Effects of sunspot umbral rotation in the onset of flares

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Abstract: By using the Kodaikanal data, the morphology of solar active regions are carefully analyzed to find out the causes for onset of flares. It has been observed that the sunspots underwent evolutionary changes during their disc passage. The emergence and decay of flux in the complex δ - type sunspot groups are found to be associated with the changes in the orientation of the prominent umbrae observed in these active region sunspots. A new diagnostic tool is arrived to predict the occurrence of solar flares by calculating the changes in the orientations of the umbrae within the sunspot groups. It is found that the umbral rotation coupled with the flux changes observed in the photospheric magnetic fields of sunspots played major roles in the triggering of flares.

Key-words. sunspots, umbrae, active regions, flares

1. Introduction

Solar flares are energetic phenomena that are observed in the solar atmosphere, wherein conversion of magnetic energy into other forms of energy takes place as a sudden outburst. However, the process of gradual accumulation of magnetic energy that is available for flare is not yet clearly understood. The primary condition for a flare to occur is the presence of one or more active regions. Flares occur not only in large, complex active regions, but also with the smallest resolvable regions. Therefore, now it is realized that size or strength of magnetic fields are not important factors for the onset of flares (Martin 1980). Flares do not occur at random locations within an active region, but invariably are related to boundaries between positive and negative fields. These boundaries are often referred to as neutral lines. Flare positions relative to photosphereic magnetic fields show that flares occur near the polarity inversion lines (Smith and Ramsey, 1967).

Regardless of different configurations depicted by different models, it is observed on many occasions that the magnetic field structure and evolutionary changes in the photosphere are associated with the flares. The development and decay of sunspots are indicators on the evolution of active regions in the photosphere. Sunspot motions are the consequences of the evolutionary changes that are observable in the sunspot groups. These sunspot motions could be significant factors in the energy buildup of flares. There are studies comparing the close relationship of sunspot proper motions and the flare productivity of active regions (Yang et al, 2004 and the references therein). It was also shown that the flare locations were near the sites where the umbrae of the sunspot underwent more rotation (Sundara Raman, Ramesh and Selvendran, 2003). Horizontal photospheric sunspot motions played crucial roles at least in some of the flares (Sundara Raman, Selvendran and Thiagarajan, 1998, Moon et al, 2002). All these studies projected the importance of making further contributions to comprehensively understand the complex movement in the sunspot groups to arrive at any critical condition towards the flare triggering mechanisms.

2. Photospheric magnetic fields and magnetic shear

Recent studies have shown that the magnetic flux from the solar interior emerges across the photosphere already in a significantly twisted state (Ishii, Kurokawa and Takeuchi, 1998). The general theoretical understanding is that the subphotospheric convective motions twist, and shear the foot points of these magnetic loops leading to topological complexities and builds up a stressed flux system and excess energy. Vector magnetic field measurements in the photosphere provide direct evidence for the twisted or sheared nature of magnetic loops. A quantitative measure of magnetic shear at the photosphere was first proposed by making a detailed study of one active region using vectormagnetogram (Hagyard, Smith, Teuber and West, 1984). They defined the azimuthal difference between the directions of the observed field and of the calculated potential field as a degree of magnetic shear and found large values of shear at the flare sites on the polarity inversion lines of bipolar active regions in the photosphere. However, there are many contradictory results relating magnetic shear and flare occurrences (see Sundara Raman, Ramesh and Selvendran, 2003). As the potential field contains minimum energy, the free energy available for the flare must be coming from non-potential fields, and locating such kinds of fields are important to understand the flare process. Evolutionary changes in sunspots are slow and take place many hours or even days prior to the flare onset. The complexity developed in the magnetic structure of the photosheric magnetic fields during the sunspot evolution induces stress, causing changes in the magnetic field pattern. We feel that the changes observed in the magnetic field pattern in active regions indicate plasma motions and outline the storage of magnetic energy departing from potential field. With this approach, we have carefully analyzed the Kodaikanal photoheligoram data to identify the morphological changes in the photospheric magnetic fields that may be related to the occurrence of solar flares.

Daily white light picture of the Sun of diameter 8" is taken regularly at Kodaikanal by using a 6" refractor. Hα spectroheliograms are also recorded daily using a Litrrow mount with a solar image diameter of 60 mm. The following procedure is adopted to measure the shear angle from the change in the orientation of the umbrae in the flare producing bipolar sunspot group. Figure 1 shows two types of bipolar groups that are commonly observed, one having separate umbra-penumbra structure and the other with multiple umbrae embedded in a common penumbra. 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 'θ' measured from north to east between this line and the rotation axis is taken as the orientation of the umbrae on that day of observation (Figure 1). Any variation in this angle from one day to the next gives the change in the orientation of the umbrae indicating the rotational motion and the shear developed in the sunspot group (Sundara Raman, Selvendran and Thiagarajan, 1998). The analyses were carried out when the sunspots were within 50° on both sides of longitude to avoid foreshortening effects. The most probable error in the measurement of angle is ± 2° when the spots were closer to the limb. It has been shown in our earlier papers that flares were triggered once the shear angle exceeds a critical value of 5°. The shear derived in this method is completely different from the magnetic shear measured from the vector magnetograms but the role of spot motions or rotations as seen for instance in the relative motion of the umbrae in the spot group is also a good indicator of the shear developed in the active region.

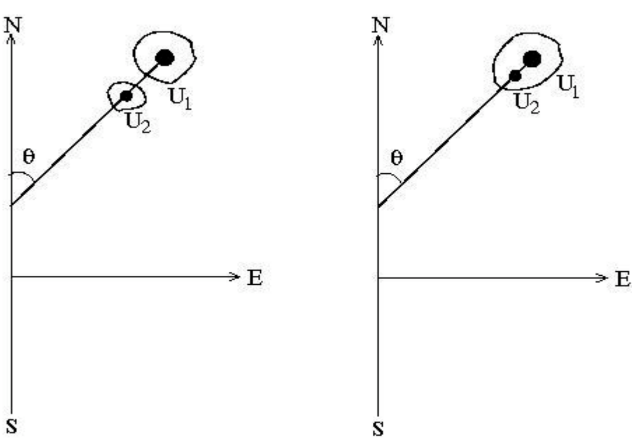

Fig. 1. Details of the technique used to measure the shear angle. U1 and U2 are the umbrae of the bipolar sunspot. Angle 'θ' gives the orientation of the umbrae in the sunspot on a day. NS is the rotation axis of the Sun.

3. The development of flares in the AR NOAA 10570

Though we have studied and analyzed many sunspot groups for measuring the shear angle in our earlier papers, the development of flare in the AR NOAA 10570 is alone described in this paper as an example. Figure 2 gives the photohliograms observed from 9 to 16 March 2004 and Figure 3 depicts the Hα spectroheliograms showing the flares observed in this active region on 11 and 14 March 2004. The image scales are marked in the Figures. The morphology of the entire spot group belonging to this active region is carefully analyzed for finding out any changes. Figure 4 depicts the chart indicating the change in the orientation of the umbrae in the sunspot group.

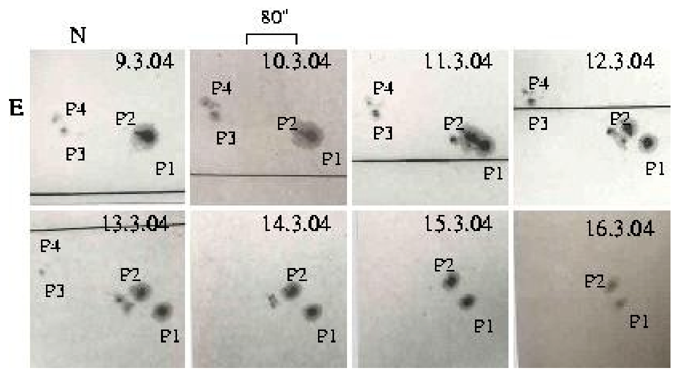

Fig. 2. White light photoheliograms of the active region NOAA 10570 observed at Kodaikanal from 9 to 16 March 2004. The umbrae P1, P2 (in the leading spot) and P3, P4 (in the following spot) are taken for shear angle calculations.

Figure 2 shows the complex sunspot group NOAA 10570 divided into two groups P1, P2 (leading) and P3, P4 (following) and the change in the orientation of these two groups were calculated independently. The leading sunspot appears as a single umbra on 9 March 2004. On the next day 10 March 2004, it has grown further. Subsequent development of the leading spot has taken place on 11 March 2004, and the penumbra is embedded with two umbrae P1 and P2 along with a satellite pore emerging adjacent to P2. The heliographic coordinates of the sunspot group on 11 March 2004 are 12°E 13°S. A longitudinal separation of 2° on the east-west is observed between P1 and P2 on 11 March 2004. A 2N flare is observed adjacent to P2 on 11 March 2004 (Figure 3). Since the leading spot contains two umbrae P1 and P2 from 11 March 2004, shear angle calculations are made in this group only from 11 March 2004. Both P1 and P2 are completely detached and appear as individual spots on 12 March 2004, and the satellite spot adjacent to P2 has grown. The configuration of P1 and P2 remains the same on the next day 13 March 2004. Both P1 and P2 are 3° apart in the east-west on 12 and 13 March 2004. The size of the satellite spot close to P2 is reduced on the next day 14 March 2004. The shear angle changes by 8° and the east-west separation between P1 and P2 increases to 4° on 14 March 2004. A 2N flare is observed again in the same region on 14 March 2004. The satellite spot disappeared on 15 March 2004 and there is no appreciable change both in the shear angle and east-west separation between P1 and P2 on 15 March 2004. On the next day 16 March 2004, the spot has gone close to the limb (56°W 13°S).

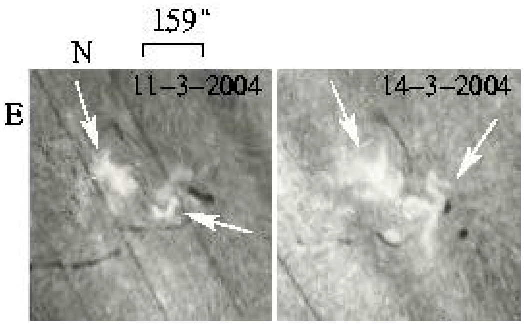

Fig. 3. Hα Spectroheliogram observed at Kodaikanal on the flare days 11 and 14 March 2004. The arrows indicate the flare regions.

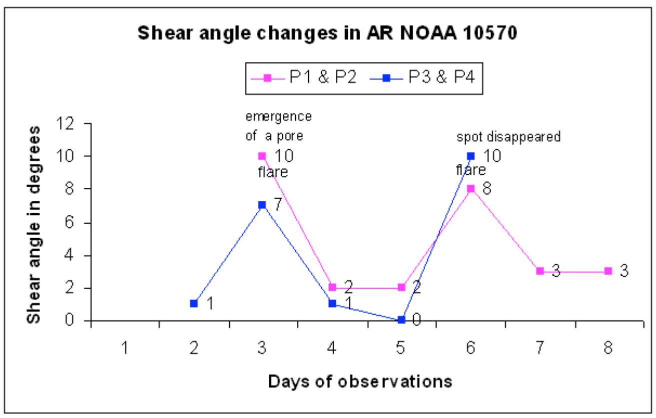

Fig. 4. Shear angle in degrees are plotted from the changes in the orientations of the umbrae. Two plots are shown to indicate the shear changes between P1 & P2 and P3 & P4.

In the case of the following spot group P3 and P4, there is a growth on 10 March 2004 compared to the previous day. The spot group is reduced on the next day 11 March 2004 and a change of 7° is observed in the shear angle. A 2N flare has taken place in the region towards the leading side on 11 March 2004 (Figure 3). The spot group P3 and P4 do not have any appreciable change in the configuration on the next day 12 March 2004. It has decayed and reduced to a pore on 13 March 2004 and disappeared on the next day 14 March 2004. A 2N flare is once again observed in the same region on 14 March 2004 (Figure 3). Shear angle in this group is calculated from 9 to 12 March 2004 since the spot group starts decaying from then onwards. Both the flares observed in this active region occurred between the locations of the leading (P1 and P2) and following (P3 and P4) groups of sunspot belonging to this active region. The emergence of flux in P1 and P2 and the decay of the group P3 and P4 on 11 March 2004 may have brought the necessary conditions in the shear angle changes for the onset of flare. As for the flare observed on 14 March 2004, the disappearance of the group P3 and P4 coupled with decaying satellite spot and the shear angle change observed in P1 and P2 may be responsible for the triggering of flares in the same location.

One more example of shear angle measurements is shown in Figure 5 that are made by carefully analyzing the evolution of the sunspot groups belonging to the three major events that occurred during October 2003. There were three big sunspot groups NOAA 0484, 0486 and 0488 observed during October 2003, each producing series of flares. The evolutionary developments in these sunspot groups leading to flares are not described in this paper. We have given only the plot made for these three major events (Figure 5), as we felt that a single plot showing the shear angle changes of all the sunspot groups studied by us will be difficult to read. The flare importance is marked in the plot, followed by KKL in closed brackets indicating these flares were observed at Kodaikanal. Flare details from *Solar Geophysical Data* are used for the missing days of Kodaikanal Hα spectroheliogram data for the events observed during October 2003. A horizontal line drawn at 5° in the Y-axis represents the threshold value of shear angle change. Once the shear angle crosses this critical limit, flares occurred in the regions belonging to these sunspot groups.

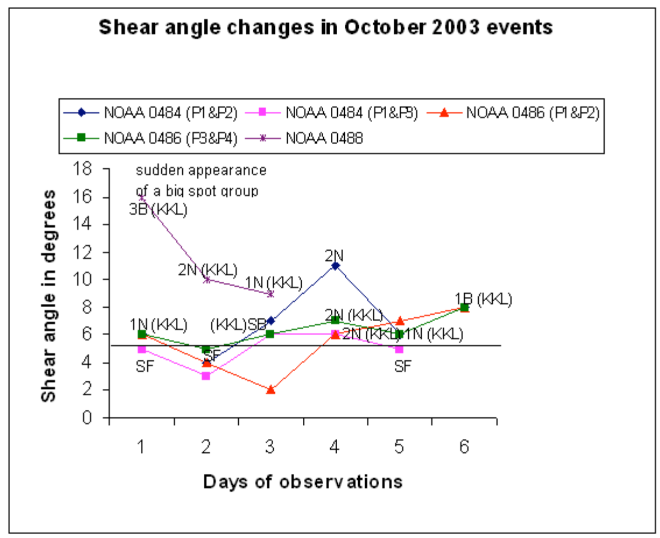

Fig. 5. Shear angle in degrees are plotted for the October 2003 flare events that occurred in the active regions NOAA 10484, NOAA 10486 and NOAA 10488. KKL indicates the flares observed at Kodaikanal.

4. Summary

Coronal levels are considered to be flare sites, but it is difficult to measure and trace the evolution of the coronal magnetic fields with any spatial resolution. It is widely believed that a dynamo process happening below the convection zone generates the magnetic fields of the Sun. The magnetic fields emerge to the solar surface due to magnetic buoyancy as a pair of opposite polarity magnetic patches. Theoretical studies emphasized on the process of magnetic reconnection from the rearrangements of opposite polarity magnetic fields in an active region for a flare onset, but the direct observational evidence of magnetic reconnection is difficult to achieve. The magnetic field lines of active regions break out to the solar atmosphere, forming magnetic loops that connect subphotospheric regions to higher layers (Galsgaard, Moreno-Insertis, Archontis and

Hood, 2005). Any small change or twist observed in the photosphere is transmitted to the corona till the conditions are favorable for magnetic reconnection to take place. Recent X-ray observations have revealed the presence of S or inverse S type ‘sigmoids’ before solar eruptions (Canfield, Hudson and McKenzie, 1999, Sundara Raman, Ramesh and Selvendran, 2001). The sigmoids are twisted bundles of coronal loops observed above the sunspots or filaments (Rust and Kumar, 1996). When there are two such tubes, say sunspots, that are close together with the initial longitudinal field in opposite directions, and also that they are twisted in opposite senses, then oppositely directed fields will come into contact. When the oppositely directed fields merge and reconnect, they annihilate one another and release magnetic energy, which is transformed into heat and kinetic energy of the plasma. The same is shown by our results inferring that the sunspot umbral rotation that are observed during the sunspot evolution represent the shear or twist developed in the active region, bringing the favorable condition for the reconnection to take place for flare onset. The umbral rotation observed by us indicates the amount of twist induced in the flux tube, which might contribute the excess energy gradually getting stored in the tube compared to the energy level in an untwisted potential field. We have used the term ‘shear angle’ to represent the change in the orientation of the umbral positions, as these changes represent the shear motions developed in the active region sunspot group.

The evolution of the active regions that are shown in our papers clearly shows that flares are triggered on the days when there is an emergence, decay or disappearance of flux associated with the shear change observed in the sunspot umbral orientation. Also it is shown that flares are triggered once the shear angle calculated from the change in the orientation of the umbrae in the sunspot group exceeds a threshold value of 5°. However, it is not yet clear whether the shear that is created from the twist in the dynamo itself is capable of acquiring the energy released at the time of the flare or any additional shear is induced in the photosphere to cater the needs of the excess energy that is blown out at the time of the flare. We have given more attention to white light observations, as the interpretation is straight forward compared to the polarization measurements of vector magnetograms. High-cadence space data are available in recent years, which make the flare research as a hot topic. High spatial and temporal resolution white light images along with the multi wavelength observations may pave the way for a better understanding of the physical processes involved in the flare triggering mechanisms.

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