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Large-scale electric currents in processes in the solar atmosphere

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Abstract. In the late 80s of the 20th century, Crimean astronomers, studying the structure of transverse magnetic fields in active regions (ARs), discovered signs of the presence of large-scale vertical electric currents – global electric currents (Abramenko, Gopasyuk 1987). In 2018–2020, we finalized and adapted the method for detecting large-scale electric currents to the data of modern instruments for studying the Sun, and began studying their dynamics on time scales of 3–5 days (Fursyak *et. al* 2020). Our researches carried out during 2020–2023 showed that: 1) Large-scale electric currents with values of the order of $\sim 10^{13}$ A exist in ARs with nonzero flare activity. 2) Large-scale electric currents extend to the upper layers of the solar atmosphere in one part of the AR, and close through the chromosphere and corona in the remaining part of the AR. This assumption for the AR NOAA 12192 is confirmed by the results of numerical simulations performed in 2016 (Jiang *et al.* 2016). 3) The greater the magnitude of the large-scale electric current, the higher the probability of occurrence of M- and X- class solar flares in the AR. 4) At the final stages of AR evolution, a nonzero large-scale electric current can have a stabilizing effect on the sunspot, preventing its decay by its own magnetic field. 5) Large-scale electric currents are involved in coronal heating processes. Ohmic dissipation of a large-scale electric current is one of the mechanisms of quasi-stationary heating of coronal plasma above the AR. Our research on large-scale electric currents and the processes in which they take part continues.

Keywords. Sun, magnetic fields, electric currents, solar activity

1. Introduction

Electric currents play an extremely important role in various processes in the solar atmosphere. The first studies of electric currents on the Sun were carried out by astronomers of the Crimean Astrophysical Observatory in the 60s–70s of the 20th century (see refs in Alfven, Carlqvist 1967; Fleishman, Pevtsov 2018). Here we briefly present the results of our research conducted in 2018–2023, which, on the one hand, is a logical continuation of the early works of Crimean astronomers, and on the other hand, based on new approaches and data from modern instruments for studying the Sun.

2. Detection and Calculation of Large-Scale Electric Current

Large-scale electric currents in active regions (ARs) are distributed over a large area, so indirect techniques are required to detect them (see Fursyak *et. al* 2020).

Stage 1 involves the restoration of the potential transverse magnetic field of the AR. To solve this problem, the IDL code developed in 1982 by T. Sakurai (Sakurai 1982) is used.

At Stage 2, in each pixel of the initial magnetograms, the vector of the real (observed) transverse magnetic field of the AR is compared with the vector of the potential transverse magnetic field.

Stage 3 involves the decomposition in each pixel of the initial magnetograms of the vector of the observed transverse magnetic field into two components – potential, directed along the vector of the potential transverse magnetic field, and non-potential ($\mathbf{B}_{t\perp}$), directed across the vector of the potential field. The nonpotential component of the transverse magnetic field vector is due to electric currents in the AR.

Stage 4 involves the analysis of the distribution of the vector of the nonpotential component of the transverse magnetic field ($\mathbf{B}_{t\perp}$) in the AR. Near large developed sunspots in the AR, the vector $\mathbf{B}_{t\perp}$ forms regular vortex structures, which are due to the presence of a large-scale vertical electric current distributed over a large area. To calculate the magnitude of the large-scale electric current around the sunspot, a contour is drawn (Stage 5) so that within the contour the direction of twist of the vector $\mathbf{B}_{t\perp}$ has one predominant direction (clockwise or counterclockwise). The magnitude of the large-scale electric current for a given point in time is calculated as the resulting vertical electric current within a contour. The shape of the contour does not change over the entire time interval of AR monitoring. In order to minimize the errors caused by the evolution of the AR, the contour within which the magnitude of the large-scale electric current is calculated is tied to the center of gravity of the sunspot. The displacement of the center of gravity of the sunspot even by one pixel on the magnetogram leads to a displacement of the contour by the same number of pixels.

The analysis of the structure of the transverse magnetic fields of the studied ARs and the calculation of local vertical and large-scale electric currents were carried out using the magnetographic data of the Helioseismic and Magnetic Imager (HMI) instrument (Scherrer *et al.* 2012) aboard the Solar Dynamics Observatory (SDO) with a spatial resolution at the level of the solar photosphere of $0.5''$ (360 km) and a time resolution of 12 minutes, available from the Joint Science Operation Center (JSOC) website at http://jsoc2.stanford.edu/ajax/lookdata.html.

The obtained values of the imbalance of the vertical electric current in the studied ARs ($< 0.1\%$) suggest that a large-scale electric current goes high into the solar corona and closes within the AR. Therefore, a large-scale electric current must be associated with various processes in the atmosphere above the AR.

3. Large-scale electric currents and flare productivity of ARs

Since electric currents in ARs are carriers of the energy of nonpotential magnetic fields, the so-called "free" magnetic energy (Melrose 1991; Fleishman, Pevtsov 2018), and a large-scale electric current extends to the upper layers of the solar atmosphere, therefore, it must be closely related to the flare productivity of ARs. Indeed, as we showed in (Fursyak *et. al* 2020), large-scale electric currents with absolute values on the order of $\sim 10^{13}$ A are present in all developed ARs. However, the absolute values of the magnitude of the large-scale electric current and its temporal variations are overwhelmingly larger in the ARs with a higher level of flare activity (see Fig. 3 and Fig. 4 in Fursyak *et. al* 2020).

Initially, we suggested that large-scale electric currents are found only in developed ARs with nonzero flare productivity. However, a later study of ARs at the final stages of evolution (Fursyak, Plotnikov 2022) showed that in approximately 25–30% of cases, a nonzero large-scale electric current is also recorded in such ARs. However, the dynamics of the magnitude of the large-scale electric current in the ARs at the final stages of evolution is very low, and its absolute values ($\sim 10^{12}$ A) are several times lower than the absolute values of the large-scale electric current in developed ARs.

4. Large-scale Electric Currents in the Processes of Sunspot Stabilization

In 2022, we studied the role of electric currents in the processes of stabilization or destabilization of sunspots in ARs at the final stage of evolution (Fursyak, Plotnikov 2022). A total of 46 ARs of the 24th cycle of solar activity were analyzed. It was shown that there are no large-scale electric currents in the ARs with the magnetic flux decay rate $> 6.0 \times 10^{19}$ Mx hr^{-1} (within the calculation errors). At the same time, a nonzero large-scale electric currents were found in 37% of the ARs with magnetic flux decay rate in the sunspot $\leq 6.0 \times 10^{19}$ Mx hr^{-1} (see Fig. 5 and Fig. 6 in Fursyak, Plotnikov 2022). Thus, on the basis of statistical analysis, we concluded that a large-scale electric current by its own magnetic field can have a certain stabilizing effect on the sunspot. However, large-scale electric current is not being the only possible mechanism which can prevent the loss of magnetic flux of the sunspot.

5. Large-scale Electric Currents and Coronal Heating Processes

It is known that only a few percent of the energy of nonpotential magnetic fields of AR, which is carried by electric currents, is released in solar flares of various classes (Zaitsev *et al.* 1998). More than 90% of this energy is released in a number of other processes. It is logical to assume that a large-scale electric current extending into the upper layers of the solar atmosphere will participate in these processes, one of the most obvious of which is the heating of coronal matter above the AR.

To assess the role of large-scale electric currents in the heating of the coronal matter, data on the intensity of UV radiation in the 131, 171, 193, and 211Åchannels provided by the Atmospheric Imaging Assembly (AIA/SDO) (Lemen *et al.* 2012) were analyzed, maps of the spatial temperature distribution in the corona were obtained, the values of the average temperature in the corona above the AR were determined, and graphs of temporal changes in the average temperature during the monitoring of the AR were plotted (Fursyak 2023). In total, 9 ARs of the 24th cycle of solar activity with different levels of flare productivity were analyzed. The following results were obtained (see Fig. 3 in Fursyak 2023):

(1) Outside of solar flare events, the average temperature in the corona above the ARs during their monitoring is close to $< lgT > = 6.2$ (1.5 MK) and does not depend on the level of flare productivity of the AR. This observation suggests that the heating of coronal matter due to ohmic dissipation of large-scale electric currents occurs in a quasi-stationary regime.

(2) During solar flares of high X-ray classes, an increase in the average temperature in the corona above the AR to values $< lgT > = 6.3$–6.5 (2.0–3.2 MK) is recorded. In this case, there is no correlation between changes in the average temperature in the corona above the AR and the dynamics of the large-scale electric current. It can be assumed that the additional heating of the corona during flares is caused not only by electric currents, but also by a number of other processes at coronal heights.

(3) On the graph of time variations of the large-scale electric current and average temperature in the corona for the AR NOAA 12494, one can note a decrease in the average temperature in the corona to $< lgT > = 5.7$ (0.5–0.6 MK) with a simultaneous decrease in the value large-scale electric current to zero values. This observation indicates that the mechanism of heating of the coronal matter over the AR by ohmic dissipation of large-scale electric currents is switched off.

In ARs NOAA 12192 and 12371, which have the highest values of the large-scale electric current, the temperature distribution maps in the corona made it possible to detect in times outside the solar flare events for AR NOAA 12192 a localized region with a temperature of 10 MK, and for the AR NOAA 12371 – hot coronal loops with the same temperature (see Fig. 5 in Fursyak 2023). It is likely that such high-temperature structures mark the location of a large-scale electric current channel at coronal heights, and the high temperature in them is due to ohmic dissipation of the electric current. For the AR NOAA 12192, the existence of the electric current with large absolute value at coronal heights is confirmed by the results of numerical simulation performed in 2016 (Jiang *et al.* 2016): Fig. 2 in this article demonstrates the presence of an electric current in the AR, propagating to heights of about 30 Mm and spatially coinciding with the direction of the large-scale electric current assumed by us in (Fursyak *et. al* 2020). Attention should be paid to the characteristic scale of the electric current channel: in the AR NOAA 12192, the assumed channel of large-scale electric current has a width of the order of $\sim(3-4)\times 10^8$ cm, and in the AR NOAA 12371 it is even smaller. According to theoretical calculations performed in (Solov'ev 2022; Solov'ev *et al.* 2022), the electric current dissipation time under such conditions will be about 10^6 s, which can be considered as a quasi-stationary energy release.

6. Conclusions

Our studies carried out during 2018–2023 showed that:

(1) In well-developed ARs with nonzero flare activity, there are large-scale electric currents of the order of 10^{13} A. We have shown that the dynamics of the large-scale electric current and its absolute values are greater in ARs with a higher level of flare productivity. We also found large-scale electric currents in 25–30% of the ARs, which are at the final stage of their evolution. Temporal variations in the magnitude of the large-scale electric current in ARs that are at the final stages of evolution are insignificant, and the absolute values of the large-scale electric current are several times lower than those in developed ARs.
(2) Large-scale electric currents extend to the upper layers of the solar atmosphere in one part of the AR, and close through the chromosphere and corona in the remaining part of the AR.
(3) At the final stages of AR evolution, a nonzero large-scale electric current can have a stabilizing effect on the sunspot, preventing its decay by its own magnetic field.
(4) Large-scale electric currents are involved in coronal heating processes. Ohmic dissipation of a large-scale electric current is one of the mechanisms of quasi-stationary heating of coronal matter above the AR.
(5) In AR NOAA 12192, when plotting temperature distribution maps in the corona in times outside solar flares, a structure with a temperature of more than 10 MK was found, and in AR NOAA 12371, hot coronal loops with the same temperature were found. Probably, such high-temperature structures represent a channel of large-scale electric current at coronal heights.

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