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The role of sunspot umbral rotation in triggering solar flares

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Abstract. The evolution of large active regions NOAA 9393 and NOAA 9433 observed during March and April 2001 respectively on their successive rotation and the active region NOAA 10069 that appeared during August 2002 were studied. Kodaikanal photoheliogram and H_α spectroheliogram data of these active regions were analyzed to identify the flare triggering mechanism. It is found that the umbral rotation in these δ -type sunspots plays an important role for the occurrence of flares. The flare locations were generally near sites where the umbrae of the sunspot underwent more rotation.

Keywords : sun - umbra - sunspot - flare.

1. Introduction

The primary condition for a solar flare to occur in the sun is the presence of active regions. A sunspot is an active region in the photosphere representing a cross section of the magnetic flux tube. The association of flares with the observed photospheric magnetic fields is in terms of magnetic field configurations and evolutionary changes (Mayfield & Lawrence 1985). The development and decay of sunspots are certainly important indicators on the evolution of active regions, since they represent highest concentration of magnetic flux. If evolutionary changes may provide necessary conditions for flares to occur, then it is quite possible that the sunspot orientation changes indicate sunspot motions and could be significant observable factors in the energy buildup of at least some solar flares. There are studies comparing the close relationship of sunspot proper motions

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with the flare productivity of an active region (Ambastha & Bhatnagar 1988; Bumba et al., 1993; Schmieder et al., 1994). Collisions or approach between sunspot groups are often observed with important flares (McIntosh & Donnelly 1972). McIntosh (1970a, b) has noted that even small sunspot groups may be associated with major flares if the spot motions are especially large. It is also shown that the separation of sunspots decreased prior to a large flare and increased after the flare (McIntosh 1969). Sunspot rotation and partially developed vortices in penumbral and fibril structure also accompany especially flare rich regions (Zirin & Tanaka 1973; McIntosh 1969, 1970b). The penumbral fibrils of approaching adjacent sunspots of opposite polarity also turn away parallel to the regions of polarity boundary (Martin 1973; Foukal 1971a, b). Therefore, flare may be a consequence of the evolution of magnetic structures near the polarity inversion line at the photospheric level.

2. Stressed magnetic fields and magnetic shear in flares

It is generally believed that flares derive their power from the free energy stored in the stressed or non-potential magnetic fields (Švestka 1976). The rapid transformation of magnetic energy into plasma heating and particle acceleration is believed to occur through magnetic reconnection when the stresses exceed a threshold value. The stressed magnetic fields are indicated by the shear developed in the active regions. The concept of magnetic shear has occupied a central position in the study of flare associated changes in the magnetic field since early 1970s (Zirin & Tanaka 1973). As an active region evolves, stresses in the coronal magnetic field may buildup in response to the changes taking place at the photospheric level such as sunspot motions, emerging flux, etc. Measurement of magnetic fields at coronal level, which is considered to be flare site, is relatively difficult. However, magnetic field measurements at the photospheric levels provide vital information about the sites of stressed magnetic field configurations in the active regions. The foot points of the active regions are anchored in the photosphere where concentrations of magnetic flux, say sunspots are present. Thus sunspot motion is frequently reported as causing magnetic shear at the photosphere (Nagy 1983; Gesztely & Kálmán 1986 Neidig et al., 1986; Kövacs & Deszö 1986). Shear motions of umbrae before a flare in δ - type spots are often reported due to successive emergence of magnetic flux. (Kurokawa et al., 1987; Kurokawa 1991; Zirin & Wang 1993; Wang 1994; Sundara Raman et al., 1998). Thus the process of magnetic energy storage is attributed to the shearing of magnetic fields due to motions at or below the photosphere where the hydrodynamic forces dominate.

The photospheric shear is best displayed by the vector magnetograms (Hagyard et al., 1984b). The necessary condition arrived for flare eruption is large angular shear and strong transverse field over an extended length along the neutral line (Hagyard et al., 1984a; Neidig et al., 1986; Machado et al., 1986). However, Hagyard & Rabin (1986) found later that such strong shears also occur in active regions without resulting flares and similar result was also reported by others (Athay et al., 1985; Lu et al., 1993; Chen et al., 1994; Schmieder et al., 1994; Debi Prasad et al., 1997). The potential field extrapolation

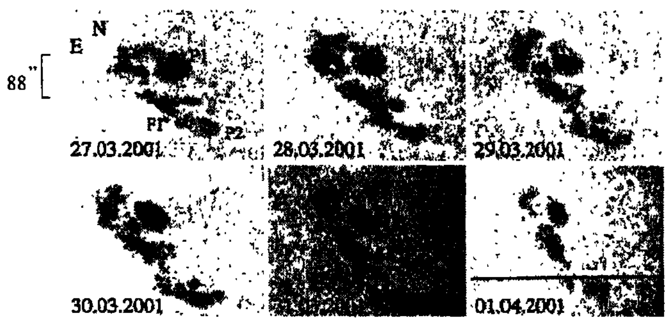

Figure 1. White light photoheliograms of the active region NOAA 9393 observed at Kodaikanal for the dates 27 March to 1 April 2001. The central regions of the umbrae P1, F1 and P2 are taken for shear angle calculations.

used in the magnetogram studies may not be the best way of representing the field, which is constantly stressed (Fletcher et al., 2001). Also shear may be present in the extended areas away from and above the photospheric neutral line (Ambastha et al., 1993). In view of this, it is desirable to study the entire geometry of the active region magnetic fields to understand the flare process.

3. Umbral rotation observed in flares

An active region is the eruption of the subphotospheric twisted magnetic flux tubes and is deep rooted in the sun. Once the active region appears in the photosphere and extends into the corona, it is possible that the subphotospheric portion may unwind the twist and transmit to the corona for the flare onset. Hence, it is particularly interesting to look for the propagation of twist from one flux system in the photosphere to another in the corona where the twist that is generated in the solar dynamo gets released at the time of the flare.

In this paper we have studied the shear developed in the active regions from the change in the orientations of the umbrae belonging to the large active regions NOAA 9393 and NOAA 9433 that appeared during successive rotations in March and April 2001. A very large active region AR 10069 that appeared during August 2002 is also taken for the analyses. Kodaikanal white light photoheliograms, H_α spectroheliograms of the flares were analyzed and the morphology of the active regions are studied. Figure 1 shows the white light observations of the active region NOAA 9393 from 27 March to 1 April 2001. The same active region that appeared on its second rotation as NOAA 9433 is depicted in Figure 2 for the dates 22 to 28 April 2001. Figure 3 shows the flares observed in H_α at Kodaikanal in these active regions. Figure 4 gives the white light photoheliograms of the dates 18 to 21 August 2002 of the active region 10069 and the Figure 5 gives the flares in H_α that occurred in this large active region. In the absence of

Table 1. Shear angle in degrees measured from the change in the orientation of the umbrae of the sunspot belonging to the active region NOAA 9393

Date	Orientation of the umbrae P_1 & F_1 in degrees	Shear angle in degrees	Orientation of the umbrae F_1 & P_2 in degrees	Shear angle in degrees
27 March 2001	26	-	70	
28 March 2001	22	4	74	4
29 March 2001	25	3	72	2
30 March 2001	24	1	60	12 flare
31 March 2001	21	3	69	9 flare
1 April 2001	20	1	66	3

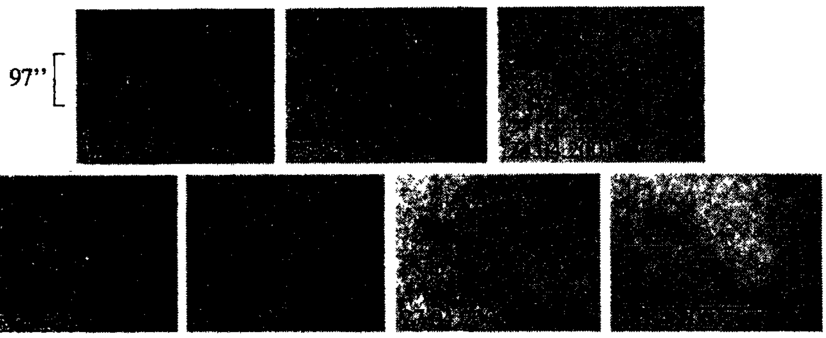

Figure 2. Kodaikanal white light photoheliograms of the active region NOAA 9433 during 22 to 28 April 2001. The centres of the umbrae F1, F2, P1 and P2 are taken for calculating the shear angles.

vector magnetograph facility at Kodaikanal, we have adopted the methodology presented in the earlier papers by Sundara Raman et al (1998, 2001) to calculate the shear created in the active region. A line is drawn connecting the centers of gravity of two umbrae belonging to a sunspot group and is extended to meet the rotation axis of the sun. The angle measured from north to east between this line and the rotation axis is taken as the orientation of the umbrae on a particular day of observation. Any variation in this angle from one day to the next gives the change in the orientation of the umbrae indicating the umbral rotation developed in this region. The calculations are done for the dates when these active regions were within 50^o on both sides of longitude to avoid foreshortening effects.

The optical flares that were observed at Kodaikanal in the active region on 30 and 31 March 2001 during first rotation of the spot NOAA 9393 were taken for the analyses

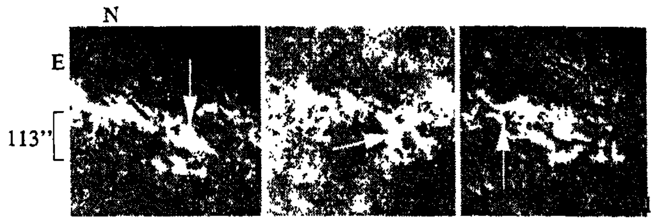

Figure 3. H_α spectroheliograms of the flares observed at Kodaikanal. The arrow marks show the flare region. The dates 30 and 31 March 2001 show the flares belonging to the active region NOAA9393, whereas the frame 26 April 2001 depicts the flare that occurred in the active region NOAA 9433.

though many X-ray flares occurred in this active region during March 2001. The regions near the umbrae P1, F1 and P2 (Figure 1) were given close attention. The spot in this region has gradually grown from one day to the next till the decay started on 1 April 2001. Due to the successive emergence of flux, the spot has grown in size in this region resulting change in the orientation of the umbrae representing the shear developed in this region. Table 1 gives the rotation of the umbrae as a measure of shear. The shear angle calculated does not show any appreciable change between P1 and F1 (table 1) and there is no flare activity in this region. On the other hand the shear angle calculated between F1 and P2 exceeded the threshold value of 5^o (Sundara Raman et al., 2001) and attained values of 12^o and 9^o on 30 and 31 March 2001 respectively (table 1). It may have resulted a 1N flare on both these days in the region between F1 and P2 (Figure 3).

The same active region appeared again as NOAA 9433 during its second rotation on 18 April 2001. The orientations of the umbrae F1 with respect to F2, P1 and P2 (Figure 2) are studied for the successive days of observations. The measured shear angles are given in table 2. There is not much of a difference observed in the shear angle between the umbrae F1 with respect to P1 and P2. The umbrae F2 started as a pore on 22 April 2001 and slightly grown from 22 to 26 April 2001. The change in the orientation of the umbrae F2 with respect to F1 is 9^o crossing the threshold value on 26 April 2001 and a 2N flare is triggered in the region (Figure 3). The pore F2 has disappeared on 27 April 2001 (Figure 2).

A very large magnetically complex active region NOAA 10069 that was on the centre of the disc on 18 August 2002 is also taken for the analyses (Figure 4). The optical flares observed at Kodaikanal in this region were alone considered for our analyses. The umbrae P1 and P2 have the same polarity, whereas P3 (Figure 4) is of opposite polarity from the SOHO MDI vector magnetograms. We have given importance to find out the changes that occurred in the orientation of the opposite polarity umbrae P1 and P3 and P2 and P3. The calculated shear angles in degrees are given in table 3. The spot size started reducing from the next day 19 August 2002 indicating decay occurring in this region. The decay factor may be responsible for the change in the orientation of the umbrae in this active region. The change in the orientation of the umbrae P2 and P3 is not appreciable.

Table 2. Shear angle in degrees measured from the change in the orientation of the umbrae of the sunspot belonging to the active region NOAA 9433 during its appearance in the second rotation (orientation of the umbrae F_1 with respect to F_2, P_1 and P_2 on successive days of observations)

Date	F_2	Shear angle	P_1	Shear angle	P_2	Shear angle
22 April 2001	18	-	72	-	58	-
23 April 2001	16	2	76	4	50	1
24 April 2001	17	1	73	3	62	3
25 April 2001	19	2	74	1	64	2
26 April 2001	10	9 flare	73	1	63	1
27 April 2001	15	5	73	0	66	3
28 April 2001	-	1	70	3	64	2

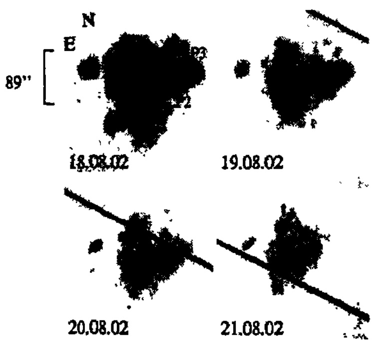

Figure 4. Kodaikanal white light pictures of the active region NOAA 10069 for the dates 18 to 21 August 2002. The central regions in the umbrae P1, P2, P3 are taken for calculating shear developed in the active region.

On the other hand 8^o and 10^o changes in the orientations were observed on 19 and 20 August 2002 (table 3) respectively between the umbrae P1 and P3. This change may have produced a 2B flare on both days 19 and 20 August 2002 and are depicted in Figure 5. The decaying magnetically opposite polarity P3 disappeared on 21 August 2002.

4. Summary and conclusions

It is now widely accepted that solar flares are driven by the magnetic reconnection that takes place in the coronal level. The magnetic reconnection is the process of the diffusion of anti parallel magnetic field lines causing reorganization or reconfiguration of magnetic fields in the active regions. Finding photospheric null is rather easy but coronal nulls are

Table 3. Shear angle in degrees measured from the change in the orientation of different umbrae in the active region NOAA 10069.

Date	Orientation change between P_2 P_3	Shear angle	Orientation change between P_1 P_3	Shear angle Shear angle
18 August 2002	60	-	63	-
19 August 2002	59	1	71	8 flare
20 August 2002	64	5	61	10 flare
21 August 2002	-	-	-	-

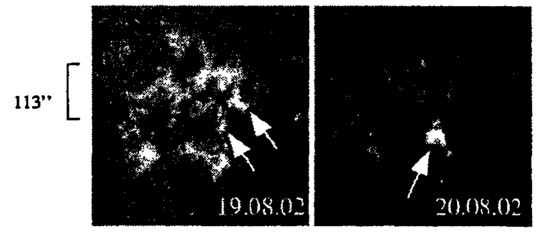

Figure 5. Kodaikanal H_α spectroheliograms showing the flares that occurred in the active region NOAA 10069 on 19 and 20 August 2002. The arrows indicate the flare regions.

difficult to observe. It is now realized that flares are caused by the small scale changes in the photosphere that produce large scale changes in the corona till the conditions are favourable for the magnetic reconnection to take place. Converging magnetic poles represent cancelling magnetic features based on the vector magnetogram results (Chae et al., 2000). It is the magnetic topological complexity together with the continual photospheric motion that may produce current sheet formation for the release of energy at the corona.

The main reservoir of stored energy may be hidden beneath the photosphere in the form of twisted magnetic flux tube. The successive emergence of these twisted flux tubes produce shear and is observed in the form of sunspot rotation. Many observations imply that the shear created in the magnetic structures show tendency to erupt. The active regions, which appear as loops in soft X-rays, are connected to the photosphere by foot points. These foot points of coronal lines move due to varieties of photospheric motions, which may continuously supply energy into the corona. The active regions studied in this paper have a large and complex sunspot with array of opposite polarity umbrae embedded in the group. Small spots are simpler, whereas the complex spots form deep in the sun and twisted up in the convection zone (Wang et al., 1991). When they emerge, they are ready to flare due to the rapid field motions, which act as the principal agents for the flare onset. The observations presented here show that flares are restricted to the locations where the umbrae of the sunspot exhibited more rotation from one day to the next. The active regions reported in this paper were highly flare productive. Many sub flares were observed in these active regions on the flare days reported in this paper (courtesy Solar Geophysical Data). These sub flares, which were not reported in our analyses, indicate the accumulation and release of energy in these active regions. Typical optical flares having importance N and B observed at Kodaikanal in these large active regions were alone taken for the analyses. Observations of high temporal resolution may throw a comprehensive picture on the factors causing these shear motions in sunspots. These observations are persistent with the photospheric flux cancellation, which leads to the reconnection at coronal null. However, it is not yet very clear what triggers the sudden explosive release of energy that is gradually accumulated due to various shear motions. The question to be settled is whether the shear motions in the photosphere represent the shear that are already developed in the rising tube or any additional shear is induced at the photosphere to further influence the dynamics of the tube. High resolution observations of optical, X-ray, helioseismology combined with the vector magnetograms and the methodology presented in this paper may hopefully be able to give a comprehensive picture to solve this problem.

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