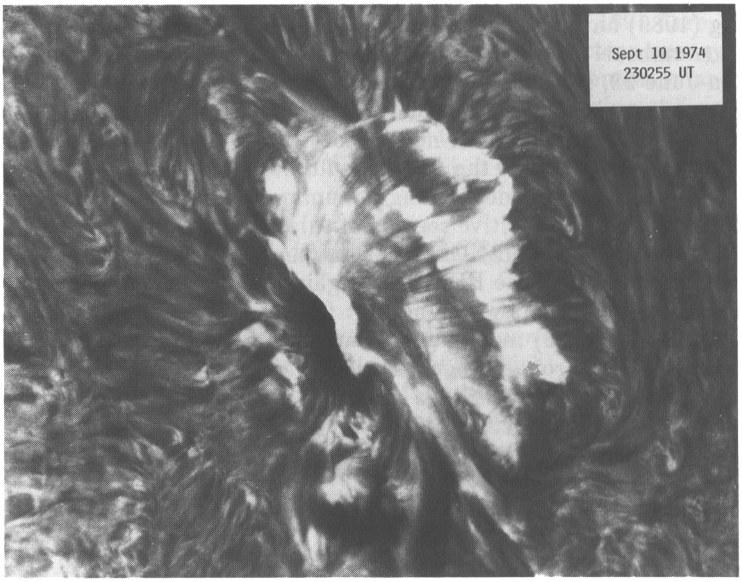

Fig. 5. A BBSO Hα filtergram showing potential structure of post flare loops on September 10, 1974 flare.

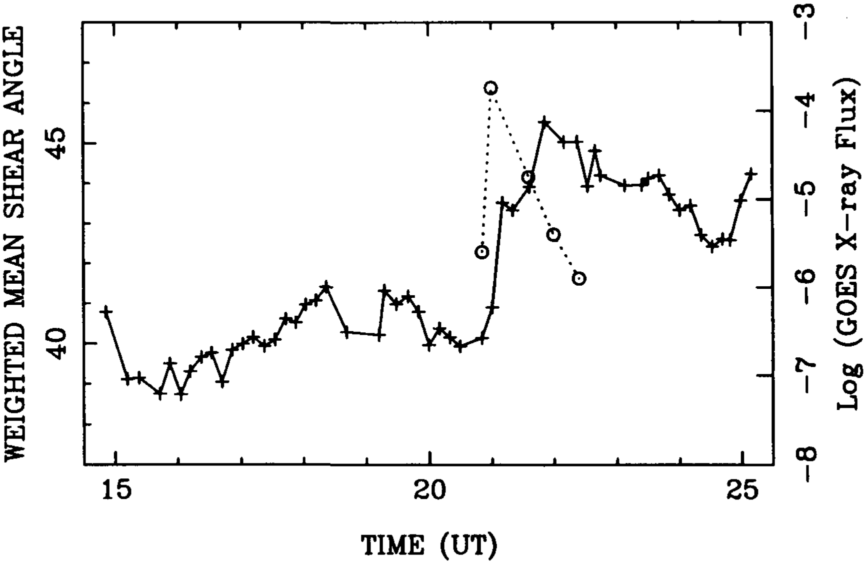

Fig. 6. A comparison of weighted mean shear angle with GOES X-ray flux (dotted line) for August 27, 1990 X3 flare.

Aleem, 1992) to study the shear of magnetic fields and the relation to flares. In general, the Hα structure changes from sheared to potential field after a flare, as evidenced by post flare loops. Figure 5 shows an example for the September 10, 1974 flare (Zirin, 1992). However, the Hα structure may only represent the field above the photosphere. Although in general it matches with the direction of transverse field in the photosphere (Wang, 1990), it is not guaranteed that this match is still valid for complex flare productive regions. Furthermore, Hα fibrils provide only the direction, and not the strength, of the transverse fields.

The first attempt to measure shear change immediately after a flare using a vector magnetograph was made by Wang (1992b). With a time resolution of about 5 minutes, I found a very surprising result, shown in Figure 6: The weighted mean shear angle suddenly jumped about 5 degrees coinciding with the flare. In a further study of this problem being conducted by Wang and Ewell (1992), four more regions show the same pattern: Magnetic shear increase coincides with the onset of flares. I summarize all these 5 cases in Table 1. All the cases show the increase of magnetic shear after flares, although time resolution varies significantly.

Table 1: Change Of Shear Angle After Flares

Date	Flare Class	Shear Change	Time Gap	Observatory
08-27-90	X3	+5°	10 min	BBSO
06-09-91	X10	+20°	3 hr	BBSO,Huairou,MSO
03-22-91	X9	+40°	5 min	BBSO
03-09-89	X4	+45°	22 hr	Huairou
03-10-89	X4	+12°	20 hr	Huairou

A detailed study of the March 22, 1991 region may have shed some light on the explanation of shear increase after the flare (Wang and Tang, 1992). We found that formation of new umbrae, emergence of new magnetic flux and increase of magnetic shear coincide with the onset of the flare. Figure 7 plots the umbral area, positive flux, and mean shear angle near the neutral line where the X-9 flare occurred. The sudden drop in the umbral area represents the emission of the flare, so it is a good indicator of the time of flare onset. The umbral area increased by 2×10^7 Km^2 , and the total flux increased by at least 2×10^{20} Mx. So the shear increase could be due to the emergence of flux twisted by subphotospheric convection.

5. DISCUSSION

It has been generally accepted that flare energy is derived from free magnetic energy. Usually, high magnetic shear and high electric currents mean high free magnetic energy. However, since vector magnetograms only observe field structure in the photosphere, the free energy may be stored higher up in chromosphere and corona. The finding that flares with two widely separated initial ribbons do not have strong magnetic shear confirms this argument (Tang and Wang, 1993). Similarly, photospheric shear may not necessarily decrease after a flare, while chromospheric and coronal shear most likely would decrease.

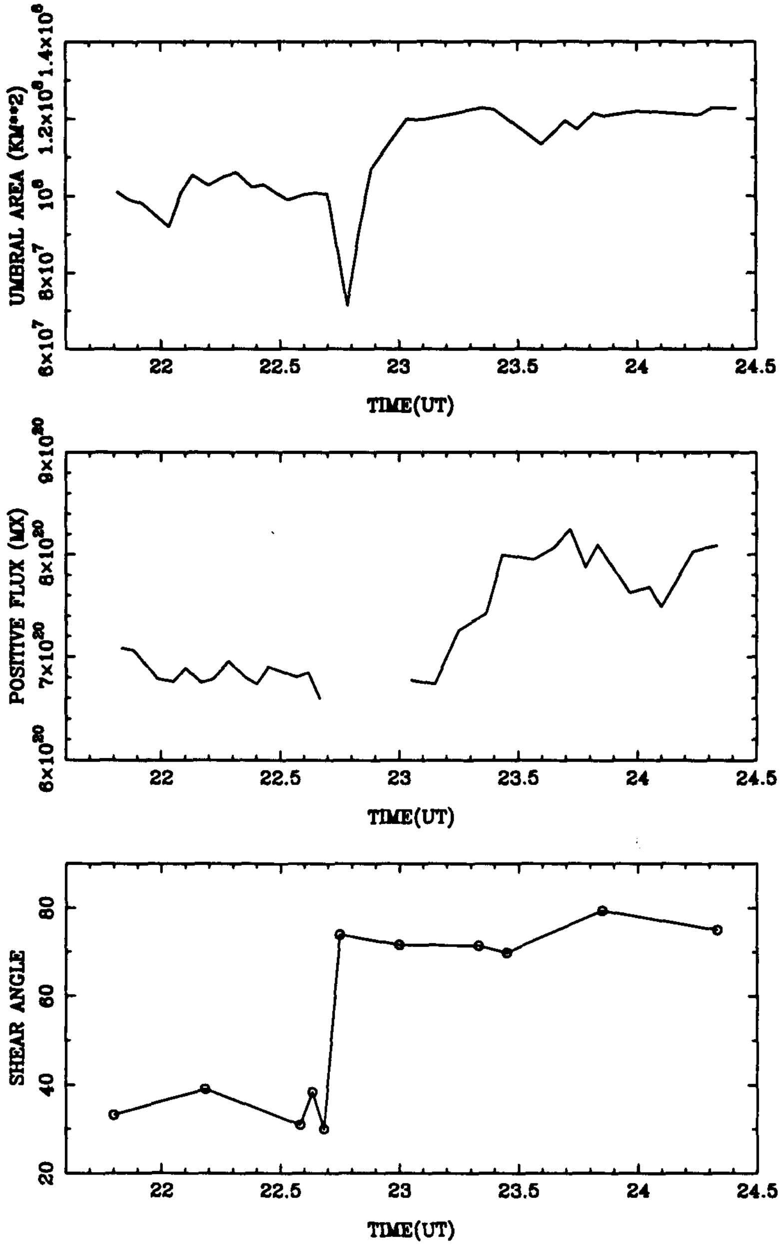

Fig. 7. Umbral area, magnetic flux and mean shear angle around the neutral line as a function of time for the March 22, 1991 X9 flare.

Why do we see an increase of magnetic shear? Akasofu (1984) proposed the direct driving model for flares, where he predicted that the magnetic shear would increase during the flare and decrease afterward. However, his model requires a large photospheric flow in the flaring region which we do not always observe. In addition, we do not observe substantial shear decrease even hours after flares. Forbes (1992) reviews models which predict magnetic shear changes during flares, and concludes that photospheric shear is not a direct measurement of energy storage in corona currents.

Finally, I would like to bring attention to the work by Tanaka (1991), where he proposed an emerging twisted magnetic knot model to explain a very flare-active δ group. Strong magnetic shear may form below the photosphere, and move upward. This model can explain flux emergence associated with shear increase, such as in the March 22, 1991 flare.

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