A&A 411, L497–L500 (2003)
DOI: 10.1051/0004-6361:20031618

Astronomy & Astrophysics

Letter to the Editor

The flares associated with the abnormal rotation rates of the bipolar sunspots: Reconnection probably below the surface

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Received 26 September 2003 / Accepted 14 October 2003

Abstract. We use the observations of Kodaikanal observatory white light pictures to study the association between the rotation rates of the bipolar sunspots and triggering of the flares. For the years 1969−1974, we compute daily rotation rates of the leading and the following spots of the bipolar sunspot groups during their life span. We find that either leading or following or both of the bipolar spot groups which 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. Other important findings are: (i) the abnormal rotation rates and the flares occur during the 50−80% of their life span of the spot group and, (ii) abnormal rotation rate of about 2°/day is required for triggering the flares. The strong relation between the occurrence of abnormal rotation rates of the sunspot groups and the occurrence of the flares enabled us to estimate the probable region of depth of reconnection below the solar surface.

Key words. bipolar sunspots – abnormal rotation rates – flares – flux tubes

1. Introduction

The sunspots are supposed to be associated with many solar activity phenomena like flares, prominences, coronal mass ejections, etc. It is believed (Priest 1981; Haisch & Strong 1991; Parker 1994) that the magnetic reconnection is one of the physical phenomenon in releasing the required amount of flare energy. However, it is not known at what level of the solar region reconnection events take place. Moreover, it is not known why some set of sunspots trigger flares and others do not. Though following studies indicate the relevance of sunspot motions for triggering the flares, much quantitative and statistical evidences are lacking. In this study, we present the same using daily motions of the bipolar spot groups observed from the Kodaikanal observatory.

The previous studies (Tanaka & Nakagawa 1973; Ambastha & Bhatnagar 1988; Sundara Raman et al. 1998) have shown that the proper motions of sunspot pairs can cause the energy build up and provide the required amount of energy involved in flaring. Sivaraman (1969) has demonstrated that the flares coincide with the period of maximum area in the evolutionary phase. Zirin & Liggett (1987) have studied the case of δ spots and showed that such spot groups are the potential candidates for the great flares. They further conclude that the driving force for one of the flare precursor such as magnetic shear may be due to spot motion, either flux emergence or the forward motion of *p* spots in an inverted magnetic configurations. Many studies (Hagyard et al. 1982; Hagyard et al. 1984; Venkatakrishnan et al. 1989; Ambastha et al. 1993), from the vector magnetograms, show the relevance of magnetic shear with the eventual triggering of the solar flares. By considering the H-α filament as a proxy for the magnetic neutral line, Sivaraman et al. (1992) quantitatively estimated change in the shear that corresponds with the occurrence of the flare. Schmieder et al. (1994) showed that in order to have the flare occurrences, the following two conditions are necessary: (i) the break up motions of different polarity regions maintained a high shear level for the continuous build up of the magnetic flux and, (ii) the rapid motions and the changes in the magnetic sources.

Most of the afore mentioned studies clearly indicate that the occurrence of the flares is associated with the complex movement and magnetic topology of the sunspots. That means flares may be attributed not only to magnetic flux build up and reconnection but also to dynamics of the active regions that acquire during the course of their raising from the convection zone towards the surface. In order to know whether dynamics of the sunspot groups, especially the rotational dynamics, may give clues to the triggering of flares, we compute the daily rotation rates of the bipolar sunspot groups during their life spans and, we show in the following study that the abnormal rotation rates of the bipolar spots eventually trigger the flares. In Sect. 2, we

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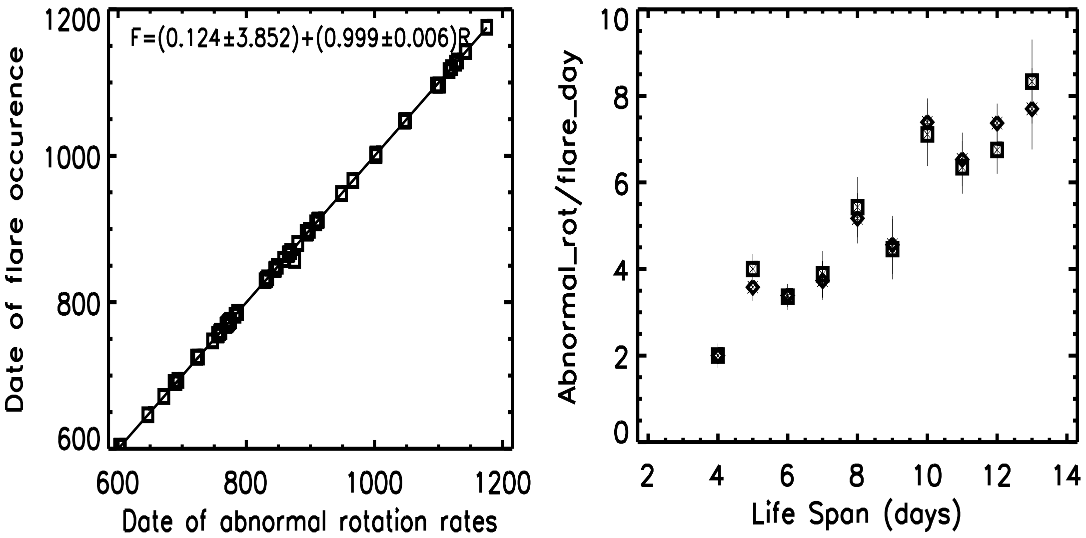

Fig. 1. a) The occurrence dates of abnormal rotation rates and the flares. The continuous line is the linear least square fit. Here R represents occurrence date of abnormal rotation rates and F is the occurrence date of the flares. **b)** The occurrence day of the abnormal rotation rates and the flares during the evolution of the bipolar spots. The $\diamond$ represents the day of the occurrence of the abnormal rotation rate and the square represents the day of the occurrence of the flare.

describe the data used and the method of analysis. Results are presented in Sect. 3 and, conclusions and discussion are presented in Sect. 4.

2. Data and analysis

For the present study and for the years 1969–1974, we consider both the data of positional measurements (heliographic latitude and longitude from the central meridian) of the bipolar sunspots taken from daily white light pictures and the occurrence of Hα flares from the Kodaikanal observatory. Sivaraman et al. (1992) have given the details of the telescope and observations of daily white light pictures. Using similar criterion (Hiremath 2002) in selecting the sunspot groups, we compute rotation rate ω_i of the bipolar sunspots as follows:

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

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 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 criterion. In the following analysis we use the combined data of the years (1969−1974), for whole region of heliographic latitudes of 0° to 40° in both the hemispheres. We define *abnormal rotation rate* as follows. Fist we compute the daily rotation rates ω_i for each pair of the bipolar spots and then compute the mean $\overline{\omega}$ with their standard deviation σ. If the absolute value of the difference $(\overline{\omega} - \omega_i) > 1\,\sigma$, then we consider the corresponding rotation rate at that date as *abnormal rotation rate* of the spot. In order to have good statistics, we combine both the rotation rates of the leading and the following spots.

3. Results

For the period of observations, we select 57 spot groups which are associated with the flares. Using Eq. (1), we compute daily rotation rates. We find that, during the course of evolution of the spot groups, the spots that have abnormal rotation rates are associated with the flares on that day or later. We also confirmed that the spot groups which do not have the abnormal rotation rates are not associated with the flares. A typical data set that relates dates of the occurrences of abnormal rotation rates and correspondingly the dates of occurrence of the flares is presented in Fig. 1a. The results show a strong association between the dates of occurrence of the abnormal rotation rates and the dates of occurrence of the flares. The correlation coefficient is found to be 99.9% with very high significance (∼100%). We also confirmed these results using the Catania and the Greenwich Photoheliographic results. In order to know at what stage of sunspot's life time the abnormal rotation rates and the flares occur, we separate the spot groups which have different life spans. In Fig. 1b, we present these results which illustrate different life spans along the x axis and corresponding occurrence days of the abnormal rotation rates and the flares are plotted along the y axis. The errors are determined using the formula $\sigma/(N)^{1/2}$, where N is the total number of the events of abnormal rotation rates and flares and, σ is the standard deviation. The results show that a spot of 4 days life span experiences on average abnormal rotation rate and correspondingly the occurrence of the flare on second day, life span of 6 days spot experiences the same events on third day and so on. To put it in other way, the events of the abnormal rotation rates of the spots on average occur between 50–80% of the life spans of the sunspots during the course of their evolution. In Fig. 2a, we present the scatter diagram between the occurrence of the abnormal rotation rates and the occurrence of the flares during particular day of evolution of the spots. The correlation is found to be 98.8% with a very high significance (∼100%).

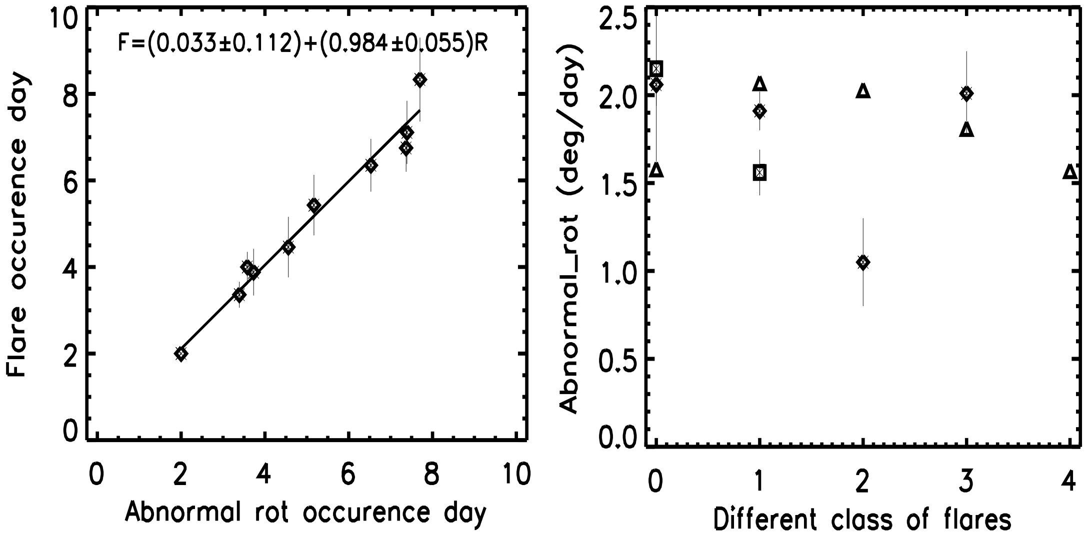

Fig. 2. a) The scatter diagram illustrating the association between the occurrence days of the abnormal rotation rates and the flares during the evolution of the spot group. The continuous line is obtained from the linear least square fit. Here R represents occurrence day of abnormal rotation rates and F is the occurrence day of the flares. **b)** The magnitude of abnormal rotation rates for different classes of the flares: the square represents f (faint), the $\diamond$ is n (normal) and the $\triangle$ represents b (bright). Here 0 along the x axis represents the S subclass flare. The numbers 1, 2, 3, 4 are higher subclass flares.

Based on the size and visual appearance of the intensity, traditionally, the flares are classified as follows: (i) sf, 1f, 2f, 3f, 4f; (ii) sn, 1n, 2n, 3n, 4n; and (iii) sb, 1b, 2b, 3b, 4b. Since we considered the dynamic events, it is interesting to know whether occurrence of different class and subclass of flares depends upon the magnitudes of the abnormal rotation rates of the spots. In Fig. 2b, we present the magnitudes of the abnormal rotation rates for different class and sub class of flares. From this figure, one can draw the following two important conclusions: (i) in order that spot should trigger the flare, abnormal rotation of $\sim 2°$/day is required and, (ii) triggering of different classes of flares is independent of magnitudes of the abnormal rotation rates of the spots. The first result indicates that the abnormal angular velocity of 2°/day ($\sim 10^4$ cm/s) is sufficient to trigger the flare. In fact this result is consistent with the theoretical expectations (Heyvaerts & Priest 1984) and analysis of the daily movement of the sunspots (Zuccarello 1992) and, the recent helioseismic (Zhao & Kosovichev 2003) inversions from the local helioseismology.

4. Conclusions and discussion

We use observations from the Kodaikanal observatory to study the association between the rotation rates of the bipolar spots during their life span and the occurrence of the flares. For the period of 1969−1974 and for different life spans, we compute the daily rotation rates ω_i of the spots. Important findings of the present study are as follows.

1. During the course of their evolution, the spots that experience abnormal rotation rates are strongly associated with the occurrence of the flares on the same day or later.
2. The abnormal rotation rates and correspondingly triggering of flares occur during 50−80% of life span of the sunspots.
3. The magnitude of the abnormal rotation rate of the spots that are associated with the flares is found to be $\sim 2°$/day and is independent of different classes and sub classes of the flares.
4. A strong association between the abnormal rotation rates and the occurrence of the flares enable us to estimate (in the following discussion) probable depth below the surface where the events of magnetic reconnection that may occur.

The usual scenario for occurrence of the solar flares is due to *magnetic reconnection* where in magnetic flux of opposite polarities merge together releasing the required amount of energy. However, it is not known whether reconnection process occur either above or below the surface. In fact some studies (Zirin & Liggett 1987; Leka et al. 1996; Canfield & Pevtsov 2000) indicate that reconnection events may be occurring below the surface. From the following argument and some of the inferences drawn, present study gives a definite clue regarding the reconnection events that may be taking place below the surface.

The *helioseismic* studies revealed many facets of structure and dynamics of the sun. The inversions from the rotational frequency yield the internal rotational profile right from surface to deep radiative interior with good accuracy. In fact the sunspots are also very good indicators that yield the dynamics of the convective envelope. Very recent studies (Javaraiah & Gokhale 1997; Javaraiah 2001; Hiremath 2002; Sivaraman et al. 2003) show that variation of initial rotation rates derived from the daily motions of the sunspot groups with respect to their life spans is almost similar to the radial variation of internal rotation profile of the solar plasma.

While raising towards the surface, the spots experience inequilibrium at certain region of the convective envelope eventually bringing their foot points closer that ultimately trigger the solar flares by magnetic reconnection. Inequilibrium can be attained either by the strong flows or rotational gradient in the convective envelope. Since flows are random, spots could have experienced inequilibrium every where in the convective envelope and correspondingly spots could have produced the flares during the course of their whole life spans. However, present study shows that spots produce the flares during a particular period (50−80% of their life span) indicating rotational gradient only at a particular depth of the convection zone. For example if we superpose this particular period of occurrence of abnormal rotations (and flares) in the Fig. 3a in the previous study (Hiremath 2002), we find that *magnetic reconnection events that eventually trigger the flares may be taking place around* 0.935 $R_{\odot}$ where rotational gradient exists. The speculation that such events taking place around 0.935 $R_{\odot}$ can be tested from the detailed MHD calculations.

Acknowledgements. We are grateful to the observers of the Kodaikanal observatory who has taken the white light and Hα pictures during the years 1969−1974. We are also grateful to the unknown referee for useful comments and suggestions.

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