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Spot and filament rotation in a sigmoidal flare

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Abstract. The role played by the rotation of the umbrae in a sunspot with respect to the Hα filament in inducing magnetic shear for the sigmoidal brightening is reported in this paper. We carried out these studies by using photoheliogram and filtergram data. In the absence of vector magnetogram at Kodaikanal, an alternative method has been attempted to evaluate shear by carefully analyzing the photospheric and chromosphric environment of the solar active regions. It has been found that a large value of shear change observed in the active region is responsible for the triggering of a sigmoidal related flare.

Key words : flares - sunspots - filaments - sigmoids - shear.

1. Introduction

The main reservoir of stored energy during the flare time might have been hidden beneath the photosphere and the released energy may be loosely related to the amount stored. It is now realized that an active region develops from the eruption of twisted sub-photospheric flux tube (Kurokawa 1987; Strurrock 1987; Tanaka 1991; Rust & Kumar 1995). After the tube penetrates the photosphere and extends into the corona, it is essentially favorable for the sub-photospheric portion to unwind and transmit the twist through the photosphere into the corona. This may have the effect of producing rotation at the photosphere, including a high shear along the neutral line that is shown by the magnetograms (Hagyard et al., 1984a). The overall twist of the active region magnetic fields observed in the photosphere and corona are related as the foot points of the coronal lines move due to varieties of photospheric motions. 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 created in the solar dynamo (Bieber & Rust 1995; Pevtsov & Canfield 1999) is shed off in the case of flares.

There is certainly a relationship between the photosphere and the Hα filament as the filament is rooted to the photosphere by its foot points. As such the twist developed in the photosphere will be transmitted to the filament and the position and structure of the filament in the close vicinity of flares will develop strongly sheared fields. It will in turn affect the pre-existing X-ray loops, which usually appear in arcades spanning the Hα filament, changing the magnetic environment of the filament, and then enhance the current in the filament (Tang et al., 1999). As a result the filament erupts, and the overlying coronal field lines will form a current sheet below the erupting filament. Thus, the magnetic field changes taking place in the photosphere is transmitted to the corona through the process like filament activation in the chromosphere.

It is now established that flares derive their power from the stressed or non-potential configuration of magnetic fields (Zirin & Tanaka 1973; Hagyard et al., 1984a, and the references therein). Optical observations first demonstrated that flares occur near the neutral lines of the longitudinal photospheric magnetic fields (Smith & Ramsey 1967; and the references therein). Subsequent to the development of vector magnetographs, high magnetic shares are identified near the neutral line at the photosphere before the occurrence of flares producing non-potential character to the magnetic fields lines (Hagyard et al., 1984a). However, such strong shears also occur in the active regions without resulting a flare (Athay et al., 1985; Hagyard & Robin 1986; Lu et al. 1993; Chen et al. 1994; Schmieder et al. 1994; Debi Prasad et al. 1997). It may be because of the fact that studies from the vector magnetograms mostly concentrate shear near the photospheric neutral line. Moreover, extended areas of non-potential structures are quite often observed in many cases, covering large areas away from the neutral lines (Gary et al. 1987). Also magnetic shear is visualized only in the photosphere, whereas such shear must also have been present in the vertical extent above the photospheric neutral line. In view of this, it appears desirable to study the morphology of the entire flare active region in both photosphere and chromosphere without restricting the shear analysis only along the photospheric neutral line. Therefore, the most important questions to be settled from pre-flare observations concern the geometry of the magnetic field, the stresses applied to them from photospheric to coronal heights, and the changing physical properties of the plasma trapped in those fields.

In this paper we have analyzed the optical observations taken at Kodaikanal and Big Bear Solar Observatory to find out some precursors which represent early change or destabilization of the magnetic field prior to the onset of the flare that occurred on 17 August 1999. A precursor is a transient event before the occurrence of the flare and need not be associated with the exact flare site itself (Gaizauskas, 1989). With this approach we have monitored the interaction between the magnetic structures adjacent to the flare and how this association influence the rest of the activity centres at different atmospheric levels of the sun.

2. Hα filaments and transverse component of magnetic fields

Thus the process of pre-flare energy storage is attributed to the shearing of magnetic fields due to the twist that occur in the active regions at or below the photosphere where the hydrodynamic forces dominate. This view suggests that the longitudinal magnetic fields remain virtually unchanged throughout the evolution of shearing. That is longitudinal fields are not stressed. So the transverse component of the stressed non-potential magnetic field is closely related to the solar flares and not the longitudinal ones (Lin et al., 1993). The non-potential nature of the observed field at the photosphere is best displayed by the alignment of transverse field along the neutral line (Martin 1980; Hagyard et al. 1982; Hagyard et al. 1984b). Based on this concept, the angular shear has been calculated from the variation of photospheric neutral line using vector magnetograms. Or in other words, shear is represented by the bundle of strong transverse fields or a set of flux loops that align with the magnetic neutral line at the time of the flare. Magnetic shear at the chromosphere was first recognized from the morphology of the Hα firbrils, which were in alignment with the neutral line position dictated by the sheared magnetic loops (Zirin & Tanaka, 1973). In fact Hα fibrils at the chromosphere trace the transverse component of the photospheric vector field (Zirin 1974). However, there are limitations in using Hα fibrils for shear calculations due to their size but on the other hand Hα filaments can minimize the errors in such studies. Hα fibrils may incline at any angle to the nearby filaments, but close to the filament they align with it (Martin 1973). Observations with high resolution show that many filaments are nothing more than a fused chain of fibrils. The observations also show the filament structure breaking down in to several fibrils that terminate in different plage features before and after a flare (Tanaka 1976; Rust 1984). Moreover, Hα filaments represent sheared magnetic field configuration and are formed where fibrils from strongly sheared paths (Harvey et al. 1971; Martin 1973). The common feature is that the variations detected seem to involve reorientation of fields and these changes in fibrils and filaments have similar pattern. Hence, pre-flare filament changes and fibril changes need not be considered as mutually exclusive events (Martin 1980). That is to say that Hα filaments and fibrils in flaring regions outline transverse component of the magnetic field (*Rust*, 1984). Also comparisons of Hα pictures and magnetic field measurements of the active regions have shown that the path traced by a filament indicates the magnetic neutral line as it lies in the vhromosphere above the dividing line between the regions of photospheric opposite polarities (Švestka 1976, and the references therein). Considering all these aspects, we have carefully estimated the shear by observing the variations in the Hα filament orientations with respect to the rotational motion of a sunspot belonging to the same active region from the changes observed from one day to the next. In this way the complete environment of the flare active centers of both photosphere and chromosphere are accounted for the measurement of shear.

3. Flare observed on 17 August, 1999

3.1. Shear measurement from the change in the orientation of the Hα filament (method 1)

The active regions above sunspot groups appear as loops in soft X-ray pictures. Some of these loops appear as S-shaped or reverse S-shaped structures that are called sigmoids (Rust & Kumar 1996). Their sizes extend up to 10° in both longitude and latitude having a life of 5 or 6 solar rotations. The sigmoids of all sizes are found to be flare productive (Canfield et al., 1999) and they actually represent twisted flux loops in the corona. Therefore, these sigmoid features tell a great deal about unstable coronal magnetic fields. We have studied the sigmoid which appeared during 14 to 20 August 1999 in the YOHKOH SXT pictures and carefully analyzed the photoheliogram and spectroheliogram data obtained at Kodaikanal along with the Hα filtergrams of BBSO for the same dates. In this way we have tried to understand how the twist that is developed in the photosphere is transmitted through the chromosphere into the corona, eventually triggering the flare on 17 August 1999.

Figure 1 shows the white light photoheliogram taken at Kodaikanal depecting the sunspot during its disk passage from 15 to 18 August 1999 belonging to the active region NOAA 8668. The BBSO filtergram in Hα from 16 to 19 August belonging to the same active region is reproduced in Figure 2. Figure 3 gives the full disk solar image showing the coronal features in soft X-ray and the flare that occurred in the region on 17 August 1999. Since an X-ray flare of importance C 5.9 has occurred during the sun set hours at Kodaikanal, i.e. 12.55.00 hrs. UT on 17 August, corresponding Kodaikanal optical observations during the flare time are not available. The sunspot is during its second rotation on the disk emerged from the eastern limb on 13 August 1999 and gradually grown having two umbrae on 15 August 1999 (Figure 1). The sunspot has further grown in size from 16 to 18 August. The change in the orientation of the umbrae within the sunspot is clearly visible on 17 August compared to the previous day (Figure 1). The gradual growth in the size of the Hα filament corresponding to this active region is observed in the fitergram and it attained a reverse S-shape on 18 August (Figure 2).

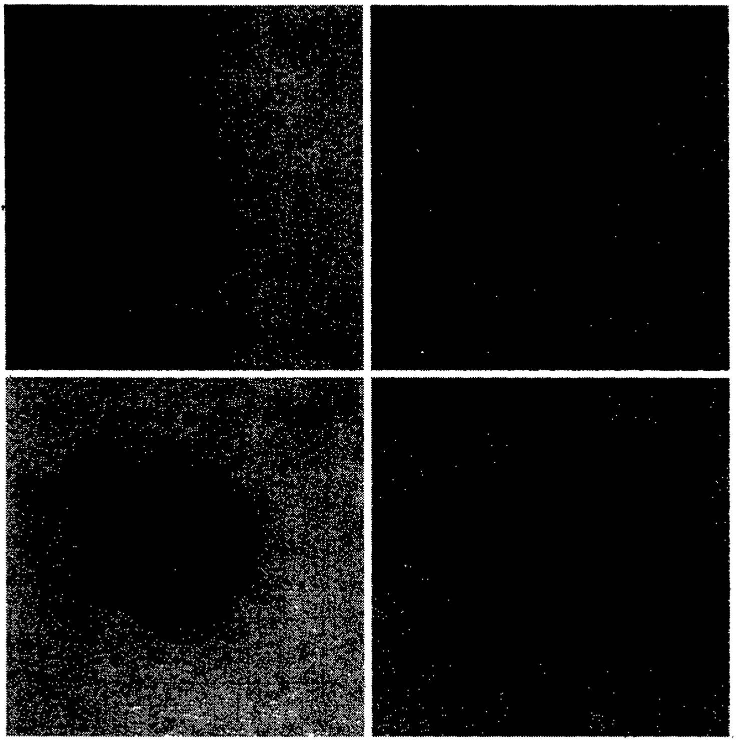

Figure 1. Kodaikanal white light photoheliogram from 15 to 18 August, 1999 showing the sunspot growth and rotation of the umbrae within the spot belonging to the active region NOAA 8668.

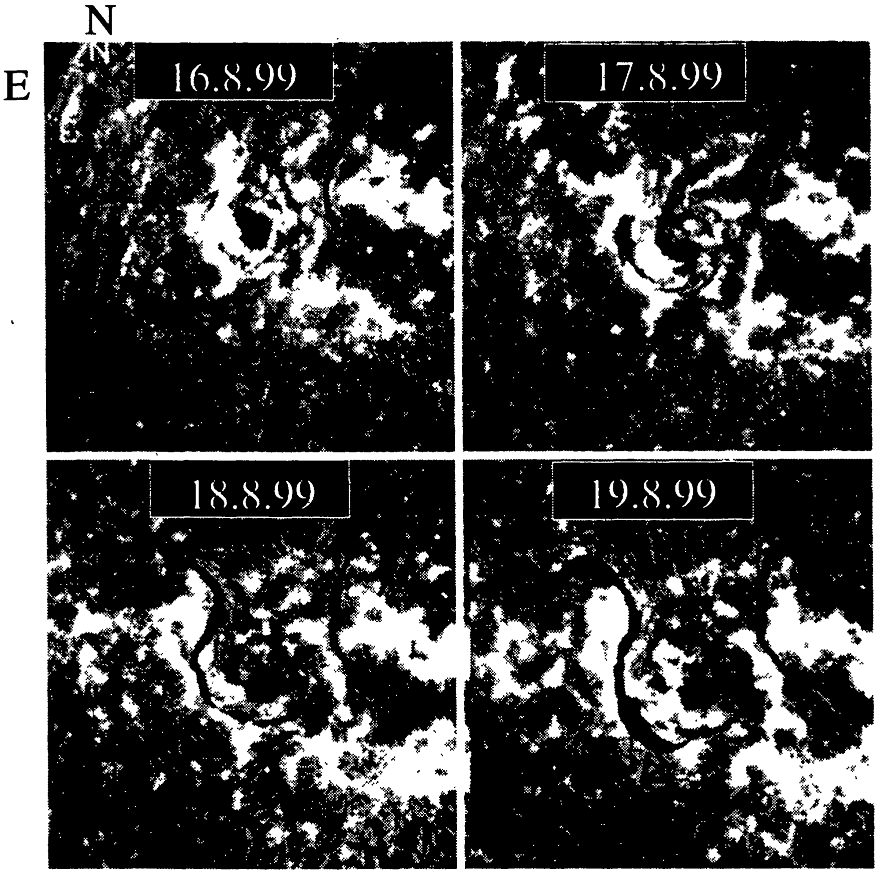

Figure 2. BBSO Hα filtergram from 16 to 19 August, 1999 corresponding to the same active region. The growth of the filament and its reverse S-shaped structure indicates the twist developed in the region.

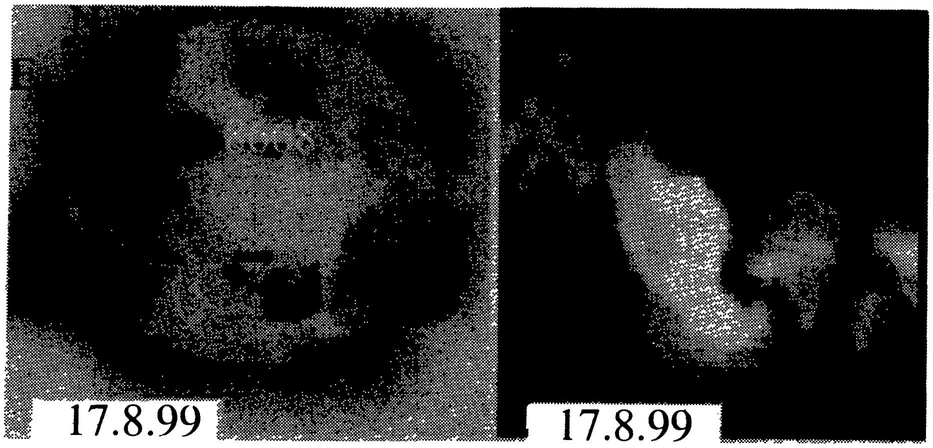

Figure 3. Full disk solar image showing the coronal features in soft X-ray wavelengths on the flare day 17 August, 1999. The sigmoid structure is visible in the left frame while the right frame shows the brightening of the same active region.

The following data reduction procedure is adopted to calculate the shear angle by using the BBSO filtergrams. A straight line is drawn connecting the centres of gravity of the umbrae of the sunspot and is extended to meet the filament and is taken as X-axis. Y-axis is drawn perpendicular to the X-axis at the point of intersection of the Hα filament. The angle between the Y-axis and the filament gives position of the filament with respect to the umbrae of the sunspot on a particular day. Any variation in this angle from one day to the next gives the variation in the direction of the Hα filament with respect to the sunspot position and is taken as shear developed in the active region. Since the filaments lay above the neutral line, there might be some ambiguity in projecting the relative position of the filament and the sunspot over the solar disk. We converted the positions of the sunspot and the filament into heliographic coordinates to identify the errors due to projection in our earlier studies, which showed that conversion to heilographic coordinates did not alter the value of shear angle significantly (eg. Rausaria et al., 1993). Therefore, in the present study we have not taken into account the errors due to projection effects. When the measurements are made near the limb, there is a ± 2° variation due to the effects of foreshortening. Using a similar procedure Sivaraman et al. (1992) made an extensive study of several cases of flares and observed that the change in the shear angle is a deciding factor for a flare to occur and not a large value of shear angle itself. They also found that flares occurred when the change in the shear angle exceeds a threshold value of 15° or more and also that greater the value of change in the shear angle, brighter the flare in Hα.

The analyses of our results are shown in Table 1 that gives the change in the orientation of the Hα filament with respect to the umbrae of the sunspot belonging to the active region NOAA 8668 as a measure of shear. On 17 August 1999 a change of 35° in the filament orientation with respect to the umbrae of the sunspot has been observed. It is felt that successive emergence of magnetic flux pushed the overlying flux, inducing more twist in the region around the filament, which in turn created large variation in the orientation of the Hα filament. It has been realized that the twist in the filament gradually builds up due to the shear motions at their foot points in the photospheric level. We believe that once the twist exceeds a threshold value of 15° obtained by Sivaraman et al. (1992), the kink instability sets in, and activates the filament eruption (Tandberg-Hanssen 1995; Rust & Kumar 1996).

Table 1. Change in the orientation of the Hα filament with respect to the umbrae of the sunspot belonging to the active region NOAA 8668

Date	Orientation angle	Change in the orientation angle with reference to the previous day
15 Aug. 1999	Filament weak	–
16 Aug. 1999	10°	–
17 Aug. 1999	25° (in opp. direction)	35°
18 Aug. 1999	16° (opp.)	9°
19 Aug. 1999	11° (opp.)	5°

3.2 Shear measurement from the changes in the orientation of the umbrae in the sunspot (method 2)

We have also measured the variation in the orientation of the umbrae of the same sunspot belonging to the active region NOAA 8668 as a measure of twist or rotation developed in the sunspot. The orientations of the umbrae in the active region have changed indicating the stressed configuration due to the sunspot growth. The translational motion of the umbrae within the sunspot developed slowly before the flare is triggered on 17 August 1999.

The following data reduction procedure is adopted to measure the shear angle. We have sketched the positions of the sunspot from the photoheliograms on the sun charts by carefully noting the pole markings. To detect the changes in the orientation of the umbrae of the sunspot on a particular day, the rotation axis of the sun was chosen as a reference for the measurement of angles. A line is drawn connecting the centres of gravity of the umbrae of the spot and this line is extended to meet the rotation axis of the sun. The angle made by this line with the rotation axis of the sun is measured from north towards east direction after corrections for foreshortening. This angle gives the orientation of the umbrae in the sunspot on the solar

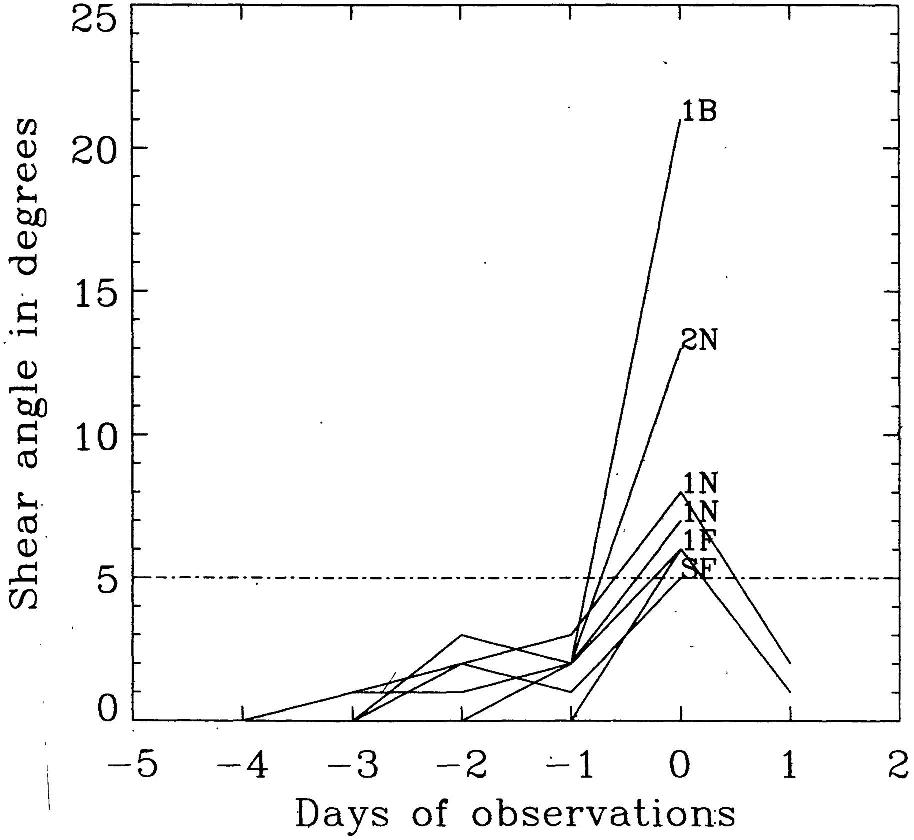

Figure 4. The plot gives the orientation changes of bipolar sunspots as shear angle in degrees versus successive days of observations in the case of some optical flares of different importance. The flare days correspond to '0' in the X-axis. The dashed line parallel to the X-axis indicates the threshold value of 5° shear angle for a flare to occur.

surface on a particular day. Any variation in this angle from one day to the next indicates the shear developed due to the orientation changes in the nucleus of the sunspot group. The most probable error in the measurements of angle is 2^0 when the spot is close to the limb. Figure 4 gives the shear angle in degrees versus successive days of observations studied by *Sundara Raman et al.* (1998) for seven cases of flares by using a similar method. They have shown that once the change in the shear angle crosses the critical or threshold value of 5^0 (shown by dotted lines in the graph parallel to the X-axis) flares are triggered. The analyses of the present study are given in Table 2 and here the changes observed in the orientation of the umbrae are listed as a measure of shear.

Table 2. Change in the orientation of the umbrae in the sunspot of the active region NOAA 8668 with respect to the rotation axis of the sun.

Date	Orientation angle	Change in the orientation angle with reference to the previous day
15 Aug. 1999	too close to limb	–
16 Aug. 1999	64^0	–
17 Aug. 1999	48^0	16^0
18 Aug. 1999	52^0	4^0
19 Aug. 1999	55^0	3^0

It appears that the factors like spot growth / decay deforms the magnetic structures by changing their orientation. It is observed from the table 2 that once the umbral orientation attains a change of 16^0 on 17 August 1999 compared to the previous day, flare is triggered. It is also shown that after relaxation, once the change in the shear becomes less than the critical value obtained from our earlier work (Sundara Raman et al., 1998) flares are not driven in the same active region though the spot has further grown in size on the next day 18 August (Figure 1). Since the change in the orientation of the sunspots on a specific day play an important role on the evolution of a flare, table 2 gives only the magnitude of angular change over one day. A large shear coupled with complexity of the magnetic structures in the photospheric level may probably place the upper limit for the flare. Finding shear with this method may become difficult when the complexity of the sunspot group increases, but still the rapid rotation that could be observed in the nucleus of the spots may forecast a flare. The present observation once again confirms our earlier result (Sundara Raman et al., 1998) that there exists a correlation between flares and large changes in the orientation angle of sunspots.

Figure 5 gives two curves one showing the change in the orientation angle of the umbrae of the sunspot of the active region NOAA 8668 and the other giving the change in the orientation angle of the Hα filament belonging to the same active region. The change in the

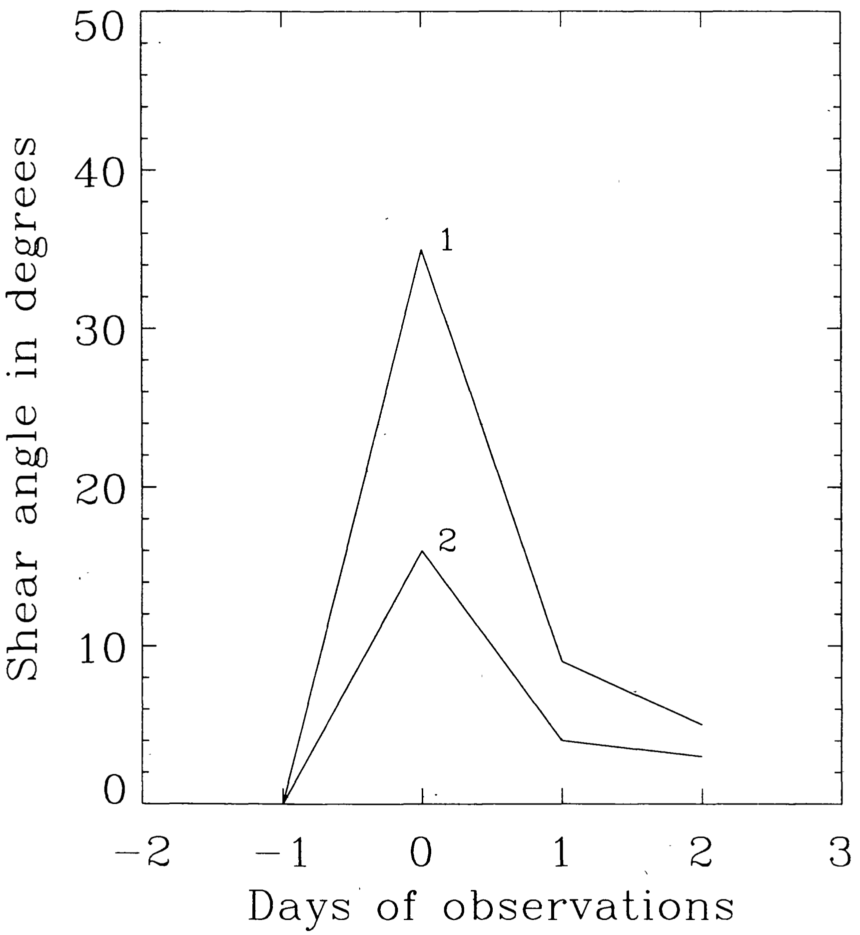

Figure 5. The plot shows the orientation changes as shear angle on successive days of observations. The flare day 17 August 1999 corresponds to '0' in the X-axis. Curve 1 shows the shear angle associated with the filament while the curve 2 represents the same for the sunspot orientation.

orientation angle of the filament (curve 1) to produce flare is large compared to the change in the orientation angle of the umbrae of the sunspot (curve 2) for the same event occurred on 17 August 1999. We infer that shear measurements from the filament orientation with respect to the photospheric activity will be a better indicator to understand the flare triggering mechanisms. In case there are no filaments associated with the flare activation, the second method will be suitable for shear analysis.

4. Summary and conclusions

The manifestation of the coronal phenomena like flares may be due to the complex processes that take place at different atmospheric levels of the sun. As the magnetic field of the active region is deep rooted in the sun, the disturbances developed in the regions below the photosphere would be transferred to the upper layers in the form of changes in the active region configurations which are quite often detected all through the solar atmosphere. That is the instability developed in the active region magnetic fields in the corona for the flare to occur is closely related to the twist developed in the photosphere. We believe that our methodology of finding shear by simultaneously analyzing the changes in the active regions at different atmospheric levels of the sun may shed light on the whole process like the environment, prehistory, and birth of flares.

The dynamic activity of the filament is widely accepted as an indication of the magnetic field change and as a primary and vital step in the flare process. We have shown that the variations in the filament orientations are caused by the relative motions of the umbral regions in the photosphere representing the primary change in the magnetic field re-organization. It has been found that, when the shear change attains a large value or crossing the threshold value, flare is triggered confirming our earlier results (Rausaria et al., 1993, Sundara Raman et al., 1994, 1998). The sunspot belonging to the active region NOAA 8668 is steadily growing due to the successive emergence of flux, which pushes the overlying flux, thus causing the rotation of the sunspot. As a result the overlying filament and the soft X-ray loop attained the reverse 'S' type distortion sense, due to the twist in the magnetic field lines. Thus the excess energy storage for the flare is attributed to the additional twist developed due to the rotational motion at the foot of the filament. Thus it is observed here that the twist is propagated from the emerging flux system to the existing filament making it to erupt once the twist exceeds a threshold value. The frequent association of flares with the filaments thus demonstrate the importance of sheared fields or current sheets to the flare process even though direct observations of sheared fields in the chromosphere is not possible. Major flares of high optical importance are ofen associated with filament eruptions. Therefore, monitoring the filament activation with respect to the adjacent active regions remains to be the top of the precursor for forecasting flares.

The sigmoids are the carriers of magnetic helicity. The flare case studied in this paper represents the association of a reverse S-shaped filament and the sigmoid eruptions indicating the helical instability. We know that the sigmoidal structure observed in the corona is flare productive but the earlier observations have not clearly indicated how the excess energy is gradually accumulated in the coronal level during the flare process. The reverse S-shaped features seen in the SXT pictures are associated with negative magnetic helicity (Rust and Kumar, 1996). The reverse S-shaped Hα filament associated with the active region NOAA 8668 is found to be left handed curving towards sunspot with counter clockwise whirls and so it is dextral with negative magnetic helicity (Chae, 2000). Our observations show the umbrae of the sunspot belonging to this active region exhibiting counter clockwise motion (Figure 1), which would twist a potential field into a left handed structure. It is also known from the explanation of Tanaka (1991) that the shear motions observed in the umbrae of the sunspot are in terms of rising left handed twisted tubes. All these factors indicate that there is a one to one correspondence between the filament chirality and the magnetic helicity sign. It is now known that the fields associated with filament eruption should start from the sun with the same chirality (Rust, 1999). Hence, it is believed that the observations presented in this paper show the filament accumulating magnetic helicity due to the gradual shear motions of the umbrae at the photospheric level. Once the filament is supplied with very high magnetic helicity due to the photospheric activity, the MHD instability sets in, which eventually activates the filament eruption. The magnetic helicity associated with the excess magnetic energy in the solar corona has been released in the form of a flare. The solar eruption in fact indicates the shedding of the excess magnetic helicity that might have been generated probably even in the sub-photospherhic level. The changes in the umbral orientation were observed first and later the flare occurred on 17 August. Therefore, it appears that the motions of the umbrae may have caused the necessary shear for the flare to be triggered through filament activation. Thus, the entire geometry of the active regions of both photosphere and chromosphere taking part in the flare activity are studied simultaneously to account for the accumulation of magnetic helicity.

The shear derived by this method is completely different from the ones computed from the studies of vector magnetograms. We would like to emphasize here that the studies of solar active regions based on photoheliogram and spectroheliogram data are still very much useful for flare predictions. The present situation indicates the need to have simultaneous multi-wavelength observations with high spatial and sufficient temporal resolution. There is no doubt that the continuous acquisition of high quality optical data will be most valuable. But along with high resolution X-ray images, the optical observations can project a comprehensive picture of the magnetic field structure that precedes a flare and how it changes as result of the flare. Further effort towards that goal is in progress as we approach towards the maximum period of the 23rd solar cycle.

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