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Evolution of the active region NOAA 10570 associated with the flares

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The structure and evolution of the photospheric magnetic fields observed in the active region NOAA 10570 are analyzed using Kodaikanal photoheliogram and spectroheliogram data. It is attempted to evaluate the shear angle changes by carefully observing the prominent umbrae belonging to the active region. These changes in the orientation of the umbrae infer the rotational motion developed in the sunspot group. It is found that the flux and shear angle changes observed in the sunspot configurations are related to triggering of flares in the active region NOAA 10570.

1. Introduction

Solar flares are energetic phenomena that occur in the solar atmosphere, wherein a sudden outburst of energy is released from localized regions in the solar atmosphere. It is now well known that condition for a solar flare to occur is the presence of one or more solar active regions. Active regions are the manifestations of magnetic fields in the solar atmosphere. Initial investigations of the relationship between flare productivity and magnetic fields are made by Giovanelli [1], Kleczek [2], Bell and Glazer [3]. Flares not only occur in large, complex active regions but also with the smallest resolvable regions. Therefore, now it is realized that the size or strength of the magnetic fields are not important factors for the onset of flares [4, 5]. 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 photospheric magnetic fields show that flares occur near the polarity inversion lines [6-9].

Time and again studies are made on sunspot groups producing flares, but still we do not have any comprehensive picture for arriving at a sufficient and necessary condition for flare occurrence. Regardless of different configurations depicted by different models, it is observed that the magnetic field structure and evolutionary changes in the photosphere are associated with the flares [10]. 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 at least some flares. There are studies comparing the close relationship of sunspot proper motions and the flare productivity of active regions [11-14]. McIntosh & Donnelly [15] observed collisions or approach between sunspot groups producing important flares. Even small sunspot groups are associated with major flares if the spot motions are especially large [16, 17]. Separation between sunspots decreased prior to a large flare and increased after the flare [18]. It was also shown that the flare locations were near the sites where the umbrae of the sunspot underwent more rotation [19]. Horizontal photospheric sunspot motions played crucial roles at least in some of the flares [14, 19-21]. 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

Major flares mostly occur near the neutral lines of photospheric magnetic fields, where there is a strong gradient in the magnetic fields, and also where the horizontal component is strongly sheared

[22-24]. Based on this, it was attempted to find out the role of magnetic shear in flares [25-27] whereupon the concept of magnetic shear occupied the central stage to understand the flare triggering processes. Strong magnetic shear are identified near the neutral line at the photosphere before the occurrence of the flares based on the studies of vectormagnetograms [28-32]. However, it has been found on several occasions that such strong shear also occurred in the active regions without resulting any flares [13, 33-36]. Also some flares showed increased magnetic shear [37], whereas observations made by Kusano et al [38] showed reduced photospheric shear. The results from the studies conducted at the Marshall Space Flight Center [39, 40] are inconclusive as the morphology of the active region magnetic fields and magnetic shear decreased, increased or unchanged as a result of solar flares. Chen et al [41] studied more than 20 flares and determined that there was essentially no apparent change in the magnetic shear associated with the flares. Wang [42] modified and defined the 'shear' as the product of the shear angle and the measured transverse field strength to describe magnetic shear in solar active regions, and subsequent studies of Wang et al [37, 43, 44] showed increase in magnetic shear after the flare. The different observational inferences relating magnetic shear and flare occurrences may be due to the fact that magnetic shear is measured from the angular difference between the observed transverse field and the model potential field near the photospheric neutral line, whereas shear may be present even in the extended areas away and above the photospheric neutral line. In view of this, we feel that it is desirable to study the entire morphology of the active region magnetic fields to understand the flare process.

3. The development of flare in the active region NOAA 10570

Vector magnetic field measurements in the photosphere provide direct evidence for the twisted or sheared nature of magnetic loops. In the absence of vectormagnetogram facilities at Kodaikanal, an alternate method has been attempted by Sivaraman et al [45], Rausaria et al [46] and Sundara Raman et al [47] to find out the shear based on the comparisons of H_α pictures and photoheliograms available at Kodaikanal. The magnetic field measurements of the active regions have shown that the path traced by an H_α filament indicates the magnetic neutral line and lies along the dividing line between the regions of opposite polarity [4,5]. Based on the concept that the changes in the magnetic field structure due to magnetic shear may change the orientation of the H_α filament, the studies done at Kodaikanal [45-47] used the argument to calculate the value of shear from the changes in the orientation of the H_α filaments with respect to the bipolar sunspots belonging to the active region by superposing the spectroheliogram image onto the photographic print of its photoheliogram mate. Using the procedure explained in these papers [45-47], it is shown that a change in the shear, not the large value of shear, is the forerunner criterion for the onset of flares. Rausaria et al [46] have shown that the shear thus calculated significantly changed over a short period before the onset of flare. In the absence of a prominent H_α filament between the regions of opposite polarity sunspots belonging to the active region, Sundara Raman et al [14] have computed and analyzed the shear angle from the changes in the orientation of the sunspot group, by concentrating the main umbrae belonging to that group. In the present paper, Kodaikanal photoheliograms were analyzed to study the flares observed at Kodaikanal in the active region NOAA 10570.

Daily white light picture of the Sun of diameter 8" is taken regularly at Kodaikanal by using a 6" refractor. $H\alpha$ spectroheliograms are also recorded daily using a Littrow mount with a solar image diameter of 60 mm. The procedure described in our earlier paper [14] is adopted to measure the shear angle. A line is drawn connecting the centers of gravity of two umbrae belonging to the sunspot group NOAA 10570 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 that 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 rotational motion developed in the sunspot group. It is fairly easy to calculate the centers of gravity of the sunspots chosen for the analyzes. The analysis were carried out for the dates when the sunspot group was within 50° on both sides of longitude to avoid foreshortening effects. The most probable error in the measurement of angles is ± 2° when the spots were closer to the limb. It has been shown in our earlier papers [14, 48] that flares are triggered once the shear angle exceeds a critical value of 5°

The optical flares observed at Kodaikanal in the active region on 11 and 14 March 2004 are considered in our analysis. Figure 1 gives the photoheliograms observed from 9 to 16 March 2004. Figure 2 depicts the Hα spectroheliograms showing the flares observed in this active region on 11 and 14 March 2004. The morphology of the entire spot group belonging to this active region NOAA 10570 is carefully analyzed for finding out any changes, and the prominent umbrae P1, P2, P3 and P4 of this sunspot group are chosen for the measurement of shear angle. Table I gives the shear angle that gives the change in the orientation of the umbrae in the sunspot group.

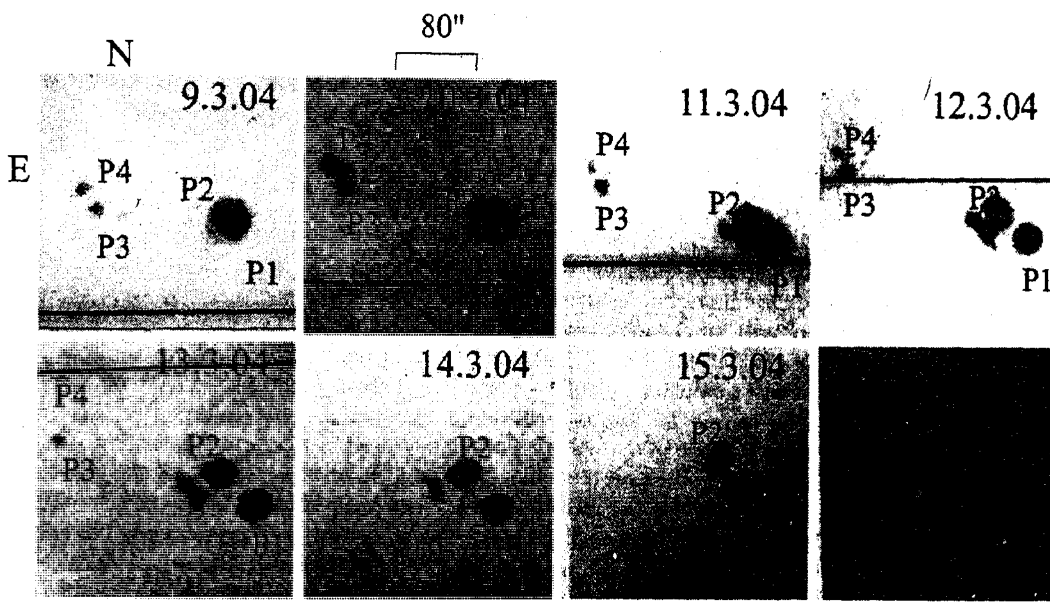

Figure 1: White light photoheliograms of the active region NOAA 10570 observed at Kodaikanal from 9 to 16 March 2004. The umbrae P1, P2 (in the following spot) and P3, P4 (in the leading spot) are taken for shear angle calculations.

Figure 1 shows the complex sunspot group NOAA 10570 divided into two groups P1, P2 (following) and P3, P4 (leading) and the change in the orientation of these two groups were calculated independently. Figure 1 shows the following 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 following 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 NOAA 10570 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 2). Since the following 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 is changed 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).

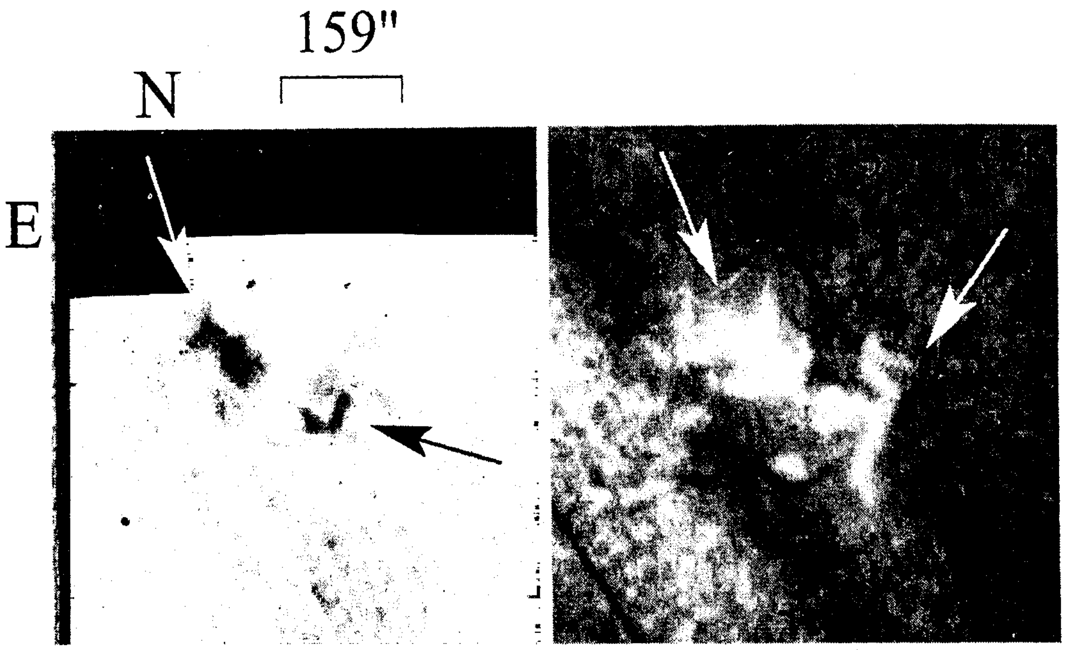

Figure 2: Hα spectroheliograms observed at Kodaikanal on the flare days 11 and 14 March 2004. The arrows indicate the flare regions.

In the case of the leading 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 following side on 11 March 2004 (Figure 2). 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 2). 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 (P3 and P4) and following (P1 and P2) group of sunspots 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 measured in this paper for the flare onset. As for the flare observed on 14 March 2004, the disappearance of the group P3 and P4 coupled with the shear angle change observed in P1 and P2 may have brought in the sufficient conditions for triggering the flare in the same location.

Table I
Shear angle in degrees measured from the change in the orientation of the umbrae belonging to the sunspot group NOAA 10570

Date	Orientation of the umbrae P1 & P2	Shear angle change in degrees	Orientation of the umbrae P3 & P4	Shear angle change in degrees
09 Mar. 2004	—	—	47	—
10 Mar. 2004	—	—	48	1
11 Mar. 2004	77	flare	55	7 flare
12 Mar. 2004	75	2	54	1
13 Mar. 2004	73	2	single pore	—
14 Mar. 2004	65	8 flare	disappeared	flare
15 Mar. 2004	62	3	—	—
16 Mar. 2004	59	3	—	—

4. Summary

Coronal levels are considered to be flare sites, but it is difficult to measure and trace the evolution of coronal magnetic field with any spatial resolution [49]. Zhang & Low [50, 51] theoretically showed the physical picture in the corona in response to new flux emergence. Theoretical studies emphasized on the process of magnetic reconnection [52] from the rearrangement of the magnetic fields in an active region for a flare onset, but the direct observational evidence of magnetic reconnection is difficult to achieve. Studies have shown that the magnetic flux from the solar interior emerges across the photosphere already in a significantly twisted state [53-55]. 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. Sivaraman et al [45] and Rausaria et al [46] showed that the sunspot motions in the bipolar regions at the photosphere destabilized the H_α filaments at the chromospheric level. By studying similar dynamical variations in the H_α filament, Sundara Raman et al [47] concluded that the filament becomes unstable due to the shearing motions of sunspots forming a current sheet below the filament where reconnection occurs and energy is released to power a solar flare. H_α filament is a dark thread like structure observed generally in H_α pictures of the Sun, and in fact is a prominence embedded in the corona overlying an inversion line of the photospheric magnetic field. The transition region between prominence and corona is very thin, and in general similar to the chromosphere-corona transition region. Recent X-ray observations have revealed the presence of

S or inverse S type 'sigmoids' before solar eruptions [48, 56]. The sigmoids are twisted bundles of coronal loops observed above the sunspots or the filaments [57, 58]. Most of the observations have shown that the magnetic shear in both photosphere and chromosphere is eventually responsible for bringing the favorable conditions for the solar eruption to occur. All these observations support the twisted flux bundle model as the fundamental processes taking place in the solar flares. The opposite polarities in an active region anchored in the photosphere are linked by flux tubes extending into the chromosphere and corona. The amount of twist the flux tubes undergoes is the measure of the excess energy stored in the tube compared to the energy level in an untwisted potential field. 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. In order that the magnetic field **B** should reverse, a current **j** must flow in the boundary layer and therefore, the term 'current sheet' is often used. 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 [59].

The evolution of the active region NOAA 10570 analyzed in this paper 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 orientation belonging to this active region. It is also shown that the observations of the umbrae P1 and P2 exhibit east-west drift that are clearly visible from 11 to 14 March 2004 (Figure 1) during its evolution, and moreover the threshold value of 5^o in shear angle change is exceeded on the flare days of 11 and 14 March 2004. It may be possible that in addition to the shear induced by the differential rotation there may exist photospheric shearing motions. However, it is not yet clear whether the shear that is created from the twist in the dynamo itself is capable of acquiring the excess 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 released at the time of the flare. Further studies of observations with high resolutions along with vectormagnetograms are needed to detect precisely the photospheric active region magnetic field configurations that may throw more light on the relationship between evolution of active regions and flares.

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