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The Flares Associated with the Dynamics of the Sunspots

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Abstract. In the present study, we consider six years data of spot groups that have well developed leading and following spots obtained from the Kodaikanal Observatory white light pictures and occurrence of Hα flares. From the daily observations, we compute the variations in rotation rates, meridional velocity, the areas and longitudinal separations. We find that among all these variations, the occurrence of abnormal rotation rates (the rotation rates that have greater than 1σ) and longitudinal minimum separation during the course of their evolution eventually lead to triggering of flares. We also find that the events of abnormal rotation rates, longitudinal minimum separation and the flares occur mainly during the 50–80% of the sunspots' life span indicating magnetic reconnection probably below ($0.935\ R_{\odot}$) the solar surface. Relevance of these results with the conventional theory of magnetic reconnection is briefly discussed.

Key words. Sunspots — rotation — magnetic flux — magnetic reconnection.

1. Introduction

Sunspots are supposed to be associated with many transient activity phenomena such as flares, coronal mass ejections (CME), etc. The following studies show the association between changes in the sunspots' dynamics, emerging flux region, twisting of the field lines above the solar surface, magnetic shear and all of these activities together with eventual triggering of the flares.

Tanaka and Nakagawa (1973) have shown that the required energy storage for the eventual triggering of the flares is due to proper motion of the sunspots. Using disc passage observations of sunspot activity NOAA 2372 during April 4–13, 1980 Ambastha and Bhatnagar (1988) show that all the sunspots within an activity group experienced the large proper motions before the major flare events. From the analysis of polarity distributions in sunspot groups that produced solar proton flares, Sakurai (1976) inferred that the origin of solar flares may be closely related with the instability that is associated with twisting of sunspot field lines in the chromosphere and the lower corona. Ishii *et al.* (1998, 2003) using a variety of solar activity phenomena conclude that emergence of twisted flux bundle is the key cause for production of the flares. Using six year (1969–1974) observations of Kodaikanal Observatory white light pictures, Hiremath & Suryanarayana (2003) showed that either leading or following or both of the bipolar spot groups that have abnormal rotation rates during the course of their evolution are strongly associated with the occurrence of flares in the later stage of their life span.

Another important precursor is the magnetic shear (Hagyard *et al.* 1984) that triggers the flares. The continued evolution of the magnetic flux causes the field's maximum shear to exceed a critical value of shear resulting in triggering of the flares. Later studies (Venkatakrishnan *et al.* 1989; Ambastha *et al.* 1993; Schmieder *et al.* 1997) also confirm the view that magnetic shear is one of the important properties for production of the flares.

Yet it is still an unsettled problem whether flares and CMEs are triggered by changes in the erupting magnetic flux resulting in shear, or dynamics of the sunspots or triggered by both (Schmieder *et al.* 1994) of these activities.

The conventional belief (Priest 1981; Haisch & Strong 1991; Parker 1994; Lin *et al.* 2003) is that the source of energy for producing the flares is due to *magnetic reconnection* of the opposite polarities wherein the flux is annihilated in a compact region. If one accepts this conventional belief, however, there are no conclusive evidences whether reconnection of the magnetic field lines occur in the solar atmosphere or below the photosphere. There are some studies (Zirin & Liggett 1987; Leka 1996; Canfield & Pevtsov 2000; Hiremath & Suryanarayana 2003) suggesting that reconnection events may be taking place below the photosphere. In both the cases of reconnection events that may be occurring above or below the photosphere, approaching of sunspots towards each other and then merging of foot points is necessary. The other two crucial conditions for magnetic reconnection are as follows: For magnetic field of strength of B and length scale L, energy released due to magnetic reconnection of opposite polarity field lines is $\sim L^3 B^2$. That means, in order to produce the observed flare energy ($\sim 10^{27}$–10^{33} ergs) (Metcalf, Leka and Mickey 2005) the length scale of reconnection region should be $\sim 10^5$–10^9 cms. The third crucial condition for the events of magnetic reconnection is that the inflow velocity in the vicinity of reconnecting region is ~ 0.1 times the Alfvén velocity (Petschek 1964), where Alfvén velocity is computed from the ambient magnetic field and density structure.

In order to confirm these three crucial conditions for the magnetic reconnection, using Kodaikanal Observatory data, we search for such events and show that whenever the sunspot groups (containing the leader and the follower) have the events of abnormal rotation rates and the minimum longitudinal separation, flares eventually trigger in that region. In section 2, we present the motivation for this study. The data analysis and the results are presented in section 3. The results with conclusive evidences for the magnetic reconnection are presented in the last section.

2. Motivation for the present study

The present general consensus is that sunspots originate below the solar surface due to an unknown dynamo mechanism. Due to very high conductivity of the solar plasma and assuming that raising flux tube does not acquire extra flux from the ambient medium, sunspots isorotate with the internal plasma and due to buoyancy rise towards the surface along the path of rotational isocontours. This implies that sunspots are very good tracers of the internal dynamics and structure of the solar interior. Hence if the sunspots which have first and second days appearance on the surface and if one computes their initial rotation rates, then one can infer rotation rate of the internal solar

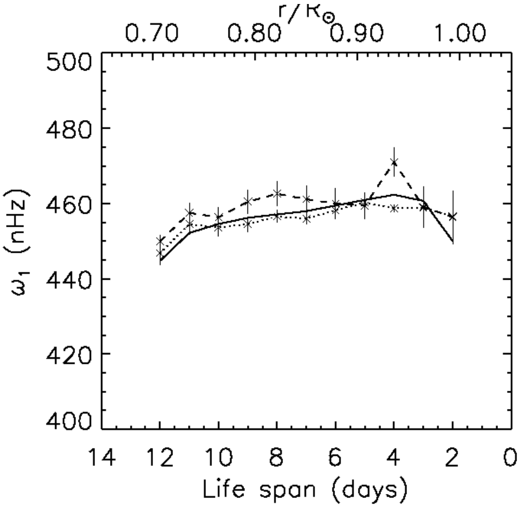

Figure 1. Initial rotation rate of the sunspot groups with respect to their life span. Continuous curve is helioseismologically inferred radial variation of rotation. Dotted curve represents the rotation rates of spot groups having areas $<$ 100 mh and dashed curve represents the rotation rates of spot groups having areas $>$ 100 mh. In the same plot, radius values are plotted along the top x axis.

plasma where the sunspots' foot points are anchored. Recent studies (Hiremath 2002 and references there in; Zuccarello and Zappala 2003) show that variation of the initial rotation rates obtained from the daily motion of sunspot groups with respect to their life spans is almost similar to the radial variation of the internal rotation profile of the solar plasma. From Hiremath's (2002) paper, we reproduce the results in Fig. 1 that illustrate the comparison between the variation of initial rotation rates of the sunspot groups for different life spans and radial variation of internal rotation profile as inferred (Antia, Basu and Chitre 1998) from the helioseismology. Note the striking similarity between these two profiles. In order to reach closer to the reality of the physics of convection zone and dynamics of the flux tubes, in the same study, the rate of change of initial rotation rates of the sunspot groups (that represent the acceleration or deceleration of the flux tubes in the ambient plasma) are compared (see the Fig. 5(b) of Hiremath (2002)) with the radial profile of gradient of rotation (that is computed from the radial variation of rotation of the plasma inferred from the helioseismology). Again we get a striking similarity between these profiles.

To conclude from that study (Hiremath 2002), for different life spans, initial sunspot dynamics over the surface represents the internal dynamics in different layers of the convection zone.

For example initial anchoring of a flux tube whose life span is 10 days is near base of the convection zone and initial anchoring of a flux tube whose life span is 5 days is in the middle of the convective envelope. However, steady rise of the flux tubes (that have leader and the follower) along the isorotation contours does not guarantee that their foot point separation remains constant. Owing to strong rotational shear (around $0.935R_{\odot}$) (see the helioseismic inferred rotational results of Antia, Basu and Chitre 1998) near the surface, either or both of the opposite polarity foot points of the flux tubes are accelerated or decelerated towards each other. That is if one computes the rotation rates, either leader or follower or both may have *abnormal rotation rates* (Hiremath and Suryanarayana 2003) during a particular life span of the sunspot group resulting in merging and reconnection (of part) of the magnetic field lines of the foot points that eventually trigger the flares. The foot points can also be merged due to meridional circulation and flux emergence in the interior that results in changing of the area of the sunspot group. Using Kodaikanal Observatory data of the sunspot groups (that have the leader and the follower spots) we test these concepts in the following analysis.

3. Data analysis and results

For the years 1969–74, we use both the data set of positional measurements (heliographic latitude and longitude from the central meridian) of the sunspot groups (that have leading and following sunspots) taken from daily white light images and the flare events in the $H\alpha$ images from the Kodaikanal Observatory. The details of the telescope and observations of daily white light images are given by Sivaraman *et al.* (1992). Using similar criteria (Hiremath 2002) in selecting the sunspot groups, we compute rotation rate ω_i of the leading and following sunspots as follows:

$$\omega_i = \frac{(l_{i+1} - l_i)}{(t_{i+1} - t_i)}, \tag{1}$$

where l is the heliographic longitude from the central meridian, t is the time of observation, $i = 1, 2, 3, \ldots n$, and n is the age of the spot group.

We compute daily *longitudinal separations* $d_i = l_L - l_F$ (l_L and l_F are the longitudes of the *leader* and the *follower*) of the foot points of the spots. Following equation (1), we compute the *rate of change of longitudinal separation* S_i

$$S_i = \frac{(d_{i+1} - d_i)}{(t_{i+1} - t_i)}. \tag{2}$$

In the following analysis we use the combined data (1969–74) for the whole region of heliographic latitudes of 0° to 40° in both the solar hemispheres. We define *life span* of a spot group as the total number of days between the first and the last appearance on the same part of the solar disk satisfying the aforementioned criteria.

For the period of observations, we select 57 well-developed spot groups that have leader and follower spots. Using equation (1) and (2), we compute daily rotation rates ω_i and rate of change of longitudinal separation S_i. Similarly we compute the meridional velocity and rate of change of areas of the sunspot groups. We find that the last two parameters are not correlating with the events of triggering of the flares and are not presented.

In Fig. 2, we present the normalized values of daily rotation rates and the rate of change of longitudinal separation observed on 28 January 1970. The continuous vertical lines are occurrence dates of the flares. The occurrence dates of flares are considered during the maximum phase. The normalized values are defined as follows: If x_i are the data points for different i days, $\overline{x}$ is the average of all data points and σ is the standard deviation of rotation rates of the leading and the following spots and the rate of change of separation of their foot points, then the normalized value is $y_i = (x_i - \overline{x})/\sigma$.

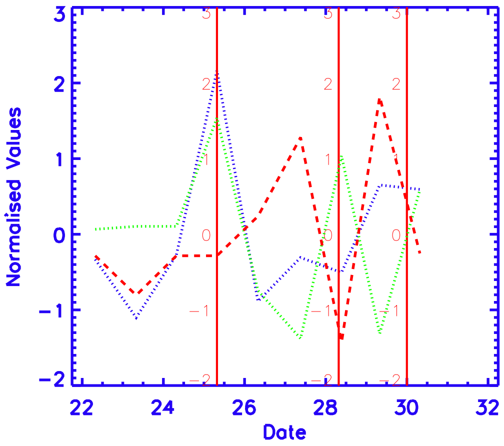

Figure 2. The normalized rotation rates and rate of change of longitudinal separation of the leader and the follower during their evolutionary phases. The blue and green dotted lines represent the normalized rotation rates of the leading and the following spots. The red dashed line represents the normalized rate of change of longitudinal separation of the leader and the follower spots. The red vertical continuous lines are the occurrence dates of the flares.

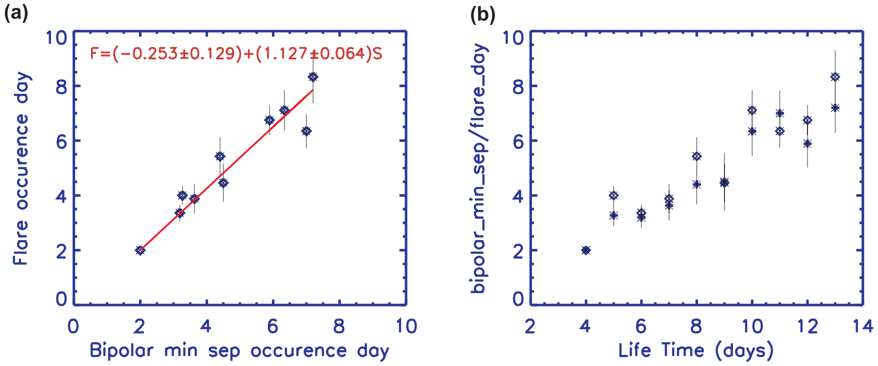

Figure 3. (**a**): The association between the occurrence of the minimum separation and the flare during the evolution of the spots. The red continuous line is obtained from the linear least square fit. Here S and F represent occurrence of minimum separation and the flares respectively. (**b**): Days of minimum separation and the flares during the evolution of spots. The symbols $\diamond$ and the square both in blue represent the day of minimum separation and the flares respectively.

Since we want to present all three parameters (rotation rates of the leader and the follower and the rate of change of longitudinal separation) that have different ranges of magnitudes, the normalization allows presentation of the three variables in a single plot. Whenever there are minimum approaching distances (represented by the negative values of the variation of separation) between the foot points of the leading and the following spots, on the same day or later the spots experience abnormal rotation rates leading to triggering of flares.

For the 57 spot groups, we note the occurrence of longitudinal minimum separation and the corresponding occurrence of the flare. The resulting correlative analysis is presented in the scatter diagram of Fig. 3(a) (left).

The correlation coefficient is found to be 94% with a very high significance (∼ 100%). One has to be cautious in interpreting the magnitudes of very high correlation coefficients (∼ 1). In the present analysis we compute the Spearman Rank-Order correlation coefficient and its significance (Press *et al.* 1992). This method of finding the correlation between two variabilities is more robust than the usual method (i.e., by linear correlation). From this method, we not only find a very high correlation but also at very high significance.

In order to know at what stage of a sunspot's life span the events of minimum separation and flares occur, we separate spot groups of different life spans. In Fig. 3(b) (right), we present the results with life span along the x axis and the corresponding occurrence of the minimum separation and the flares along the y axis. The errors are determined using the formula $\sigma/(N)^{1/2}$, where N is the total number of events of minimum separation and flares and σ is the standard deviation. As we found in the previous study (Hiremath and Suryanarayana 2003), for the events with abnormal rotation rates, a spot with a 4 day life span experiences on average a minimum separation and correspondingly the occurrence of a flare on the second day. A spot with a life span of six days experiences the same events on the third day and so on. In other words, abnormal rotation rates of the spots and the minimum distances of the foot points on average occur at between 50 and 80% of the life span during the course of their evolution, probably indicating annihilation of magnetic energy below the surface (Hiremath and Suryanarayana 2003).

If we assume that the flares occur due to magnetic reconnection, then it is interesting to know the magnitude of minimum separation during the occurrence of the flare. In Fig. 4(a), we present the minimum separation (in degrees) of the leading and the following foot points during the occurrence of the flare. For 57 spot groups, totally we have 85 flares and in each class we have the following number of flares: (i) sf : 1, (ii) sn : 30, (iii) sb : 8, (iv) 1f : 2, (v) 1n : 23, (vi) 1b : 10, (vii) 2f : 0, (viii) 2n : 3, (ix) 2b : 8. Though we have less number of flares for the classes sf and 1f, we have the following important conclusion. In order that reconnection events occur below the surface, the approaching spots that experience abnormal rotation

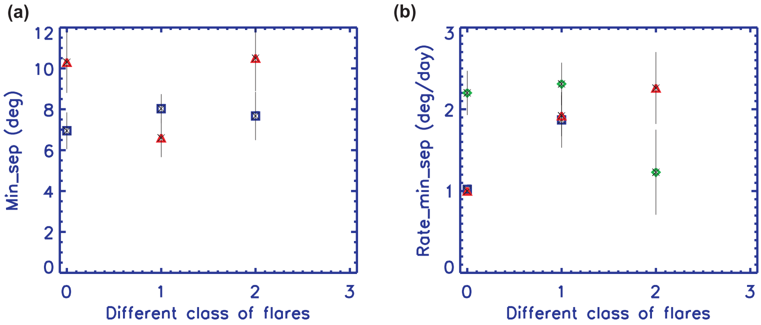

Figure 4. **(a)**: Minimum separation for the different classes of flares: the square in blue color represents n (normal), the △ with red color represents b (bright). Here 0 along the x axis represents the S subclass flare. The numbers 1, 2, 3 are higher subclass flares. **(b)**: The rate of change of longitudinal minimum separation for different classes of flares: the square in blue color represents f (faint), the ◇ with green color is n (normal) and the △ with red color represents b (bright). Here 0 along the x axis represents the S subclass flare. The numbers 1, 2, 3 are higher subclass flares.

rates should have a minimum longitudinal separation, on average 6°–10° in the photosphere. It is also interesting to know the speed at which foot points of the spots approach each other during the occurrence of the flare. In Fig. 4(b), we present the rate of change of minimum separation for different classes of flares. The foot points of the spots that eventually trigger the flares approach each other on average at a rate of $\sim 1°$–$2°/\text{day}$.

4. Discussion and conclusions

Since the majority of spots that have leading and following parts are bipolar (Zirin 1988), we assume that all the spot groups that are considered in the present study are *bipolar*. Thus we can invoke the theory of *magnetic reconnection* for the interpretation of the results.

As pointed in the introduction, from the present study, we satisfy the three crucial conditions for the magnetic reconnection as follows.

As for satisfying the first condition of magnetic reconnection, Fig. 2 indicates that whenever foot points of the bipolar spots approach each other flares trigger.

To satisfy the second requirement, the present analysis (see Fig. 4(a)) shows that on the surface the average minimum separation between bipolar spots is $\sim 6°$–$10°$ in longitude ($\sim 10^9$ cms) during the occurrence of flare events. By taking a clue from our previous study (Hiremath and Suryanarayana 2003) that the reconnection may be occurring below the surface at a depth of $0.935 R_\odot$, from simple plane trigonometry, one can estimate the thickness (length) of the reconnecting region to be $\sim 10^5$ cms which is in the required range of 10^5–10^8 cms.

For satisfying the last requirement of magnetic reconnection, the strength of the background magnetic field in the vicinity of the reconnecting region is required. The region outside the sunspot has a background magnetic field strength of ~ 1 G (Stenflo 1994). This is not the same as the strength of the magnetic field (~ 40 G) of the localized small scale magnetic structures as determined by the Hanle method. On the other hand, we want to determine the strength of the large-scale global magnetic field in the sunspot-free region. Observational (Duvall *et al.* 1979; Stenflo 1994) and theoretical (Hiremath and Gokhale 1995) estimates of the magnetic field strength of such a region show that it is ~ 1 Gauss.

Thus, at the surface of the photosphere, in the region outside the sunspot, the Alfvén velocity $v_a (= B/(4\pi\rho)^{1/2}$, where B is the strength of the magnetic field and ρ is the density) is found to be $\sim 10^5$ cms/sec. The results from Fig. 4 show that the leading and the following spots that approach each other during the occurrence of the flare have a separation velocity of $\sim 1°/\text{day}$ (10^4 cms/sec). This result satisfies the requirement that $v_{in} = 0.1 v_a$ (where v_{in} is the inflow velocity in the vicinity of the region of flare occurrence). *Thus, this study strengthens the conventional view that flares may be occurring due to magnetic reconnection.*

The overall conclusion of the present study is that during the course of the evolution of leading and following sunspots and in order to trigger flares, the foot points associated with the abnormal rotation rates of the leading and following spots should have an approaching velocity of 1–2 deg/day and ultimately reach a minimum separation of $\sim 6°$–$10°$ for probable magnetic reconnection below the surface.

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