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Evolution of photospheric currents during the development of the M4.0 flare on September 26, 2011

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We investigate the evolution of the vertical component of the electric current (j_z) at the photospheric level during the moderate M4.0 flare (GOES class) with the powerful pulse of hard X-rays. In the active region (AR) NOAA 11302, where the flare occurred, a sunquake is recorded according to Doppler measurements. This circumstance indicates the strong perturbation propagating into the lower layers of the solar atmosphere. We compare the results with those obtained in the study of the similar M5.7 event on May 10, 2012. We have shown that the change in the currents ($j_z > 0$ and $j_z < 0$) in the AR near the magnetic field neutral line occurs in its part adjacent to the main core of the flare, the center of primary energy release. The efficiency of the work with density distribution maps j_z for the analysis of the photospheric magnetic field of the AR during the flare is shown. Questions related to the localization of the energy release center on the surface of the photosphere within the AR range (the criteria for selecting the area for averaging the values of the j_z) and the amplitude of the current changes during the flare are discussed. The obtained change in the averaged values of the current agrees with the peak of the hard X-ray emission and the instant of registration of the sunquake.

Keywords: Solar flares; magnetic fields; electric currents

1 Introduction

Over the last two decades, the possibility of investigating the changes taking place in the lower layers of the solar corona appeared because of a large array of space data. Now, for instance, the full vector magnetic field data is available with the time interval

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of 720 seconds, starting in 2010 from the *Helioseismic and Magnetic Imager* (HMI: Scherrer et al. 2012) onboard the *Solar Dynamic Observatory* (SDO). In addition, the main part of HMI data is the sequence of magnetograms and dopplergrams in the projection along the line-of-sight (LOS) with the time interval of 45 seconds. Plus, extrapolating nonlinear force-free fields into the corona (Wiegelmann 2004; Metcalf et al. 2008) makes it possible to localize the concentration of the force lines very low in the chromosphere where the electric currents are substantially enhanced. Thus, evidence of the accumulation of the energy of the magnetic field can be obtained at low altitudes. The problems associated with the consumption of stored current free energy for pulsed energy release make it possible to investigate, that is, to study non-stationary phenomena occurring in active regions (ARs) caused by a change in the magnetic field. Otherwise, we can investigate the flare and/or coronal mass ejection (CME) in the context of a change in the magnetic field calculated at the photosphere level and up to the coronal heights in the *Nonlinear Force-Free Field* (NLFFF) approximation by the optimization method (Wheatland et al. 2000) in the form realized in (Rudenko, Myshyakov 2009) and, further, using the potential approximation high in the corona.

We recall that the problem of the relationship of electric currents and flares has been discussed since the first ground-based measurements of the full vector magnetic field, for example (Rust 1968; Severnyi 1988). However, only in the era of space observations and the development of the theory (Kostyuk, Pikelner 1974; Zaitsev, Stepanov 2008; Fisher et al. 2012; Lee et al. 2010; Hood et al. 2012), it has become possible to investigate a flare in the context of magnetic field changes (*i.e.* the rapid energy release with increasing emission and the development of a CME. We pointed out this circumstance in (Livshits et al. 2016).

In this paper, we restricted the study of the variation of the AR magnetic field at the level of the photosphere during the pulsed M flare (the *Geostationary Operational Environmental Satellite* (GOES) classification), based on the calculation of the vertical current j_z component. One of the criteria for selecting the M4.0 event on September 26, 2011 in the AR NOAA 11302 was the discovery at that time of the sunquake (SQ: Kosovichev, Zharkova 1998) on the photosphere, associated with the flare as indicated in Buitrago-Casas et al. (2015). This fact indicates the propagation of the part of the flare perturbation downward (Russell et al. 2016), and it is probably possible to detect some dynamics and localize the region of energy release near the photospheric level.

The analysis of the observational data and the results of the calculations obtained in our study are contained in Sections 2 and 3. Comparison of the investigated event (M4.0 flare on September 26, 2011) with the previously well-studied flare M5.7 event on May 10, 2012 (Livshits et al. 2016; Grigor'eva, Livshits 2017) with explanations for the calculations are given in Sections 3 and 4. All data used or mentioned in the paper are publicly available.

2 Data analysis of the M4.0 flare on September 26, 2011

Typically for ARs with sunspot groups of the area of the order of 1000 parts per million (ppm) of the solar disk hemisphere or more, the presence of a powerful activity center

(the flare onset area localized in ARs either within the penumbra of the sunspot or near the neutral line of the local magnetic field) predisposes to a series of flares of high GOES classes. This is mentioned in the paper (Grigorieva et al. 2012) on the study of the AR NOAA 10030 in July 2002. The analysis of observational data in the open access for our case, – the activity of the AR NOAA 11302 (from its appearance on the limb 21 to September 28, 2011) in *Extreme Ultraviolet-Ultraviolet* (EUV-UV) lines using solar images from the *Atmospheric Imaging Assembly* (AIA: Lemen et al. 2012) onboard the SDO, and in the hard X-ray (HXR) range on the *Reuven Ramaty High Energy Solar Spectroscopic Imager* (RHESSI: Lin et al. 2002) shows its significant flare productivity. And this follows from the solar region summary report of the *Space Weather Prediction Center* of the *National Oceanic and Atmospheric Administration* (NOAA), too.

The flare emission of interest to us that occurred in the AR NOAA 11302 on September 26, 2011 with the beginning at 05:06 UT in the soft X-ray (SXR) emission according to GOES data was studied in detail in Kushwaha et al. (2014) using RHESSI data. There, the authors provide diagnostic and physical parameters of the flare plasma, in particular, the increase of the emission flux in the low-energy GOES channels at the beginning of the HXR pulse phase, the rapid time evolution of the X-ray and microwave (MW) flux, and the strong nonthermal character of the X-ray spectrum (photon spectral index $\gamma \sim 3$). We agree with these authors that all this, together with the increased flare activity of the AR, is an argument in favor of the "early impulsive flare" scenario (Sui et al. 2006).

However, in view of the strong noisiness of the magnetic field data in this AR (just in the period of its flare activity), information on the AR magnetic field can only be limited, as can be seen from the open data (SDO/HMI). The authors of Kushwaha et al. (2014) tried to get round this problem. To obtain the temporal evolution of the photospheric magnetic field in the 00:30-05:30 UT interval (for two smaller regions, "R1" and "R2", in the center of this AR), they used 3-minute averaged HMI data from the line-of-sight to estimate the photospheric magnetic flux (see Fig. 10 in their paper). The analysis of the vector magnetic field was made only for the time before the beginning of the event, at 05:00 UT (see Fig. 11 ibidem).

We suggest using another characteristic based on the full vector magnetic field HMI data, without averaging them, to study the time evolution of the magnetic field, which will be discussed later in Sections 2.2 and 3.

2.1 X-ray emission

The indication of the processes associated with the powerful pulsed energy release in the M4.0 event under investigation can be obtained from the independent data of the X-ray telescope with a broadband view of the all sky (the *Wideband All-sky Monitor*, WAM: Yamaoka et al. 2009), in addition to studies of HXR RHESSI emission performed in Kushwaha et al. (2014). This telescope is installed on the *Suzaku* satellite, its effective area in the range of ∼100 keV is 100 times larger than the area of each detector at the RHESSI). A detailed study of solar flares recorded with *Suzaku*/WAM is given in Ishikawa et al. (2013).

So on September 26, 2011 the *Suzaku*/WAM registered powerful HXR emission in the 50-110 keV channel at 05:06:21.0169 UT (see the *grey curve* in Fig.1), which

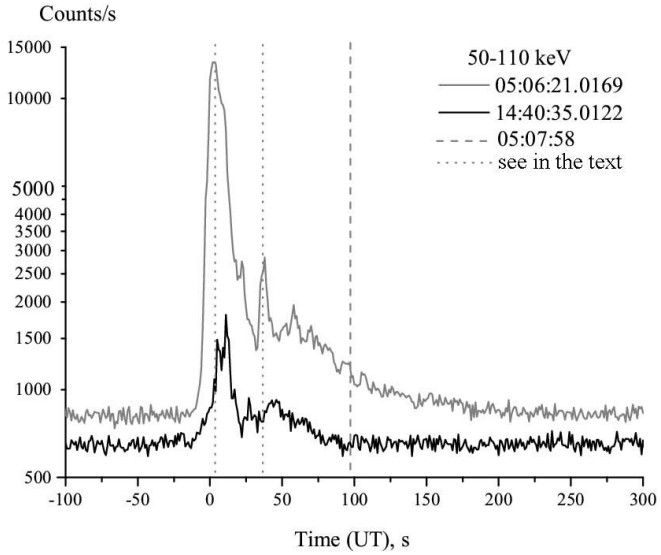


Figure 1 The HXR emission flux on September 26, 2011 (*Suzaku*/WAM) from two GOES class M flares that occurred in the AR NOAA 11302 at 05:06:21 UT (*grey*) and at 14:40:35 UT (*black*) curves. Scales: (left) the counting rate in the channel with the energy $E = 50$–110 keV; (bottom) the time in UT-seconds with a combined 0-count for both events. Vertical lines: the (*dashed*) line corresponds to the seismic activity in the M4.0 event shown on the grey curve; (*dotted*) lines – HXR RHESSI peaks, for more detail see the text.

agrees with the RHESSI data in the channels with the energy > 25 keV (see Fig. 2b in Kushwaha et al. 2014). Figure 1 shows very clearly the two emission peaks visible on the grey curve (*Suzaku*/WAM) corresponding to the times of two HXR RHESSI peaks, which are marked with vertical dotted lines at 05:06:24 UT and at 05:06:56 UT. According to Kushwaha et al. (2014), the MW-bursts recorded at 17 GHz and 34 GHz frequencies with the Nobeyama Radioheliograph (Nakajima et al. 1994) associated with these HXR peaks. In addition, the second flare is the M2.6 event with the onset of SXR emission at 14:37 UT (GOES data) with the registered HXR emission weaker by an order of magnitude at 14:40:35.0122 UT (Suzaku/WAM, see the black curve in Fig. 1) occurred in the same part of the AR. The localization of both the HXR sources is visible, for example, on the reconstructed RHESSI images using the CLEAN method in the 25–50 keV channel at the appropriate time (see, for example, the RHESSI images hsi_qlimg_11092612_025050.png and _11092642_025050.png from hessi.ssl.berkeley.edu/hessidata/metadata/qlook_image_plot/2011/09/26/. Also in Fig. 1, the vertical dashed line indicates the significant feature in the M4.0 event – the time of the onset of seismic activity (registration of the SQ), according to Buitrago-Casas et al. (2015). This moment almost coincided with the SXR peak (05:08 UT, GOES data) registered in both channels.

Similar acts of energy release (with HXR emission ∼25–50–100 keV), repeated within the same activity center, are probably characteristic for ARs, elongated along the East–West direction (with the detected magnetic field emergence). Such a scenario is shown in Livshits et al. (2016), in which an unusual case was investigated (the M5.7

flare on May 10, 2012 with the emergence of a new field of opposite polarity in the shadow of the sunspot and the onset of the development of the flare sigmoid).

2.2 The magnetic field: the vertical electric current

The simplest, in our opinion, calculated characteristic associated with the change of the local magnetic field in the AR can be the value of the "vertical" (actually radial) electric current j_z. We are interested in the map of the distribution of its density in the AR and, accordingly, its evolution over time during the flare. Such a map is obtained by calculating the value of the electric current in the projection on the normal to the photospheric surface at each calculation point. To do this, we use the disambiguated HMI vector magnetic field data (Centeno et al. 2014) in open data, and the Ampère's law (Guo et al. 2013), as it is done in (Sharykin, Kosovichev 2015; Sharykin, Kosovichev, Zhimovets 2015). Such current distribution maps j_z can, for example, be constructed with a time interval of 12 minutes according to the SDO/HMI data for different ARs. Earlier, this characteristic was very informative in terms of detecting the source of primary energy release in the study of nonstationary processes on May 10, 2012 in AR NOAA 11479. The localization of the region with increased values of j_z of opposite signs within the considered AR pointed to the location associated with the HXR RHESSI source and the flare core in the EUV range before the onset of the event (Livshits et al. 2016).

To analyze the flare M4.0 event, which occurred on September 26, 2011 in AR NOAA 11302, we obtained the series of such maps from 04:00 UT to 05:36 UT with a 12-minute time interval (before, during and after the flare). As our research has shown, these maps are subject to the influence of noise of the initial magnetic field data in the AR, but can be re-calculated if necessary after post-processing of these maps. This is shown in Fig. 2, where the fragment of the calculated vertical current density distribution map at the time 05:12 UT, closest to the flare peak, is located at the top left (*panel* a). The result after applying post-processing is at the top right (*panel* b). For the calculation procedure, regions within the AR with values of $\pm$2000 G, *i.e.* near the strong magnetic fields of this AR, were taken. The ring-like formation visible at the center of the fragment of the map at 05:12 UT located on the segment of the magnetic field neutral line (NL) in the AR, perpendicular to the main NL, was removed without loss of informativeness. The "defects" on HMI magnetograms detected in this way are related to the unresolved π-ambiguity during automatic signal processing in a particular region of the HMI image due to the complexity of the polarity separation line (Rudenko, Anfinogentov 2014).

In Fig. 2, examples of the electric current density distribution are selectively shown before the beginning of the event (*panel* c), after (*panel* d) and closest to the HXR RHESSI peak moment (*panel* b), where the cross indicates the HXR source. The concentration of regions with increased j_z values of opposite signs (dark/light color) along the NL and these values themselves increase by the time closest to the peak of the flare HXR emission as it turned out. In our case, the j_z values associated with negative polarity (see *panel* b) increase more and the HXR source position coincides with the highly complex segment of the NL. The analysis of the corresponding numerical j_z values during the evolution of the vertical current density at the photosphere level during the M4.0 flare on September 26, 2011 is presented in Section 3.

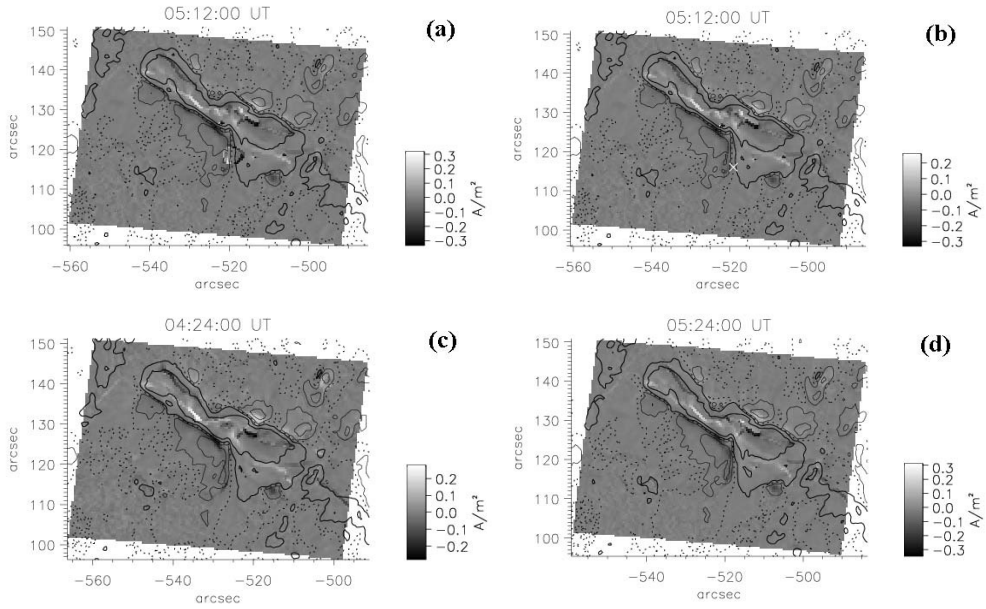


Figure 2 The distribution of the vertical (radial) current density is shown in the fragments in grayscale (*background*). The j_z-data are presented for an isolated region of the photospheric surface, over which the current density integral was calculated. (a): calculated for the time 05:12 UT closest to the M4.0 flare peak with the automatic method for resolving π-ambiguity and (b): – after the "manual" correction of the method; (c, d): the selected examples at 04:24 UT before the flare and after – at 05:24 UT, respectively. The HXR RHESSI source position marked with the *cross*. The magnetic field (SDO/HMI_LOS) at levels $\pm[300; 1000]$ G: the negative polarity (*light grey thin* contours) and the positive polarity (*dark thick* contours); the neutral line in the AR is shown bythe *dotted* line. Bars – current values in A/m^2. Scales – the distance from the center of the disc in angular seconds.

3 Flare activity and evolution of photospheric electric currents

Nonstationary processes in the lower layers of the solar atmosphere, where strong electric currents can occur, are associated with changes at the photospheric level in the region of strong magnetic fields. Moreover, various phenomena occurring in the AR can be due to this change. For example, a change in the configuration of the magnetic field can lead to a sudden energy release, to increased emission and the development of various plasma motions (CME, jets, eruptions, etc.), which is simultaneously observed in pulsed flashes. This concept underlies our research.

Here we emphasize that the large area of the AR NOAA 11302 (1300 parts per million of the solar disk hemisphere on September 25, 2011) and the length along the East–West direction ($\sim$ 220 arcsec) allowed us to consider specific parts and localize activity in the center of the sunspot group near the strong magnetic field. Therefore, we selected a small part in the AR, which contained the brightness in the 171 Å line

(the flare core), visible to the SDO/AIA images. Further, to obtain characteristic associated with the temporal variation of the magnetic field, we averaged the photospheric electric current calculated in the projection on the Z-axis at each point (the pixel belonging to this small part of the full vector SDO/HMI data), dividing the resulting integral value of the vertical current j_z to its area in square meters. As a result, the number of successive averaged values ($< j_z >$) were obtained for both polarity signs for an isolated region of the photospheric surface, over which the current density integral was calculated. These $< j_z >$ are calculated with the 12 minute interval (from 04:00 UT to 05:36 UT) in the region where the new field surfaced (Kushwaha et al. 2014), and the flare occurred (in the panels of Fig. 2, the white rectangle is marked).

Thus, the light curves for the electric current variation during the M4.0 flare for the vertical components $- < j_z >$ and $+ < j_z >$ were plotted (see Fig. 3(b)), averaged over the area $S = 1.062E + 015$ m^2 (see the *black rectangle* in Fig. 3(a)). We draw attention to the fact that the course of the positive and negative current components is in anti-phase until 05:00 UT. And at the moment 05:12 UT it turns out to be in-phase, at the moment of time close to the HXR emission peak (at 05:06:21 UT, *Suzaku*; at 05:06:24 UT, RHESSI). There is also a weak positive trend in the light curves of the averaged values of both signs. The registration SQ-time associated with seismic activity beginning at 05:07:58 UT (Buitrago-Casas et al. 2015), in this 12 minute time interval is indicated by the vertical dash-dotted line in Fig. 3(b).

Unfortunately, SDO/HMI data on the full vector magnetic field are available to us only at an interval of 720 seconds, and it is not possible to specify the time of the value change more precisely.

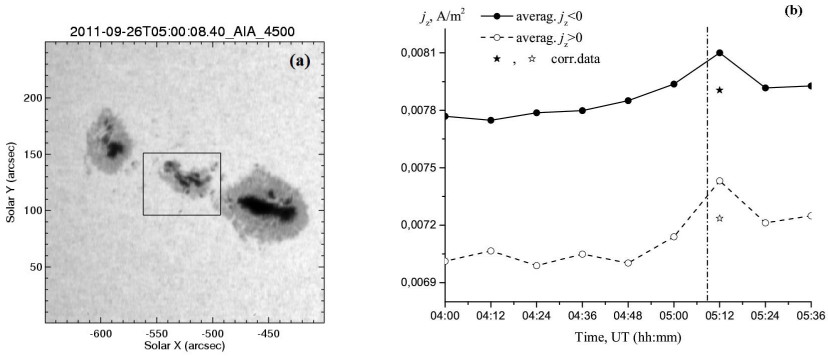


Figure 3 (a) The fragment of the white light filtergram with the AR NOAA 11302 on September 26, 2011 at 05:00:08.40 UT (the 4500Å line, SDO/AIA: *background*). The active center in which the vertical current j_z was calculated during the M4.0 flare (*black* rectangle). Scales – the distance from the center of the disc in the angular seconds. (b) The evolution curves of the averaged current, the *solid* curve ($j_z < 0$) and the *dashed* curve ($j_z > 0$)). For the negative current, $|j_z|$ is shown. Asterisks are the corrected j_z values (see the text of the paper). The vertical *dot-dash* curve corresponds to the seismic activity of the flare (05:07:58 UT, according to Buitrago-Casas et al. (2015)). Scale below: UT-time in hours and minutes.

Also note that the modulus of averaged values of currents j_z of opposite signs do not coincide, on the contrary, as it turned out in the calculations for the event associated with the M5.7 flare on May 10, 2012 (see Fig. 6(c) in Livshits et al. 2016). In our case, the $-j_z$ component predominates in the calculation region (the *black solid curve* in Fig. 3(b)). The explanation for this discrepancy is the limited size of the region taken for calculations, that is, not all the regions of the current amplification involved in the development of the flare process have appeared inside the area S. This happened because in this study we wanted to maximally approximate the area boundaries to the flare core in the active center of the AR under investigation. However, this did not affect the overall current behavior: the anti-phase, the increase of the values of both current components in the time interval 05:00-05:12 UT and the subsequent tendency to recover to values before the flare peak.

In choosing the area for our vertical current calculation, we were guided by our statements made earlier (Livshits et al. 2016; Grigor'eva, Livshits 2017). This determined the following criteria: on the one hand, the region on the photosphere (SDO/HMI), within which the flare core and the small J-shaped feature are localized, visible in the EUV range corresponding to the chromospheric emission and emission of the transition layer (SDO/AIA). This feature is indicated in Kushwaha et al. (2014). And on the other hand, we took into account the research area limited the black rectangle in (Fig. 1(a), Kushwaha et al. 2014), supplementing their analysis of the event at the photospheric level. Although our verification of calculations by the area reduced by an order of magnitude did not bring the increase in the $< j_z >$ values of both signs at the time of the flare HXR peak.

In fact, the choice of an area for averaging vertical currents at even the photosphere level is not always unambiguous. Ideally, we select a part on the vertical current density distribution map with the largest values of both signs localized near the NL in the AR. This region corresponds exactly to the flare generation region (see, for example, in the EUV range) and the primary energy release, as was the case in the M5.7 flare event on May 10, 2012 (Livshits et al. 2016). Thus, we have information obtained at the photospheric level on the magnetic field enhancement without knowledge of its spatial distribution.

Another way of selecting an area for integration is proposed in the work in developed AR (Liu et al. 2017). The authors employ a combination of NLFFF extrapolations (Wiegelmann 2004) and photospheric maps of the squashing factor "Q" (Titov 2007; Titov et al. 2011), arguing that by doing this they exclude the magnetic flux areas not used in eruptive activity and that in this way they exclude regions of the magnetic flux that are not used in eruptive activity. The procedure proposed by the authors in their work, in our opinion, seems much more complicated: in addition to calculating the j_z itself, it is necessary to know the magnetic field spatial distribution and calculate the Q-factor.

The significant difference between the M4.0 flare from the unusual flare M5.7 event, which affected the choice of area for the integration of photospheric currents, was the absence of a sigmoid magnetic field structure in the AR. We made the NLFFF extrapolation of the photospheric magnetic field to the coronal heights of 40 Mm before the M4.0 flare, but it was not possible to identify the corresponding magnetic configuration. Also, it was not possible to detect lines tracing the dark J-shaped feature in the AR center visible in EUV lines (SDO/AIA). That is, there was no clear

indication of the characteristic linear dimension of the region associated with the primary energy release, namely, the longitudinal size of the sigmoid. The appearance of a new magnetic transient of opposite polarity was registered for ~ 1 minute before the beginning of the M4.0 flare in the AR center (Kushwaha et al. 2014), which agrees with the time of reversal of the polarity sign at the center of the sunspot during the M5.7 flare May 10, 2012 year (Livshits et al. 2016; and Grigor'eva, Livshits 2017). Such the feature is characteristic of the site in the photosphere, associated with subsequent flare energy release.

4 Discussion and conclusions

We note at once that in this research of the flare phenomenon we wanted to draw attention to the advantage of using a relatively simple characteristic associated with a change in the magnetic field without knowledge of its spatial distribution. This characteristic can be the calculated values of the photospheric electric current, even with noisy SDO/HMI data in the AR. For the phenomenological estimation, we used maps of the density distribution of the value j_z – the values of the currents of both signs within the AR calculated in the projection on the normal at the point of computation by full vector magnetograms (SDO/HMI). To quantify this value, we proposed the dynamics of the averaged values of the current over the area within the AR. In other words, we considered the time evolution of the averaged values of $< j_z >$ of both signs in the course of the flare for an isolated region of the photospheric surface, over which the current density integral was calculated.

As we noted in Section 3, this photospheric area should ideally correspond to the linear dimensions of the region of primary flare energy release that is, to contain the region corresponding to the region of the flare generation. This size can be obtained, for example, from the shape of the magnetic configuration in the form of a sigmoid, which took place in the M5.7 event on May 10, 2012, when it was clearly visible in the picture plane (Livshits et al. 2016). Another way to determine the site in the absence of a sigmoid-like magnetic field configuration is to limit the photospheric area S to a rectangular region containing the largest values of both signs j_z localized near the NL within the AR. This was used in the case of the M4.0 flare, when only the J-shaped structure in the EUV lines (SDO/AIA) was observed, which is probably the filament in the AR NOAA 11302 (Kushwaha et al. 2014). These methods of determining the region of primary energy release are easier to perform than the limitation of the area by localization of large values of the squashing factor Q within the AR (Titov 2007; 2011) used in Liu et al. (2017). In other words, the photospheric values of $< j_z >$ do not depend on the extrapolation of the magnetic field. Since both methods of choosing the photospheric S, proposed by us, are consistent with each other, this allowed us to find interesting facts.

We have shown that during the M4.0 flare on September 26, 2011, a number of features are revealed in the evolution of vertical currents in the AR at the photosphere level.

1. The concentration of areas in the AR with large j_z values near the NL increases by the time moment close to the HXR emission peak. The part inside the AR

with maximal j_z values located close to each other forms the core of the primary energy release.
2. Evolution of the averaged values of the opposite signs $< j_z >$, calculated in the photospheric S, associated with the energy release region, shows the in-phase behavior at the time close to the flare emission peak. Prior to the beginning of the event and after it, the course of the $< j_z >$ of both signs turns out to be in anti-phase.
3. There is a some general trend of $< j_z >$ values of both signs, apparently associated with an increase in the overall activity of the AR.

Thus, points 1–3 confirm the results of the investigation of the flare M5.7 event on May 10, 2012 in Livshits et al. (2016); Grigor'eva, Livshits (2017) even in the absence of sigmoid magnetic field configuration in the AR and less pronounced amplitude of changes in the photospheric values $< j_z >$.

In addition, our assumption was confirmed that, at least in flare events of M GOES class, the position of the SQ source on the photosphere is within the region with the largest j_z values associated with the energy release region. The amplification and concentration of the j_z values of opposite signs near the NL magnetic field in the AR begins before the flare event. Early detection of the source of primary energy release in the AR from photosphere maps of the distribution of the vertical current density and the evolution of averaged j_z values can be useful in predicting flare activity, especially when detecting the sigmoid structure of the magnetic field.

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