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Flares associated with abnormal rotation rates: Longitudinal minimum separation of leading and following sunspots

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Abstract. Using six years (1969−1974) of data of sunspot groups from the white light pictures of the Kodaikanal Observatory, we compute rotation rates of the leading and the following sunspots and the rate of change of longitudinal separation during their life times. We find that (i) the spots that are associated with abnormal rotation rates (i.e, rotation rates that are greater than 1σ from the mean rotation) and that approach at a separation rate of 1−2 deg/day also experience minimum longitudinal separation (∼6°−10°) of their foot points during the course of their evolution; (ii) spots that have a minimum separation eventually trigger flares; and (iii) events with abnormal rotation rates and minimum approaching distances of the foot points occur on average during between 50−80% of the life spans, indicating the annihilation of magnetic energy, probably below the surface. These results support the conventional physical scenario of magnetic reconnection that may be responsible for triggering flares.

Key words. sunspots – Sun: flares

1. Introduction

The conventional picture of the formation of sunspots is that they originate below the solar surface due to an unknown dynamo mechanism. Due to the very high conductivity of the solar plasma, sunspots are glued to the internal plasma and due to buoyancy raise towards the surface. This implies that sunspots are very good tracers of the internal dynamics and structure of the solar interior. Previous studies (Gokhale & Hiremath 1984; Javaraiah & Gokhale 1997; Hiremath 2002, and references there in; Sivaraman et al. 2003; Zuccarello & 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 similar to the radial variation of the internal rotation profile of the solar plasma.

In order to know whether dynamics of the sunspots-especially the dynamics due to rotational rates-give clues about the triggering of flares, we computed the daily rotation rates of sunspots (that have leaders and followers) during their life time and we have shown that the abnormal rotation rates of either leading or following spots or both eventually trigger the flares (Hiremath & Suryanarayana 2003). In that study, because of the strong association between abnormal rotation rates of sunspots and the occurrence of flares, it is possible to estimate the probable region of the depth of magnetic reconnection below the surface. For such reconnection events to occur, a close approach of their foot points and contact of the flux tubes below the surface may be necessary. In the present study, we search for such events and show that triggering of a flare occurs at the time of minimum distance between the leading and the following spots. In Sect. 2, we describe the data used and the method of analysis. Results are presented in Sect. 3. The physical phenomenon of magnetic reconnection that may be responsible for triggering the flare is discussed in Sect. 4 and overall conclusions are presented.

2. Data and analysis

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 Hα 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:

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

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

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Table 1. Kodaikanal observations related to the Greenwich Group numbers.

Kodai No.	Green No.	Year	Mon	Date of flare	Flare type
13 105	21 482	1968	1	29	1−*n*
”	”	”	2	2	*s*−*b*
13 483	21 894	1969	2	20	1−*n*
”	”	”	2	25	2−*b*
”	”	”	2	26	2−*b*
13 510	21 936	1969	3	21	2−*n*
13 621	22 064	1969	8	2	
”	”	”	8	3	
13 625	22 068	1969	8	2	*s*−*n*
13 640	22 086	1969	9	26	1−*b*
13 683	22 138	1969	10	8	1−*n*
”	”	”	10	10	1−*f*
13 696	22 152	1969	11	2	1−*f*
13 713	22 176	1969	11	24	2−*b*
13 743	22 210	1969	12	26	*s*−*n*
13 776	22 247∗	1970	1	17	1−*n*
13 778	22 251	1970	1	25	1−*n*
”	”	”	1	28	2−*b*
”	”	”	1	30	1−*n*
13 783	22 255	1970	1	26	1−*n*
13 784	22 261	1970	1	29	
13 791	22 272	1970	2	9	2−*b*
”	”	”	1	10	1−*n*
”	”	”	1	11	2−*b*
”	”	”	1	12	*s*−*b*
13 792	22 274	”	2	7	1−*b*
13 811	22 291	1970	2	21	*s*−*n*
”	”	”	2	25	*s*−*n*
13 859	22 351	1970	4	9	
13 860	22 349∗	1970	4	9	*s*−*n*
”	”	”	4	11	*s*−*n*
”	”	”	4	13	*s*−*b*

∗ Ambiguity in identifying these spot group numbers with Greenwich group numbers.

Table 2. Kodaikanal observations related to the Greenwich Group numbers.

Kodai No.	Green No.	Year	Mon	Date of flare	Flare type
13 870	22 362	1970	4	24	1−*b*
”	”	”	4	25	*s*−*n*
13 875	22 370∗	1970	4	25	
13 881	22 379	1970	5	7	*s*−*n*
”	”	”	5	8	1−*n*
13 891	22 392	1970	5	15	*s*−*n*
”	”	”	5	16	1−*b*
13 901	22 411	1970	5	30	1−*b*
13 916	22 433	1970	6	13	1−*n*
”	”	”	6	14	*s*−*n*
”	”	”	6	16	1−*n*
13 932	22 448	1970	6	27	*s*−*n*
”	”	”	6	30	1−*n*
13 937	22 454	1970	6	30	*s*−*n*
”	”	”	7	1	*s*−*n*
13 973	22 495∗	1970	8	6	*s*−*n*
13 980	22 508	1970	8	24	2−*n*
14 021	22 556	1970	9	27	1−*n*
”	”	”	9	28	*s*−*n*
”	”	”	9	29	*s*−*n*
14 064	22 608∗	1970	11	13	1−*n*
”	”	”	11	14	1−*n*
14 108	22 664	1970	12	1	*s*−*n*
14 120	22 679	1971	1	21	1−*n*
”	”	”	1	25	1−*n*
14 128	22 686	1971	1	31	1−*b*
”	”	”	2	3	1−*n*
14 144	22 710	1971	2	16	1−*b*
14 175	22 738	1971	3	21	*s*−*b*
14 184	22 755	1971	4	11	1−*n*

∗ Ambiguity in identifying these spot group numbers with Greenwich group numbers.

the spot group. The term *rotation rate* of the sunspots means the *(synodic) angular rotation velocity*. We compute daily *longitudinal separations* $d_i = l_\mathrm{L} - l_\mathrm{F}$ (l_L and l_F are the longitudes of the *leader* and the *follower*) of the foot points of the spots. Following Eq. (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. The combined data set is presented in Tables 1−3. The columns are: (i) Kodaikanal spot group number; (ii) Greenwich spot group number; (iii) the year of observation; (iv) the month of observation; (v) the date of flare occurrence; and (vi) the flare type. From the Kodaikanal data archive, we could not get the flare types for the following Kodaikanal sunspot group numbers: 13 621, 13 784, 13 859, 13 875, 14 652−14 784. The stars (attached to the Greenwich group numbers) in the second column of Tables 1−3 indicate the ambiguity in identifying the Kodaikanal group numbers with the Greenwich group numbers.

3. Results

For the period of observations, we select 57 well-developed spot groups that have leader and follower spots. Using Eqs. (1) and (2), we compute daily rotation rates ω_i and rate of change of longitudinal separation S_i.

Typical white light images of the evolutionary phase of a spot group that has leading and following sunspots is illustrated in Fig. 1. The spot group grows and decays in the southern hemisphere of the solar disk. Although from the 25th onwards new complex sunspots emerge near the equator, the identity of the leading and the following spots can still be traced unambiguously. In Fig. 2a, we present the rotation rates (in units of deg/day) and the daily longitudinal separation (in units of deg) of the leader and the follower of such a spot group as presented in Fig. 1. In Fig. 2a, the numbers near the vertical lines are the scale values presented along the y axis (rotation and longitudinal separation). In Fig. 2b, we present the rate (in units of degrees/day) of change of longitudinal separation.

Table 3. Kodaikanal observations related to the Greenwich Group numbers.

Kodai No.	Green No.	Year	Mon	Date of flare	Flare type
14 191	22 764	1971	4	16	2−*n*
”	”	”	4	20	2−*b*
14 277	22 877	1971	8	19	1−*n*
”	”	”	8	27	*s*−*n*
14 290	22 894*	1971	9	15	1−*n*
”	”	”	9	17	*s*−*n*
14 322	22 931	1971	11	16	*s*−*n*
”	”	”	11	17	*s*−*n*
14 325	22 940	1971	12	2	1−*b*
14 381	23 013	1972	2	15	1−*b*
”	”	”	2	18	*s*−*b*
”	”	”	2	21	1−*n*
14 384	23 020	1972	2	18	1−*n*
”	”	”	2	19	*s*−*n*
”	”	”	2	21	*s*−*b*
”	”	”	2	24	*s*−*n*
”	”	”	2	25	*s*−*n*
14 458	23 110	1972	5	27	2−*n*
”	”	”	5	28	1−*n*
”	”	”	5	30	1−*b*
”	”	”	6	5	*s*−*b*
14 462	23 113	1972	6	5	*s*−*n*
14 517	23 179	1972	7	7	2−*b*
14 593	23 272	1972	11	24	*s*−*n*
”	”	”	11	25	*s*−*n*
14 635	23 312	1973	2	5	1−*n*
14 647	23 328	1973	2	25	*s*−*b*
14 652	23 332	1973	3	6−7	
14 657	23 338	1973	3	20	
”	”	”	3	24	
14 681	23 377	1973	6	8−10	
14 712	23 412	1973	9	2−4	
14 743	23 453	1973	12	21	
14 776	23 491	1974	4	13	
14 784	23 500	1974	4	26	

* Ambiguity in identifying these spot group numbers with Greenwich group numbers.

In Fig. 3, we present the normalized values of daily rotation rates and the rate of change of longitudinal separation. 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 $y_i = (x_i - \overline{x})/\sigma$. 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.

In Fig. 3, 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. From the same figure, one can also notice that in order to trigger flares, foot points of the leading and the following sunspots should move towards each other at a rate of 1−2 deg/day.

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. 4a (left). In 6 years many flares do not satisfy the criterion of a strong association between the minimum longitudinal separation and triggering of the flare. However, we selected only those H-α flares that correspond to the sunspot groups' heliographic coordinates and time on that day.

Moreover, 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. 4b (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 & 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 50−80% of the life span during the course of their evolution, probably indicating annihilation of magnetic energy below the surface (Hiremath & 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. 5a, we present the minimum separation (in degrees) of the leading and the following foot points during the occurrence of the flare. In order that reconnection events occur below the surface, the approaching spots that experience abnormal rotation 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. 5b, 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 ∼1°−2°/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

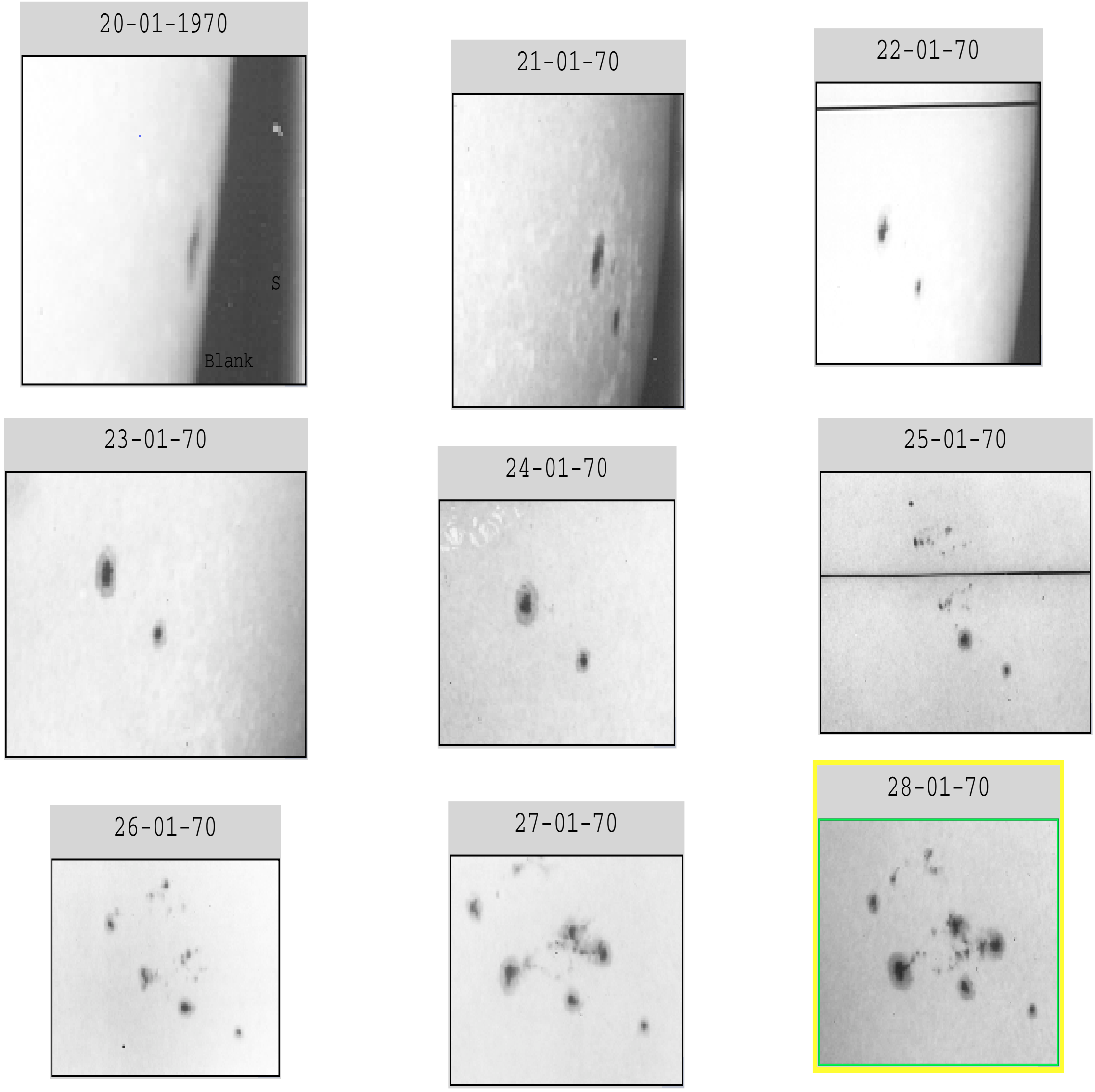

Fig. 1. The evolution of a typical sunspot group that contains leader and follower spots observed from the Kodaikanal Observatory. On the images of the 22 and 25, the horizontal line represents the solar equator. For all the observations, the spot group is south of the equator. The corresponding Greenwich group number for this sunspot group is 22 251.

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.

Presently it is believed (Priest 1981; Haisch & Strong 1991; Parker 1994) that the source of energy produced in solar flares is due to *magnetic reconnection* in a very compact region wherein oppositely directed magnetic fluxes, in the limit of finite electric conductivity, annihilate each other and release the required amount of flare energy. Oppositely directed magnetic flux of large length scale L merges with inflow velocity $v_{\rm in}$. This merging of flux will form a current sheath. The law of magnetic induction dictates the course of evolution of the plasma. The condition of infinite electric conductivity fails in the region of magnetic field reconnection by producing very high gradients of current and electric fields. Dissipation of these strong currents leads to annihilation of the magnetic field in the region of magnetic reconnection where a steady state exists so that convective and resistive terms in the induction equation are equal. There are two crucial requirements for the reconnecting region that eventually produce the flares. The first requirement is the amount of energy released by the annihilation of the magnetic field B and a cube of length L, estimated to be $\sim L^3 B^2$. That means that in order to produce the observed typical flare energy of $\sim 10^{27}$–10^{30} erg, the length (L) of the reconnecting region below the surface must be $\sim 10^5$–10^8 cm and the strength of the magnetic field should be 10^5–10^3 G. The second requirement, from the standard flare mechanism (Petschek 1964), yields the relation $v_{\rm in} = 0.1 v_{\rm a}$, where $v_{\rm in}$ is the inflow velocity with which magnetic lines merge and $v_{\rm a}$ is the Alfven velocity in the vicinity of the magnetic reconnection. From the present study, we satisfy the two requirements as follows.

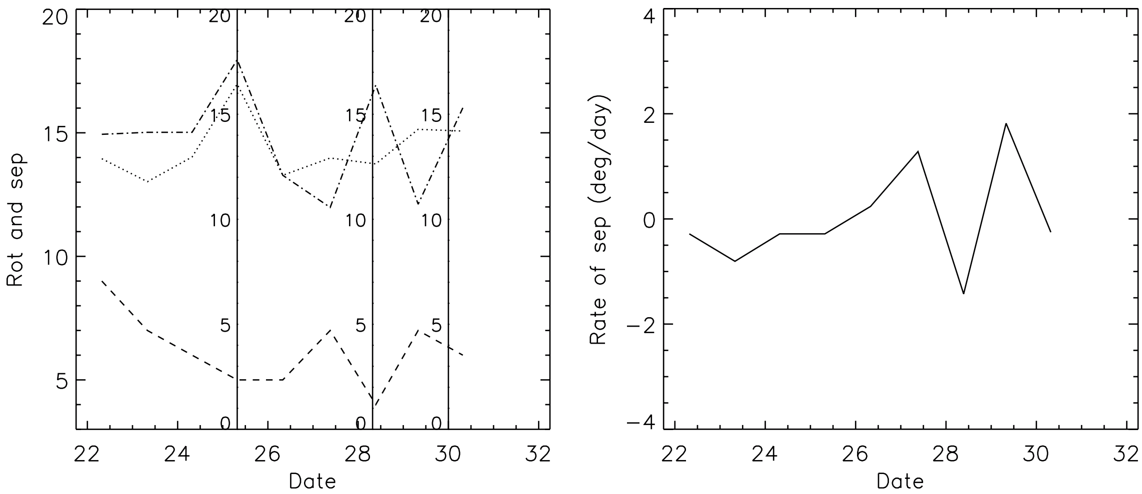

Fig. 2. a) *Left*: rotation rates and change of longitudinal separation of the leader and the follower during their evolutionary phases. The dotted and dash dotted lines represent the rotation rates (deg/day) of the leading and the following spots. The dashed line represents the change of longitudinal separation (in degrees) of the spots. The vertical continuous lines are the occurrence dates of the flares. The numbers near the vertical lines are the scale values presented on the y axis (rotation and longitudinal separation). **b)** *Right*: the typical rate of change of the longitudinal separation (deg/day) of the leader and the follower spots during their evolutionary phases. For both the figures the corresponding Greenwich number of the group is 22 251.

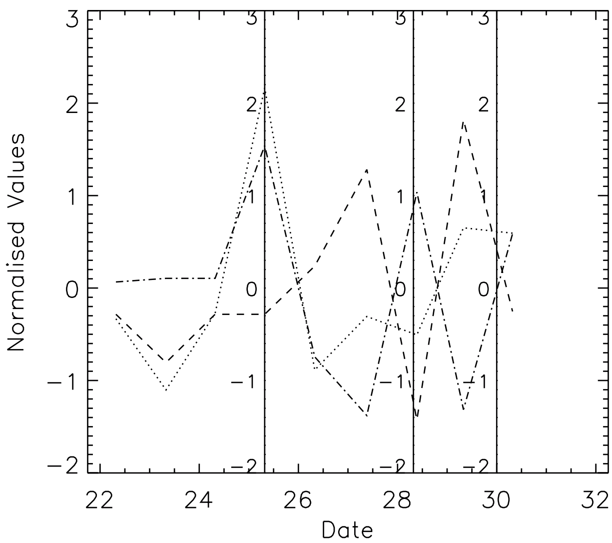

Fig. 3. The normalized rotation rates and rate of change of longitudinal separation of the leader and the follower during their evolutionary phases. The dotted and dash dotted lines represent the normalized rotation rates of the leading and the following spots. The dashed line represents the normalized rate of change of longitudinal separation of the leader and the follower spots. The vertical continuous lines are the occurrence dates of the flares. The corresponding Greenwich number for this sunspot group is 22 251.

To satisfy the first requirement, the present analysis (see the Fig. 5a) shows that on the surface the average minimum separation between bipolar spots is ~6°−10° in longitude (~10^9 cm) during the occurrence of flare events. By taking a clue from our previous study (Hiremath & 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 ∼10^5 cm which is in the required range of 10^5−10^8 cm.

For the second requirement, 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 & Gokhale 1995) estimates of the magnetic field strength of such a region shows that it is ∼1 Gauss.

Thus, at the surface of the photosphere, in the region outside the sunspot, the Alfven 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 ∼10^5 cm/s. The results from Fig. 3 show that the leading and the following spots that approach each other during the occurrence of the flare have a separation velocity of ∼1°/day (10^4 cm/s). This result satisfies the requirement that $v_{in} = 0.1 v_a$. *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 ~6°−10° for probable magnetic reconnection below the surface.

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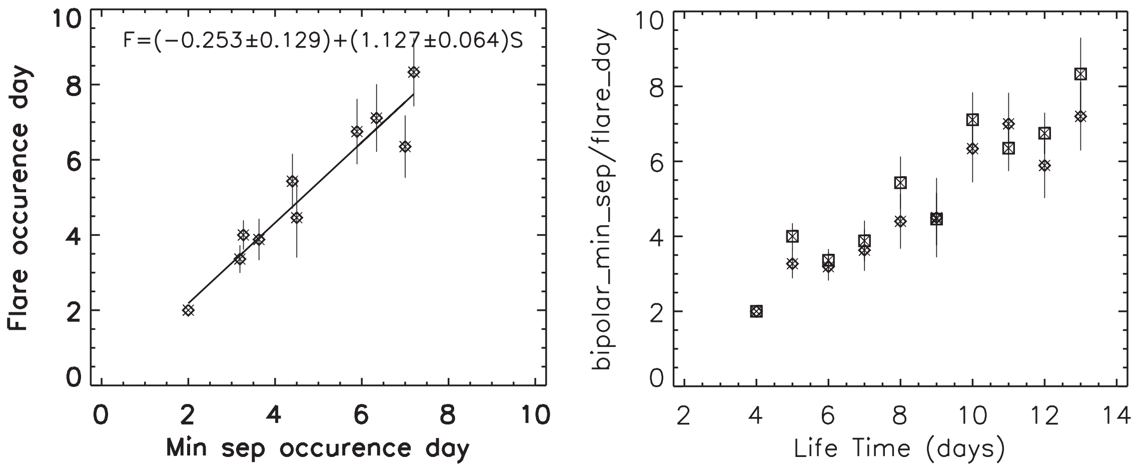

Fig. 4. a) *Left*: the association between the occurrence of the minimum separation and the flare during the evolution of the spots. The continuous line is obtained from the linear least square fit. Here S and F represent occurrence of minimum separation and the flares respectively. **b)** *Right*: days of minimum separation and the flares during the evolution of spots. The symbols $\diamond$ and the square represent the day of minimum separation and the flares respectively.

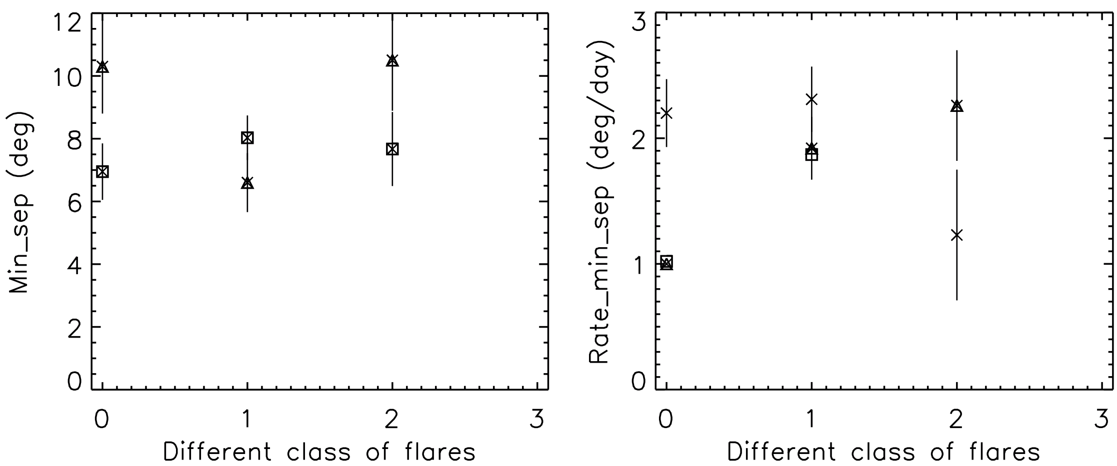

Fig. 5. a) *Left*: minimum separation for the different classes of flares: the square represents n (normal), the $\triangle$ represents b (bright). Here 0 along the x axis represents the S subclass flare. The numbers 1, 2, 3 are higher subclass flares. **b)** *Right*: the rate of change of longitudinal minimum separation for different classes of 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 are higher subclass flares.

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