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Longitudinal magnetic field gradients and vertical electric currents in active regions with different flare productivity levels

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Abstract. The purpose of the work performed was to search for parameters of longitudinal magnetic field gradients and vertical electric currents, and their values, which could serve as the basis for creating criteria for short-term forecasting of changes in the flare productivity of an active region (AR). In the course of the study, a threshold (critical) value of the average unsigned vertical electric current density ($< |j_z| >$) was identified, equal to 2.7 mA m^{-2}; it is shown that in all ARs with high flare activity, the value of $< |j_z| >$ is above the threshold; it is shown that a rapid increase in the parameter $< |j_z| >$ above the critical value, especially in ARs, in which additional ascent of the magnetic flux was recorded during their monitoring time, indicates an increase in AR flare activity in the time interval of 18-20 hours. A threshold value of the transverse component of the longitudinal magnetic field gradient between pairs of sunspots in the AR ($max(\nabla_\perp B_z)_{sp}$), equal to 0.118 G km^{-1}, was also found. In the AR NOAA 11283, a study of the dynamics of the value made it possible to detect a time delay of 19 hours between the beginning of its stable growth and the time of the beginning of the development of the first of a series of powerful solar flares.

Keywords: Sun: activity, flares, magnetic fields, electric currents

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1 Introduction

Solar flares and coronal mass ejections have a significant impact on living organisms and technical systems on Earth, in its atmosphere and outer space. Considering the level of development of civilization and, at the same time, the almost complete absence of effective countermeasures, a qualitative forecast of solar activity becomes a task closely related to the everyday needs of humanity.

There are a large number of criteria that allow one to assess the probability of a solar flare (or series of solar flares) occurring in an active region (AR) with a lead time of up to several days (see Altyntsev et al. (1982); Severny et al. (1979), and many others). In recent decades, due to the emergence of new instruments for studying the Sun, which have high spatial and temporal resolution, it has become possible not only to clarify existing forecast criteria, but also to develop new ones, based, among other things, on the study of the dynamics of certain parameters in the solar atmosphere over significant (several days) time intervals. We present the results of a study on the dynamics of the gradients of longitudinal magnetic field and vertical electric currents in ARs with different levels of flare productivity based on observations obtained during the 24th solar cycle. These results may be of some interest in the context of forecasting solar flare activity with a lead time of about a day.

2 Methods and data used

The gradient (or rather the transverse component of the gradient) of the longitudinal magnetic field $\nabla_{\perp} B_z$ is calculated between pairs of sunspots in the AR as the absolute value of the difference in the maximum (minimum) values of the magnetic field strength in the sunspots, divided by the distance between these points (more detailed see Fursyak (2023)):

$$\nabla_{\perp} B_z = \frac{|B_{zimax} - B_{zjmax}|}{\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}} \tag{1}$$

To calculate the magnitude of the vertical electric current (more detailed see Fursyak (2018)) an integral approach is used. Method based on the Stoke's formula:

$$I = \frac{1}{\mu_0} \int_L B_l dl \tag{2}$$

where $\mu_0 = 4\pi \times 10^{-7}$ H m^{-1} is the magnetic constant in the SI; L is a closed rectangular contour of 5×5 pixels in size; B_l – the values of the transverse components of the magnetic field in the direction of the contour bypass; dl – the integration element equal to the pixel size on the magnetogram.

All studies were performed using magnetographic data from the Helioseismic and Magnetic Imager (HMI/SDO, Scherrer et al. (2012)), available on the Joint Science Operation Center (JSOC) website[1], data series hmi.sharp_cea_720s.

3 Results

3.1 Vertical electric currents

Statistical analysis made it possible to detect a relationship between average unsigned density of the vertical electric current averaged over the monitoring time of the AR $<\overline{|j_z|}>$ (time averaged is indicated by the overbar) and the level of flare activity of the AR (flare index, FI, Abramenko (2005)) with Pearson's r = 0.66 (see Fig 1), and the threshold (critical) value of the $<\overline{|j_z|}>$ equal to 2.7 mA m^{-2} (vertical red dotted line with a long dash; also see Fursyak (2018)). The latest results (vertical red dotted line with a short dash) showed that flares of X-ray classes X are observed only in ARs for which the value of the parameter $<\overline{|j_z|}>$ not lower than 2.85 mA m^{-2}. It can also be seen (blue vertical dotted line with a short dash) that for all ARs with low activity the value of $<\overline{|j_z|}>$ is no higher than 3.3 mA m^{-2}.

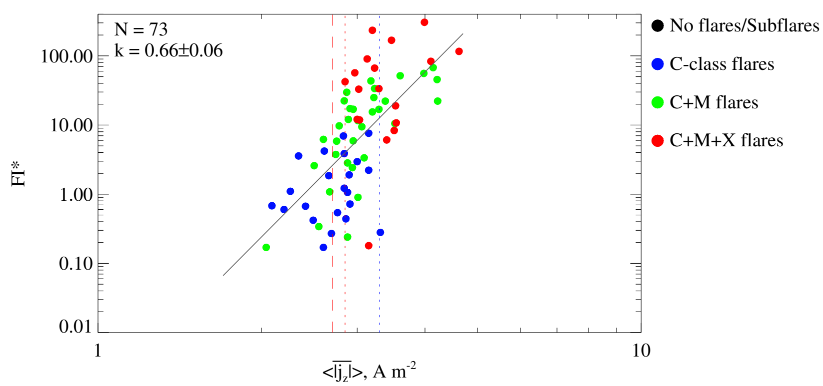

Fig. 1. Relationship between average unsigned density of the vertical electric current averaged over the monitoring time of the AR and the flare index of the AR ($<\overline{|j_z|}>$ – FI) for a sample of 73 ARs of the 24th solar activity cycle.

The most interesting was the study of the dynamics of $<|j_z|>$ in the ARs NOAA 11158 and 12673, which have high activity, in which an growth of the magnetic flux

[1] http://jsoc2.stanford.edu/ajax/lookdata2.html

was observed during their monitoring time. It is shown (Fig. 2, AR NOAA 11158 for example) that: 1) there is a rapid increase in the parameter $< |j_z| >$ above the critical value; 2) the moment of the beginning of a rapid increase in the value $< |j_z| >$ does not coincide in time with the beginning of the growth of the total unsigned magnetic flux (Φ) of the AR; 3) the total unsigned magnetic flux of the AR increases over a time interval of several days, while the time of rapid increase of the value $< |j_z| >$ does not exceed 6-7 hours; 4) a rapid increase in the value of $< |j_z| >$ is observed 18-19 hours before the start of the first powerful solar flare in the AR.

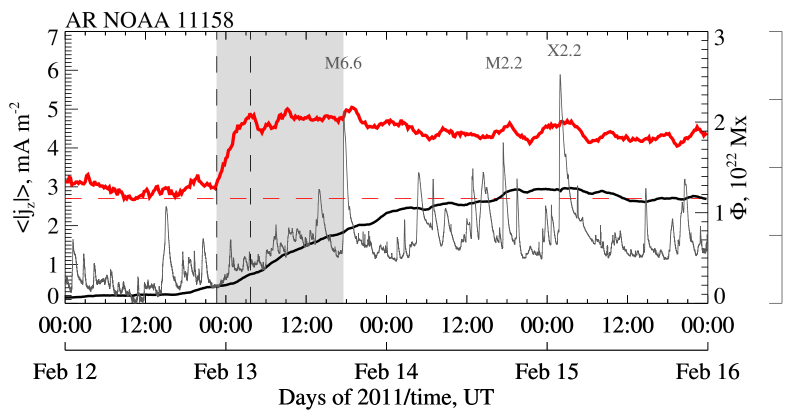

Fig. 2. Dynamics the parameters $< |j_z| >$ (red curve) and Φ (black curve) for the AR NOAA 11158. The following are shown: the critical level of $< |j_z| >$ (horizontal red dotted line); the time interval of the rapid increase of the parameter $< |j_z| >$ (vertical dotted lines); the time interval between the onset of the increase in the magnitude of $< |j_z| >$ and the first powerful X-ray solar flare (marked in gray). The most powerful solar flares recorded in the AR are indicate.

3.2 Longitudinal magnetic field gradients

Statistical analysis (Fig. 3) made it possible to detect a relationship between the maximum value of the transverse component of the longitudinal magnetic field gradient between pairs of sunspots $max(\nabla_{\perp} B_z)_{sp}$ and level of AR flare activity with the Pearson's r = 0.63, as well as a threshold value equal to 0.118 G km^{-1} (Fig. 3 vertical red dotted line with a long dash; also see Fursyak (2023, 2024)). It is also shown that for all ARs with low activity the value $\overline{max(\nabla_{\perp} B_z)}_{sp}$ (time-averaged parameter) is no higher than 0.2 G km^{-1} (Fig. 3, vertical blue dotted line with a short dash).

A study of the dynamics of the value in the AR NOAA 11283, in which intense movement of one of the developed sunspots was recorded, showed the following

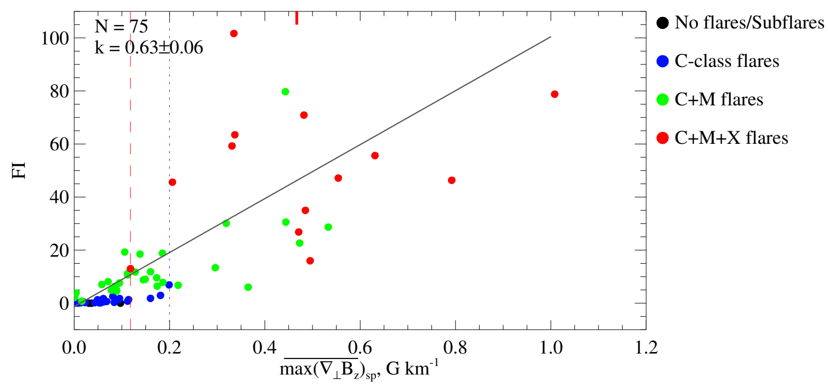

Fig. 3. Relationship between maximum value of the transverse component of the longitudinal magnetic field gradient between pairs of sunspots in the AR averaged over the its monitoring time and the flare index of the AR ($\overline{max(\nabla_{\perp}B_z)_{sp}}$ – FI) for a sample of 75 ARs of the 24th solar activity cycle.

(Fig. 4): 1) there is a stable smooth increase in the magnitude of $max(\nabla_{\perp}B_z)_{sp}$ above the threshold value with practically unchanged total unsigned magnetic flux of the AR; thus, the increase in the parameter $max(\nabla_{\perp}B_z)_{sp}$ is due solely to the movement of the sunspots in the AR; 2) an increase in the value $max(\nabla_{\perp}B_z)_{sp}$ above the threshold value is observed 19 hours before the M5.3 class X-ray flare, the first of a series of powerful flares in the AR.

4 Summary

Studies of longitudinal magnetic field gradients and vertical electric currents carried out based on observational data obtained during the 24th solar cycle allow us to draw the following conclusions:

1. There is a relationship between the value of the average unsigned vertical electric current density averaged over the AR monitoring time $< \overline{|j_z|} >$ and the level of flare activity of the AR (flare index) with Pearson's $r = 0.66$.
2. A threshold (critical) value of $< \overline{|j_z|} >$ equal to 2.7 mA m^{-2} was detected; exceeding the threshold value is typical for ARs with higher flare activity.
3. In the ARs NOAA 11158 and 12673 a sharp increase in the $< |j_z| >$ value above the threshold level was observed 18-19 hours before the first solar flare of high X-ray class.
4. There is a relationship between the magnitude of the transverse component of the gradient of the longitudinal magnetic field between pairs of sunspots in the AR ($max(\nabla_{\perp}B_z)_{sp}$) and the level of its flare activity with a Pearson's $r = 0.63$.

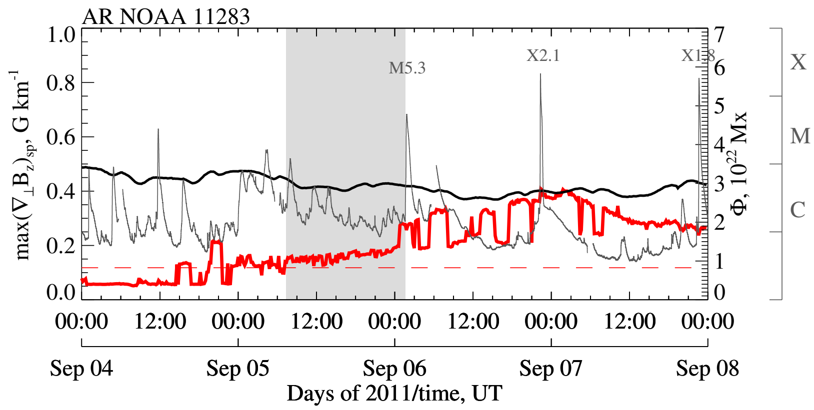

Fig. 4. Dynamics of the parameters $max(\nabla_{\perp}B_z)_{sp}$ (red curve) and Φ (black curve) for the AR NOAA 11283. The following are shown: the critical level of the $max(\nabla_{\perp}B_z)_{sp}$ (horizontal red dotted line); the time interval between the onset of the increase in the magnitude of $max(\nabla_{\perp}B_z)_{sp}$ and the first powerful solar flare (marked in gray). The most powerful solar flares recorded in the AR are indicate.

5. A threshold value of the parameter $\overline{max(\nabla_{\perp}B_z)}_{sp}$ equal to 0.118 G km^{-1} was detected.
6. In the AR NOAA 11283 a time delay of 19 hours between stable increase the parameter $max(\nabla_{\perp}B_z)_{sp}$ above the threshold level and the time of the beginning of the first of a series of powerful solar flares (M5.3 X-ray class) was detected.

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