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Magnetic Reversal in the 22nd Solar Cycle and Spatial Distribution of LDE-type Flares

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Abstract. The spatial and temporal distributions of BEARALERT regions are investigated on daily basis between 1987 and 1989 using synoptic maps of coronal magnetic fields prepared at the Wilcox Solar Observatory. We have analyzed data for 32 BEARALERT regions during the ascending phase of the 22nd solar cycle. Each active region was analyzed in terms of six vector variables. A total for 338 daily vector variables were analyzed. Some statistical tests are presented speaking in favor of enhanced flare activity (of both long duration events, LDE, and impulsive events) in those active regions located inside the reversed sectors (RSs), or along the boundaries (Bs) of the solar sectors where the process of magnetic field reversal takes place. The flare occurrence is found to be smallest inside the 'old' sectors (OSs).

1. Introduction

The purpose of this article is to continue an analysis of possible relation between active region flaring locations and the sectors where the process of magnetic reversal of the Sun is observed. In previous article (Antalová & Jakimiec 1995) we analyzed the relation between the spatial distribution of the 32 BEARALERT regions (Zirin & Marquette 1990), characterized by 338 daily observable vectors and long-lasting magnetic sectors. Antalová & Jakimiec (1995) found that mean values of sunspot group area, magnetic orientation and flare activity are significantly greater for those active regions which are located along the boundary (B) of magnetic sectors or in the reversed sectors (RSs) than for those active regions located in the old magnetic sectors (OSs). In section 2 we discuss general questions concerning the magnetic reversal of Sun and LDE–type flaring. Section 3 recalls the data and the main descriptive parameters characterizing the daily values of BEARALERT regions as well as the main results obtained earlier. The large and complex sunspot groups relate to RSs and sector boundaries (Antalová 1994a). Hence, it might be argued that the enhanced flare production in RSs is the simple result of appearance of large and complex groups. Section 4 presents further analysis of the relation of flare activity of active regions and their location in magnetic sectors. Finally, section 5 summarizes our findings.

Table 1. The mean values and standard deviations obtained for six analyzed variables. The upper part covers the 338 daily vectors collected in the 32 BEARALERT regions. The lower part corresponds to 183 flare-rich daily values and their sectorial distribution (x6). We have 49 daily vectors for active regions located in the OSs, 73 along the Bs and 61 daily vectors in the RSs.

var.		x1	x2	x3	x4	x5	x6
var.	N	A	MO	FI$_{\rm LDE}$	FI$_{\rm I}$	FI$_{\rm T}$	S
mean	338	2.78	2.20	0.74	1.04	1.40	1.01
st. dev.		0.44	0.71	0.89	0.61	0.64	0.79
mean	49	2.78	1.88	1.09	1.08	1.52	0.00
st. dev.		0.28	0.60	0.62	0.56	0.47	0.00
mean	73	2.97	2.21	1.48	1.18	1.79	1.00
st. dev.		0.26	0.60	0.69	0.53	0.50	0.00
mean	61	3.05	2.67	1.60	1.22	1.87	2.00
st. dev.		0.39	0.77	0.68	0.60	0.56	0.00

2. Link Between Locations of Magnetic Unipolar Sectors and LDE–type Flares?

To begin with we should stress that the concept of magnetic sectors where large-scale magnetic fields are of the same polarity is justified only above the source surface – which lies at approximately 1.5 solar radii above the photosphere, as it is only here where such fields can be regarded as purely radial (Hoeksema 1991, Stewart & Bravo 1995). On the other hand, H–alpha flaring occurs at the heights of a few thousand kilometers above the photosphere and, hence, it seems to be unreasonable to try to link these two phenomena. It is also known that long duration events (or LDE–type flares) are often associated with the type II and IV metric radio bursts, microwave richness (Chertok 1995), and solar energetic particle events (SEPs) in interplanetary space, which are connected with coronal mass ejections (CMEs). The observations performed on-board the *Yohkoh* satellite distinctly show that 'a soft x-ray (SXR) LDE' occurs on the top of a coronal arch (Feldman et al. 1995) where the dense hot thermal plasma is confined and it linked with an eruptive flare (Švestka 1995). As claimed by Feldman et al. (1995), 'this confined bright region is a major puzzle that is difficult to explain by any model based on a simple loop geometry with magnetic field lines oriented parallel to the major loop axis.' The height of the coronal arch summit is about 0.1 – 0.2 solar radii (Švestka et al. 1989) which is still an order of magnitude smaller when compared with that of the source surface height. Comparing GOES SXR events with CMEs for 1986 data, Burkepile et al. (1994) have found that a CME phenomenon is partly interrelated with some LDE–type flares. Similar conclusions have been reached by Reames (1994), Storini et al. (1994a), Cliver ('the long-duration component of flare emission is the by–product of a CME', 1995) as well as Gosling & Hundhausen ('it is important to understand optical and X flares in all of their various aspects, including their connection to the CME phenomenon', 1995). Large-scale coronal changes and CMEs are located approximately at a height of the source surface radius. Hence, a serious connection between LDE–type flare sites and Hoeksema's unipolar sectors might be envisaged.

2.1. Magnetic Reversal of Large-scale Magnetic Fields

Large scale magnetic structures and their relation to flares as well as to the global magnetic field reversal of the Sun have been studied using different methods (Bumba 1976, Sýkora 1980, Gaizauskas et al. 1983, Stepanian 1994, Ambrož 1992, Harvey 1992, Martin et al. 1992, Saniga 1992, Sýkora et al. 1994, Storini et al. 1995b, Antalová 1994, 1995). To investigate the reversal of large–scale magnetic fields we consider the sectorial distribution of proxy unipolar fields. The magnetic sectors are represented by the source surface field as modeled by Hoeksema & Scherrer (1986) and by Hoeksema (1991, 1993). The source surface radius is located at 2.5 solar radii (Hoeksema 1991). We suppose that a gradual change in the pattern of magnetic sectors is one of the symptoms of a global reversal of large-scale magnetic fields. This is the main reason which motivated us to compare the flare activity of active regions located in the OSs and RSs as well as along their boundaries (Antalová 1994, 1995; Antalová & Jakimiec 1995).

2.2. Old and Reversed Sectors

Magnetic unipolar sectors having the 'correct' polarity of the current solar cycle are those showing a reverse polarity when compared with the polarity of the same solar hemisphere characterizing the minimum phase of the previous cycle (Antalová 1994). In the 22nd cycle *the sectors of positive magnetic polarity in the northern hemisphere,* as well as those of *negative magnetic polarity in the southern hemisphere,* are the magnetic sectors of *reversed polarity* (RSs). The unreversed, or the 'old' 22nd cycle sectors (OSs), in the northern (southern) hemisphere have negative (positive) magnetic polarity, respectively.

3. Active Region Data Description and Analysis

We continue analysis of the same sample as described by Antalová & Jakimiec (1995) on daily basis, i.e. the sample of 32 active regions which were classified, after Zirin & Marquette (1990), as BEARALERT regions. The data was obtained between 26 December 1987 and 18 November 1989. Some of the active regions had complete passage (from six days before to six days after the passage across the central meridian (CM)), but some of them had only five to eleven daily values during their life. A total of 338 daily vectors were collected. Each individual data vector comprises six variables (denoted as x1, x2, ..., x6), describing following daily characteristics of a given active regions.
x1 (A) - Sunspot group area as published in *Solar Geophysical Data*;
x2 (MO) - Magnetic orientation of the sunspot group bipole: '1' means the normal Hale orientation of an active regions, '2' stands for a sequence of more than one Hale oriented bipole observed in an active region, '3' denotes the fact that the axis of bipole is tilted by about 90° to the East-West direction, and '4' groups such active regions in which the reversed bipole orientation (i. e.,

the fact that the following (leading) polarity lies westward (eastward) from an active regions center);
x3 (FI_{LDE}) - The flare index computed from all long lasting SXR (LDE–type) flares observed in a given active region in a given day. Let us recall the selection criterion of the LDE–type flares: the flare duration exceeding 2 hours above the quiet SXR GOES level after the analysis of the daily Sun SXR profile as observed by GOES, published in *SGD*. The occurrence of LDE–type flares of different GOES classes is weighted with respect to their SXR maxima (e.g. a flare C7.9 has FI = 8 and the corresponding FI value for an X3.2 flare is 320);
x4 (FI_I) - The flare index of impulsive flares prepared in the same way as x3, but in this case only short lasting flares (of an impulsive–type) are included.
x5 (FI_T) - The total flare index ($FI_{LDE} + FI_I$) of an active region;
x6 (S) Solar sectors: '0' shows the location of an active regions in an old cycle magnetic polarity sector (OS), '1' – along the sector's boundary (B), and '2' - when active regions is located in the sector with a new cycle magnetic polarity (RS).

The variables of the continuous type (x1, x3, x4 and x5) were reduced to a logarithmic scale ($\log_{10}x$), because the original variable distribution had a strong skewness. Table 1 presents the mean values and standard deviations of the analyzed variables obtained for the data sample of 338 daily vectors. The mean values are computed from daily values of all BEARALERT active regions and not only from genuine flaring active regions , so large values of standard deviations are expected. Antalová & Jakimiec (1995) analyzed separately the flaring days (183 days, for which x5 was not equal to zero) and the days with no flare activity. From all of those 183 flaring days we had 49 daily vectors for active regions located in the OSs, 73 for active regions located along sector boundaries (B) and 73 in the RSs. In lower part of Table 1 the sectorial distribution of the mean values of x1 – x6 are given for these flare-rich days.

As mentioned above, it was also found that the mean values of sunspot group area, magnetic complexity, and flare activity are significantly greater for the active regions that are located along the BSs or in the RSs than for those located in the OSs. Fig. 1 visualize these differences.

4. Flaring Related to Area and Magnetic Complexity

As shown earlier (Antalová 1994, Antalová & Jakimiec 1995), large and complex sunspot groups relate to the RSs and Bs. Hence, it might be argued that the enhanced flare production in RSs is simple the result of appearance of large and complex groups (Fig. 1). Therefore, in the next step we consider active region flaring as a function of both the area of an active region and its magnetic complexity. This is why we introduce the new, 'normalized' variables:
y1 = x3/x1 = FI_{LDE}/A - the daily flare index for LDE–type flares related to the sunspot group area on the given day.
y2 = x4/x1 = FI_I/A - the daily flare index of impulsive flares related to the sunspot group area on the given day.
y3 = x3/x2 = FI_{LDE}/MO - the daily flare index for the LDE-type flares related to the magnetic complexity of the active regions on the given day.
y4 = x4/x2 = FI_I/MO - the daily flare index for the impulsive flares related

to the magnetic complexity of the active regions on the given day.

The mean values of the variables y1–y4 were calculated separately for the sectors O, B and R and then the differences between these sectors were tested. Fig. 2 visualize the results.

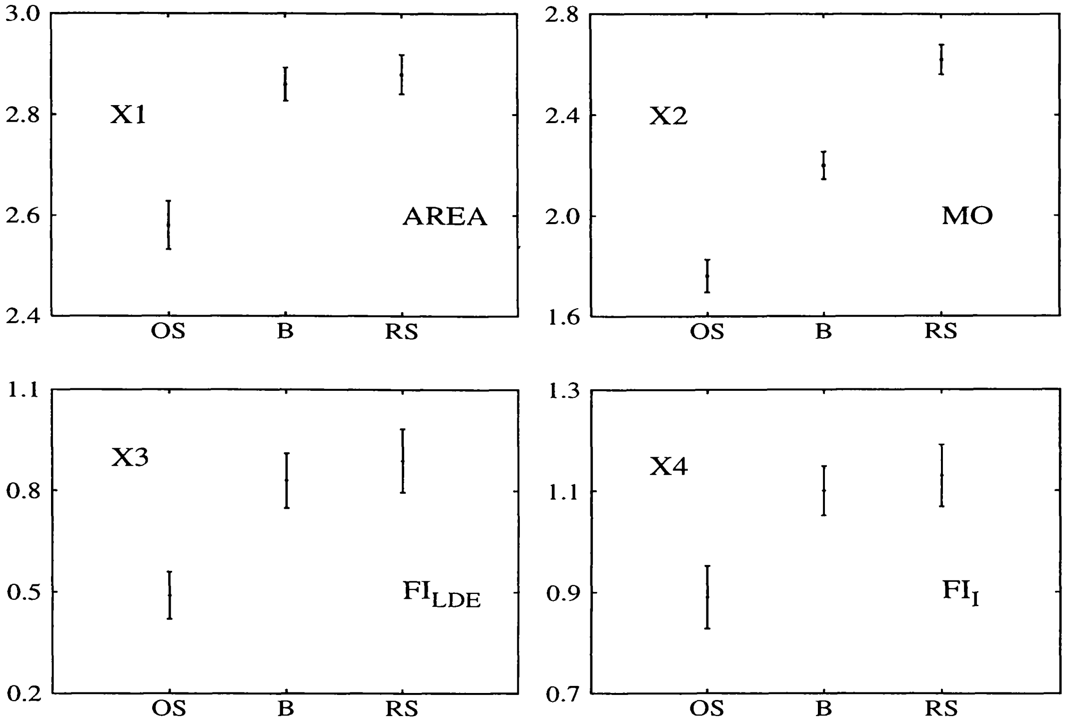

Figure 1. The mean values of x1 – x4 and their standard error bars plotted as function of active regions sectorial locations.

4.1. Flaring in Relation to Sunspot Group Area

We have found that differences in values of y1, namely, y1(RS) – y1(OS) and y1(B) – y1(OS), are statistically significant. It means that active regions located in RSs and along Bs are not only capable of producing sunspot groups of a significantly larger area, but also active regions with a significantly higher LDE-type flare activity than those active regions located in the OSs. On the contrary, for y2, when the impulsive flare activity is related to sunspot group area we do not find significant differences between OS and B or RS sectors, however the y2 mean value is the lowest in OSs comparing to y2 in B and RSs.

4.2. Flaring in Relation to Magnetic Complexity

Comparing LDE–type flare activity in the relation to magnetic complexity (y3) we do not find significant differences between active regions located in OSs and B or RSs. Therefore, the occurrence of LDE flares is mainly determined by development of active regions . Although, as in the case of y2, the mean value of y3 is the lowest in OSs. However, y4 (the impulsive flare activity in the relation to magnetic complexity) is significantly lower in RSs than in OSs and

B. We should recall here, that both the magnetic complexity (x2) as well as the impulsive flare activity (x4) are significantly higher in RSs than in OSs (see Fig. 1). So, in RSs, the impulsive flare activity regarding this extremal magnetic complexity of active regions is relatively small; it is smaller than one would expect.

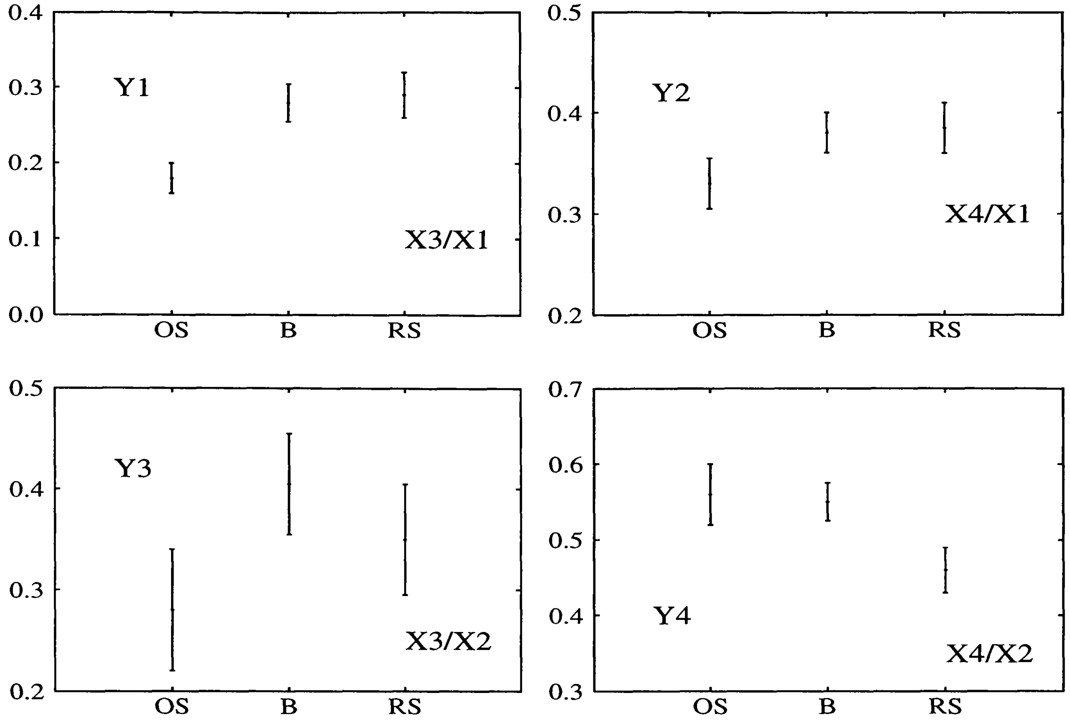

Figure 2. The mean values (with their standard error bars) of the variables y1 – y4 plotted for active regions located in the O, B, R magnetic sectors.

5. Results and Discussion

We have performed an analysis of the sectorial distribution of 32 BEARALERT regions based on the synoptic magnetic maps of modeled source surface fields (Hoeksema 1991). Using the sample of 338 daily values we have arrived at the following results:

1. Practically no flaring difference was found between the active regions located along sector boundaries and those observed in reversed magnetic sectors. We have thus confirmed earlier findings of Bumba and Obridko (1969), Dittmer (1975), McIntosh (1992) as well as Stewart and Bravo (1995), indicating that during each phase of a solar cycle flare-rich active regions are seen along a global magnetic neutral line of the Sun. (Let us recall that *the global magnetic neutral line* coincides with the notion of sector boundaries adopted in this paper).

2. Our statistical tests also indicate that flare-mighty active regions are situated not only along sector boundaries, but they are also found inside of the sectors of reversed magnetic polarity. For example, in the case of an X9.8 flare of 29 September 1989, (characterized by the largest ground-level cosmic ray enhancement ever observed – Kudela et al. 1993) the parent active region – NOAA 5698 – was just situated along the Bs; on the other hand, the active region NOAA 6659 (endowed by the largest flares of June 1991 – McIntosh 1993, Antalová 1994) was undoubtedly present inside of an RS.

3. Kahler et al. (1995) as well as Shea et al. (1995) found connection between magnetic sectors, acceleration and transport of interplanetary protons by large-scale shocks driven by CMEs.

4. The presence of a global magnetic reversal process in a given RS of the Sun seems to be important for the development of magnetically complicated and therefore flare-rich sunspot complexes. We suspect that the flare-ability to recognize the large-scale magnetic changes reflecting the global magnetic field reversal process is linked to unbalanced, large-scale magnetic patterns rather than to pulse-like local emergence of an active regions magnetic flux. But the question arises why it is related to RS only, when the same unbalanced polarity patterns are also observed in old sectors. Apparent difference between RSs and OSs is caused by their opposite magnetic polarity, and this obviously play an important role in the interaction of these fields with the local magnetic field of an AR; however, at present this question remains open.

5. From the statistical test of y1 we have found out that active regions located in RSs and along the Bs are not only capable of producing sunspot groups of a significantly larger area than those located in the old sectors, but also, with significantly higher LDE-type flare activity in the relation to the sunspot group area.

6. Looking at impulsive flare activity we see that in the relation to area (y2) it does not reveal statistically significant differences between the Bs and sectors.

7. When we relate LDE–flaring to the magnetic orientation (y3) we have not found statistically significant differences between O, B, R sectors.

8. The behavior of x4 clearly indicates that RSs and the Bs seem to be preferred sites of impulsive flaring. On the other hand, the impulsive flare activity in the relation to magnetic complexity (y4) is significantly lower in RSs than in OSs or Bs. So, the impulsive flare activity in RSs is smaller than we could expect taking into account the magnetic complexity of ARs located in RSs.

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