SOME FEATURES OF THE EVOLUTION OF THE MAGNETIC COMPLEX OF ACTIVITY INCLUDING AO NOAA 11944 AND NOAA 11946, DURING ITS PASSAGE ACROSS THE SOLAR DISK

© 2025 Iu.S. Zagainova[a], V.N. Obridko[a], V.G. Fainshtein[b], G.V. Rudenko[b]

[a]*Pushkov Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation RAS, Troitsk, Moscow, Russian Federation*

[b]*Institute of Solar–Terrestrial Physics, SB of RAS, Irkutsk, Russian Federation*

**e-mail: yuliazag@izmiran.ru, yuliazagainova@mail.ru*

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Abstract. The evolution of properties of the magnetic activity complex (MAC) during its passage across the solar disk on (03-12).01.2014 was analyzed. This MAC comprises two active regions (ARs) magnetically coupled by the equator, that are located in different solar hemispheres: AR NOAA 11944 in the Southern Hemisphere and NOAA 11946 in the Northern Hemisphere. Time dependences of total unsigned magnetic fluxes of all spots, including pores, and specifically for each polarity were plotted for each AR. The variation of total unsigned magnetic flux F(t) for all MAC sunspots was examined with respect to the variation of total area of the corresponding sunspots S(t). In all cases, the magnetic flux increases non-monotonically, reaches its maximum, and decreases afterwards. We found differences in the pattern of changes in F(t) and S(t) during the period 10.01-12.01, which are related to the characteristics of radiation bursts in the hard X-ray range and solar flares in soft X-ray range. No halo-type coronal mass ejections were detected in the MAC during the entire observation period, and relatively few limb CMEs were detected when the MAC was close to limbs.

Keywords: *Sun, active region, activity complex, sunspot, magnetic flux*

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1. INTRODUCTION

When analyzing solar phenomena, such a concept as "activity complex" (AC) has been used for many years. Different groups of researchers at different times put different meanings into this concept. In the monograph [Obridko, 1985], the works in which the term "activity complex" was used are listed, and where it is proposed to understand by the CA a set of several active regions (ARs) existing on the Sun for many revolutions and united by a common magnetic field. It is noted that the special importance of SAs consists in the fact that they represent the main links in the chain connecting local magnetic fields with the global organization of solar activity (SA) and the general magnetic field of the Sun

Yazev [2015] gave the following definition of a spacecraft: an activity complex is a special area on the Sun where, over a long period of time (several solar revolutions), a complex large-scale magnetic structure develops, in the composition of which active regions can appear both sequentially and simultaneously. The total number of ARs included in the total magnetic system of spacecraft can reach several dozens. The appearance of new ARs occurs in the form of consecutive discrete injections of new portions of magnetic flux into the magnetic structure of the spacecraft. The core of the spacecraft is formed by the spacecraft nuclei - areas of constant spot formation in the center of the spacecraft. A spacecraft core can contain several groups of spots. In his work, Yazev [2015] noted that a special interest in spacecraft is attracted by the fact that they are the main sources of geoeffective perturbations on the Earth. In a series of recent papers by this author and colleagues, the evolution of SCs in several CA cycles was investigated and their relation to coronal holes was studied [Yazev et al., 2022a; 2022b; 2022c]. For example, for the 24th CA cycle [Yazev et al., 2022b], a catalog of the SCs registered in this cycle was compiled and the main characteristics of the SC evolution within the cycle were established. It turned out that new SCs arise mainly in the vicinity of already existing SCs.

In [Obridko & Schelting, 2013], we review the evolution of the concept of "activity complex" over many years and propose a new concept of global activity complexes (GACs) on the Sun, which consists in combining objects of global and local fields within a single concept. Thus, a GCA includes not only ARs but also coronal holes.

A number of researchers have used the term "complex of active regions (CAO)" in their works (see, for example, [Ishkov, 2013; Obridko and Schelting, 2013]). Below, relying on [Ishkov, 2013] and other publications cited therein, the following definition can be given for the CAO: "A complex of active regions is a set of two or more groups of sunspots connected by a common magnetic field. The evolution of such complexes reveals the connection and interaction of individual components".

The main characteristics of the CAO: *a* - groups of spots can be located sequentially one after another at approximately close latitudes, extending along longitude up to 30° (latitudinal CAO), or along the nearest longitudes (up to 20° in latitude) (longitudinal CAO); *b* - usually 2 to 4 AOs coexist in a CAO, usually one of the groups of spots is noticeably larger than the others; *c*− the most significant characteristic that determines the appearance and development of the CAO is its total magnetic field at the level ≥100 Gs; *d*− the most important feature of the CAO is the presence of a relatively long interaction and magnetohydrodynamic connection between spots and groups of spots in the CAO. Active region complexes are considered to be the main source of extreme and large solar proton events.

Later in [Zagainova et al., 2022], the concept of a "magnetic activity complex" (MAC) was introduced, which includes active regions observed on the Sun's surface with groups of spots whose shadows are connected by the calculated magnetic field lines. In fact, MCA is, in several respects, a type of CAO. We considered it possible to introduce a new definition (MCA) for the following reasons. The lifetime of an MCA can be relatively short, while the lifetime of a spacecraft is usually at least 2− 3 solar revolutions. In addition, the magnetic coupling of the two ARs is carried out by calculated magnetic field lines linking the spot shadows of the two ARs, i.e., predominantly strong $B \geq 1000$ Gs magnetic fields are involved. The field lines in the MCA link either the shadows of the head and trailing spots of the two ARs (as in [Zagainova et al., 2022], when the magnetically linked ARs are located in the same solar hemisphere at close latitudes), or the shadows of the head spots, as in this paper, when the magnetic coupling of the two ARs is provided by the field lines across the solar equator. The latter means that the polarity of the magnetic field in the shadow of the headspots of ARs is opposite. Magnetic coupling of the trailing spots of opposite polarity is also possible. Finally, we note that we do not include unstained AOs and AOs with pores in the MCA, since such AOs, although they can be connected for some time by magnetic field lines with the MCA spots, but the magnetic connection between such AOs and MCAs will last much less than the lifetime of the MCA itself. This is explained by the short lifetime of pores, which, on average, is ~8 h. In the event analyzed by us, AO NOAA 11943 turned out to be such an AO. Visually, in the images in the UV wavelength range between MCAs and unstained ARs and ARs with pores, one can observe loop structures for a long time, but often due to projection effects and the small scale of such structures, we cannot unambiguously determine where exactly the bases of the loop structures are located. Moreover, loop structures are observed in GCAs not only between spots, but often their bases are detected near coronal hole boundaries or in quiet regions. For this reason, it is impossible to unambiguously distinguish MCAs from UV loops within a GCA.

In this paper, the evolution of the properties of the MCA during its passage through the Sun's disk (03− 12).01.2014. The MCA consisted of two magnetically bound AOs located in different hemispheres of the Sun: AO NOAA 11944 (Southern Hemisphere) and NOAA 11946 (Northern Hemisphere). It is revealed that in the period (04-10).01.2014, the headspots of these ARs were connected by magnetic field lines passing through the solar equator.

2. DATA AND METHODS OF DATA ANALYSIS

The coronal loop structures linking ARs were identified from the observations of the SOHO and SDO spacecraft. Further, we found magnetic field lines with bases in the shadows of the spots connected by AO loop structures from calculations of the magnetic field above the solar surface using data from the SOLIS instrument (NSO) in the potential approximation using an original program based on the use of *Bd-technology* in the framework of the "potential field - source surface" model [Rudenko, 2001]. [Rudenko, 2001]. Then, we determined the dates for which the AOs within the MCA are bound by the field lines (see Fig. 1). For these dates, the characteristics of solar flares associated with the MCA were determined using GOES and HESSI Flare List data (https://hesperia.gsfc.nasa.gov/hessidata/dbase/hessi_flare_list.txt). The occurrence of coronal mass ejections (CMEs), including halo CMEs, in the MCA was also analyzed using the CME and halo CME catalogs (https://cdaw.gsfc.nasa.gov/CME_list/HALO/) and (https://cdaw.gsfc.nasa.gov/CME_list/). The total shadow area of its sunspots as a function of time was calculated from SDO/AIA data (http://jsoc.stanford.edu/ajax/exportdata.html) during the MCA existence phase. The magnetic field characteristics $\alpha(t)$, $B(t)$ in each pixel of the sunspot shadow of the MCA were determined using vector field measurements by the SDO/HMI instrument (http://jsoc.stanford.edu/ajax/exportdata.html). Here α is the angle between the direction of the magnetic induction vector **B** and the direction of the positive normal to the solar surface **n,** $B = |\mathrm{B}|$. The details of finding α are described in [Zagainova et al., 2022]. Using the calculated values of B, pixel area S_p, and α, the value of the unsigned magnetic flux in the shadow of each analyzed spot was found. The problemπ -uncertainty of the direction of the transverse component of the magnetic field was solved using the method proposed in [Rudenko and Anfinogentov, 2014].

Fig. 1.

The following is the formula for finding the magnetic flux from the spot shadow:

$$F = \int_1^N B_{pi}\, S_{pi} \cos(\alpha(_i)) \quad , (1)$$

where $_{pixel}$ number in the spot shadow $i = 1...N$; B_{pi}– average magnetic induction in pixel number i in the spot shadow; S_{pi}– area of pixel number i; α_i - average angle between the magnetic induction vector and the normal to the Sun's surface in pixel number i.

3. RESULTS

We investigated the variation with time of the following properties of the MCA as it passes through the Sun's disk (see Fig. 2): 1) the magnetic flux from the shadow of spots of each polarity in each AO forming the MCA; 2) the total magnetic flux from the shadow of all MCA spots $F(t)$; 3) the shadow area of all MCA spots S(t); 4) the number and characteristics of solar flares in the soft and hard X-ray bands; and 5) the number and characteristics of halo CMEs and limb CMEs with sources in the MCA. Fig. 1 shows the analyzed MCA for three adjacent time moments.

Fig. 2.

Note that this MCA was not observed in the previous and subsequent solar revolutions. Therefore, conditionally, according to the dependences in Fig. 2, the evolution of the MCA was divided into 3 stages: the stage of origin up to ~06.01.01.2024, the stage of peak development ~(07–08).01.01.2024 and the final stage after ~ 09.01.01.2024. We can see a good correlation between the studied parameters at a large time interval: from ~ 04.01.01.2024 to ~ (9– 10).01.2024. Further the correspondence is difficult to establish: at the stage of almost monotonous fall of $F(t)$, several maxima can be seen on the dependence $S(t)$. Comparing the two dependences after January 9 and taking into account formula (1) for the magnetic flux, we can assume that at the final stage: and/or there is a reduction/fractionation of large spots (more than ~10 TIR) in the complex; and/or there is a new sampling of a large number of small spots (less than ~10 TIR), which weakly affects the magnitude of the total unsigned magnetic flux due to the weak field in such spots, but can significantly affect the total area of the spots; and/or there is a change in the configuration of the magnetic field in the MCA, when the field lines of force are more pressed against the solar surface, which is characteristic of weak fields. The pressing of the field lines against the Sun's surface may reflect an increase in the inclination angles of the magnetic induction vector, which, in turn, may lead to a change in the magnitude of the magnetic induction, according to the findings of [Zagainova et al., 2022]. Both of these parameters of the magnetic field in the spot shadow affect, in accordance with formula (1), the magnetic flux

Fig. 3.

Fig. 3 shows the variation with time of the unsigned magnetic flux in the spot shadow of each polarity for each AO in the MCA. From Fig. 3 shows that the magnetic flux in each group of spots increases non-monotonically, reaches a maximum value, and then decreases. The behavior of the magnetic flux in the trailing spots of AO 11944 draws attention. This flux reaches its maximum value much earlier than in other cases and then decreases much more steeply, reaching a quasi-plato. Note also that in the shadow of the trailing spots in the northern group during the period from~ (8– 10).01 the magnetic flux from the shadow of the trailing spots is higher than the magnetic flux in the leading spots of this AO. It seems to be predominantly in the trailing parts of the MCA ARs that significant spot transformations occur, determining the course of $F(t)$ and $S(t)$, especially at the final stage of the MCA existence

Thus, we have presented a morphological description of the main features of the behavior with time of different types of magnetic fluxes from the sunspot shadow. The growth of the magnetic flux can be caused by an increase, on average, of the spot shadow area (see Fig. 2) and, simultaneously, of the maximum and/or average magnetic field in the spot shadow (for the relation between the magnetic field in the spot shadow and the shadow area, see [Zagainova et al., 2022]), as well as by an increase, on average, of the inclination angles of the magnetic induction vectors in the spot shadow (see formula (1) for the calculation of the magnetic flux). At the same time, the different character of the change in the magnetic flux from the shadow of all MCA spots and the area of these spots during the period (9– 12).01.2014 seems difficult to explain. One cannot also exclude an increase in the number of spots with time at the initial stage of the MCA evolution. The reasons really determining the character of change with time of different types of magnetic fluxes requires a separate study.

During the observation period from January 3 to January 12, 2014, the MCA registered many solar flares with different X-ray scores (B, C, M), but predominantly of the C class. No powerful flares with X score were registered. In the hard X-ray range, no less than 206 flares of different power were registered in the MCA, and their frequency of occurrence depends on the stage of development of the MCA. Thus, we note an increase in the density of vertical lines in Fig. 3, i.e., the number of flashes, starting from 09.01.2024. This can be interpreted in such a way that frequent magnetic reconnections occur in the MCA at the final stage, and they are small-scale. And on January 8 there is a period when there were no flares at all. Moreover, this period falls on the maximum values of the total magnetic flux from the shadow of all spots, i.e., on the peak of the MCA development. The following solar flares of class M in the soft X-ray range were registered in the MCA during its motion across the Sun's disk: January 3, 2014.: AO 11944 [M1.0 (12:41), M1.0 (12:41), M1.1 (21:09)]; January 4, 2014: AO 11944 [M1.3 (10:16), M4.0 (19:05)]; January 7, 2014: AO 11946 [M1.0 (04:49), M1.0 (03:49)]. January 7, 2014: between AO 11944 and 11943 (coordinates S15W11) a flare of X1.2 (18:04) was registered.

Although both hard and soft X-ray flares can occur in different AOs of the MCA, we refer these flares to the MCA as a whole. In this case, an interesting question that also requires a special study becomes interesting: how, for example, flares in the soft X-ray range that occurred in one AO of the MCA can affect the properties of the magnetic field in the shadow spots of another AO of the same MCA? The authors have shown in a series of publications that sufficiently powerful flares of X magnitude, which are associated with fast CMEs, lead to strong changes in the maximum value of the magnetic induction and the minimum angle α in the shadow of many AO spots (see, e.g., [Zagainova and Fainshtein, 2021; 2022]). We can expect that solar flares of any score will also affect the properties of the magnetic field in the shadow of MCA spots, and thus the total magnetic flux, since MCA implies the presence of magnetically connected spots.

In the graphs of Figs. 2 and 3, the proximity in time of the increase in the total area of spots and, simultaneously, the increase in the number of flashes in the hard X-ray range in the interval (9–12).01.2014 draws attention. The closeness of the two phenomena can be explained, for example, as follows. If the increase in the total area of sunspots in the AO MCA is associated with the appearance of new spots of different polarity, this may lead to a change in the magnetic configuration of the MCA accompanied by an increase in the number of magnetic reconnections leading to solar flares. However, the question remains open as to the nature of the changes in the total magnetic flux of the MCA in this case.

The halo-type CMEs were not registered in the MCA. However, two halo CMEs with M and X class flares were observed near the neutral line between the MCA and AO 11943 without spots, i.e., not in the MCA, but in the GCA! When the MCA was near the solar limb, relatively few limb CMEs were observed in the activity complex

4. CONCLUSION

As the MCA passes across the solar disk, the magnetic properties and shadow sizes of the spots forming this activity complex change significantly. The unsigned magnetic flux from all spots, including pores, of the MCA, as well as separately for the leading and trailing spots for each AO forming the MCA, increases, reaches a maximum value, and then decreases. The total area of the MCA spots $S(t)$ increases until 09/01/2014 in an approximately similar manner to the total magnetic flux $F(t)$ from MCA spots, and then the pattern of change in $S(t)$ is significantly different from the change in $F(t)$. As the MCA moves across the Sun's disk, it produces solar flares of various scores in the soft X-ray range, with the exception of powerful flares of score X. A large number of bursts of radiation in the hard X-ray range have been recorded. At the same time, no halo-type coronal mass ejections were registered in the MCA and relatively few limb CMEs were registered.

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CONFLICT OF INTERESTS

The authors of this paper declare that they have no conflicts of interest.

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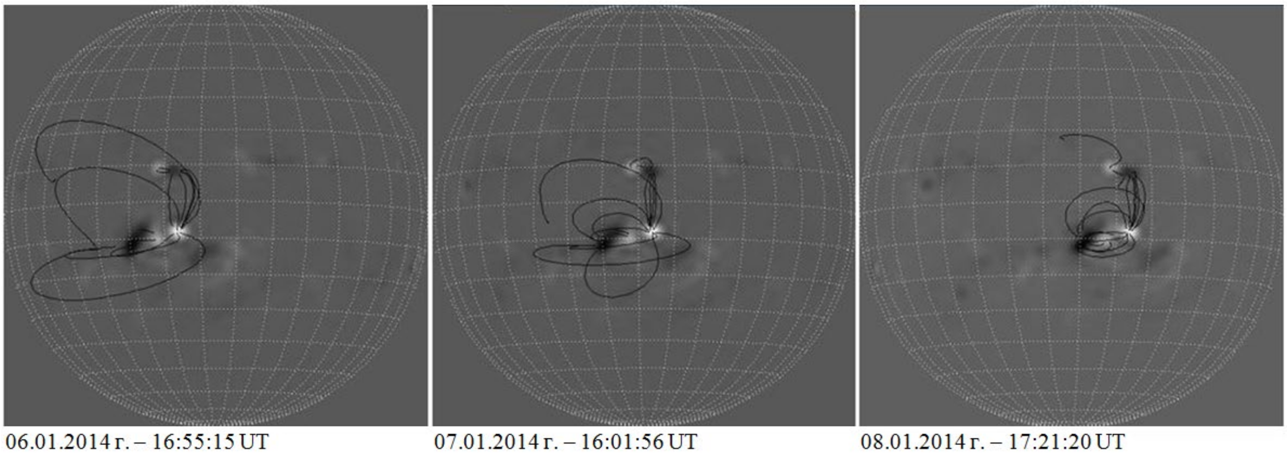
FIGURE CAPTIONS

Fig. 1. Images of the Sun's disk from the MCA when it is near the central meridian for three moments of time. Below the equator in the Southern Hemisphere of the Sun is NOAA AO 11944, above is AO 11946. The white areas correspond to the positive polarity of the radial magnetic field, while the dark areas correspond to the negative polarity of the radial magnetic field. The curved black lines are the calculated magnetic field force lines.

Fig. 2. Variation with time of the total unsigned magnetic flux $F(t)$ from the shadow of all sunspots (black shaded squares) and the area $S(t)$ of the shadow of all sunspots (circles) in the period 03 - 11.01.2014. The areas of the plots where the error in determining the values of the studied sunspot shadow parameters is large due to projection effects are shaded.

Fig. 3. Variation with time of the unsigned magnetic flux in the shadow of spots of each polarity for each AO in the MCA. The upper plot is plotted for AO 11946, the lower plot is plotted for AO 11944. Vertical lines mark the moments of solar flares in the hard X-ray range. Circles and black shaded black squares refer to the head spots, circles and unshaded squares refer to the trailing spots.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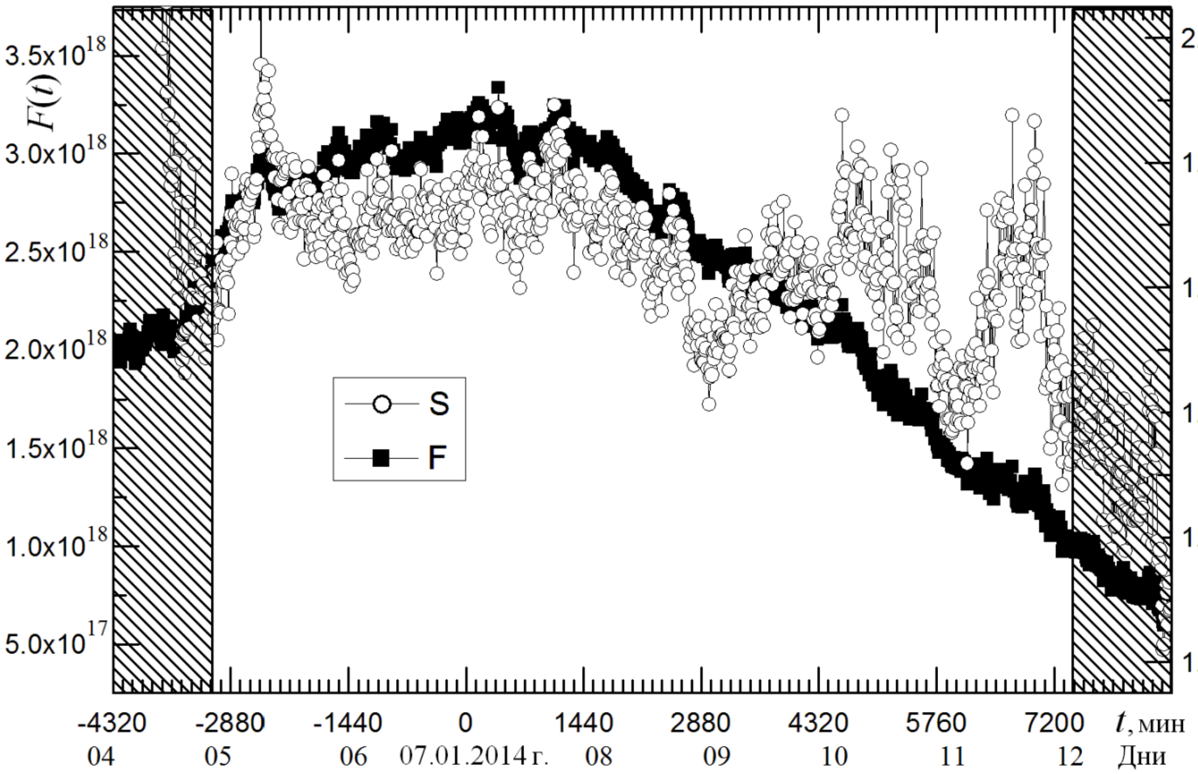
08.01.2014 г. – 17:21:20 UT

Fig. 1.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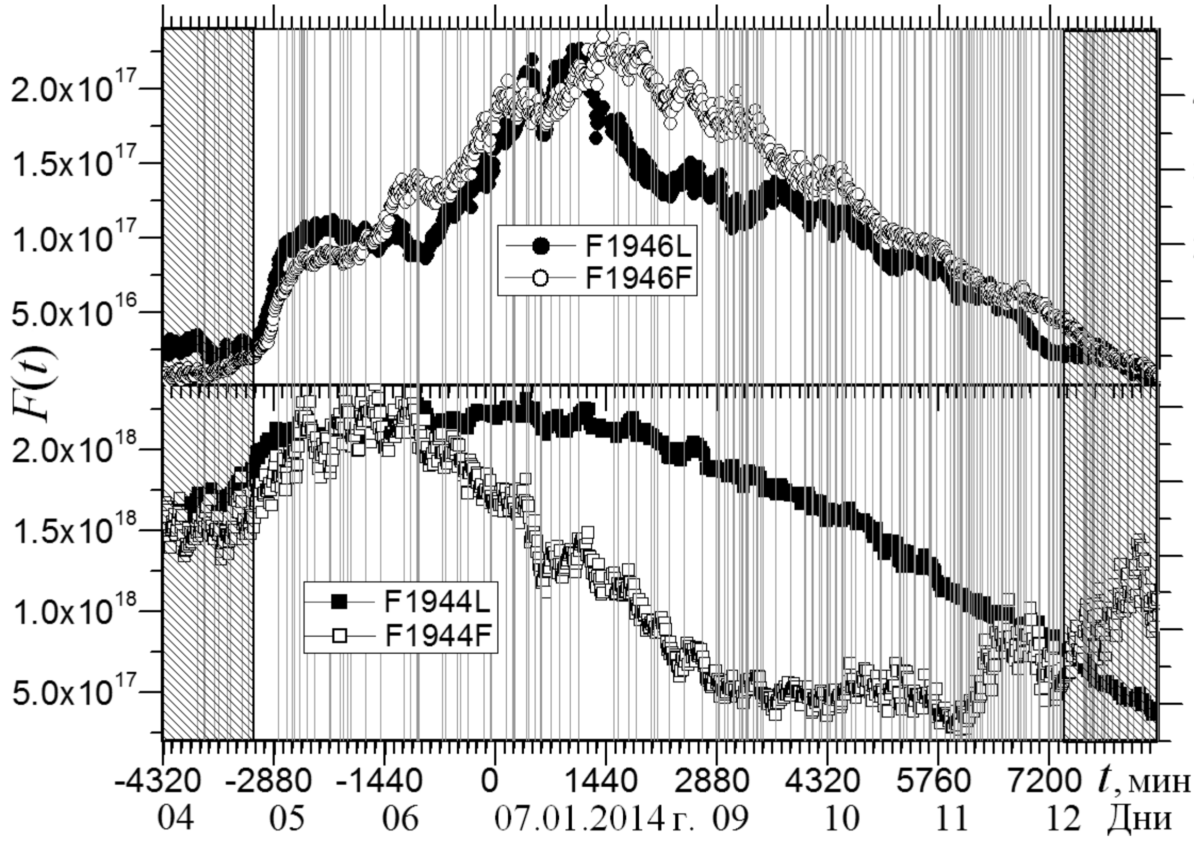

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Fig. 3.