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On Consistent Dynamics of the Magnetic Field and Relativistic Electron Fluxes in the Geostationary Orbit Region

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Abstract—The paper presents the results of studying the dynamics of the magnetic field and electron fluxes of the Earth's outer radiation belt with an energy of >2 MeV according to the *GOES-15* geostationary satellite during a fairly long period (October 16, 2016 to February 16, 2017) of moderate and weak magnetospheric activity caused by the arrival of a sequence of high-speed solar wind streams. The main variations in the electron flux in the geostationary orbit are caused by the movement, deceleration and acceleration of particles in the outer radiation belt of the Earth under the influence of geomagnetic activity. The results of a comparative analysis of variations in electron fluxes and components of the magnetospheric field testify to the predominant influence of the magnitude and structure of the magnetospheric field on the dynamics of relativistic electron fluxes in the outer radiation belt. Changes in the components of the magnetospheric magnetic field and in electron fluxes are results of a single process that occurs together with changes in the magnetosphere as a whole.

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INTRODUCTION

The Earth's radiation belts are a structural formation in the magnetosphere that exists due to the presence of a sufficiently strong internal, quasi-dipole magnetic field and the closure of its field lines, due to which charged energetic particles are trapped. Along with intraterrestrial sources of the magnetic field, the magnetosphere contains large-scale current systems (magnetopause currents, tail currents, ring current), formed and changing under the influence of the interplanetary medium: the solar wind (SW) and interplanetary magnetic field (IMF) [1]. The structure of the magnetosphere is determined by the superposition of the internal field and the field of external sources. Thus, the magnetosphere is a dynamic structure that changes over time. The most variable is the outer magnetosphere, in which the magnetic field of magnetospheric currents is comparable to or exceeds the internal magnetic field of the Earth [2]. At the same time, the magnetosphere is a self-consistent system, the response of which to external influence depends on its current state and is not uniquely related to the instantaneous values of the solar wind parameters: the same conditions in the solar wind can affect the magnetosphere differently, depending on prehistory, that is, on its internal state.

The movement of charged particles in the magnetosphere is controlled by the magnetic field. The fluxes of radiation belt particles are most stable in the inner magnetosphere, where the intraterrestrial magnetic field dominates, experiencing slow, secular variations. With distance from the Earth, the fluxes of trapped particles begin to experience variations associated with changes in magnetospheric current systems.

The strong variability of the outer electron radiation belt has already been shown by the results of research on an artificial Earth satellite (AES) of the Electron series (see, for example, [3]). The results of a statistical study of 276 moderate magnetic storms ($|Dst|_{\max} > 50$ nT) according to geostationary satellite data showed that, during the recovery phase, in ~53% of storms the electron flux increases, while it decreases in 19% and remains unchanged in 28% [4]. The main processes leading to the acceleration of electrons occur in the inner magnetosphere. In geostationary orbit, only echoes of these processes are visible against the background of large-scale variations in particle fluxes associated with disturbances of the magnetospheric field. Similar statistical studies on 78 storms based on data obtained in the core of the outer radiation belt by the *Van Allen Probes* spacecraft yielded results of 45, 32, and 23%, respectively [5].

To explain the decrease in the intensity of the flux of energetic electrons in the Earth's outer radiation belt during the main phase of a magnetic storm, a mechanism associated with the adiabatic expansion of the drift shells of the inner magnetosphere while maintaining the third adiabatic invariant was proposed in [6]. The preservation of the first invariant leads to a decrease in the energy of particles falling into a region with a weakened magnetic field. Along with the process of reformation of the outer radiation belt under the influence of magnetic field variations, of course, mechanisms leading to particle losses also operate. Particle precipitation during interaction with waves due to pitch-angle diffusion and electron loss during magnetopause displacement during the main phase of a magnetic storm are the main mechanisms of particle loss [7]. Resonant interaction of particles with waves of different natures (electromagnetic ion cyclotron (EMIC) waves, chorus waves, plasmaspheric hiss), as well as combinations of them, can lead to their precipitation into the atmosphere (see, for example, [8, 9]). Work [10] presents the results of estimating the fluxes of electrons precipitating from the outer radiation belt at L = 3.5–6 (June 19, 2013) in the energy range of 0.58–1.63 MeV: 6.8% of the total flux. From the very beginning of the development of the theory of radiation belts, which was based on the results of experimental studies, three most fundamental processes were identified that control the bulk of particles: injection into the region of trapped radiation, radial diffusion, accompanied by adiabatic acceleration, and particle loss [11]. In the theory of B.A. Tverskoy [7], the transfer of particles across drift shells can occur during magnetic disturbances such as sudden pulses, which was first considered by E. Parker [12]. The theory of radial diffusion due to the emergence of inductive electric fields during sudden magnetic field pulses substantiates the existence of diffusion waves of relativistic electron fluxes [7]. According to *GLONASS* spacecraft data, it is shown that the experimentally obtained speed of diffusion waves corresponds to the theory of diffusion under the influence of sudden impulses [13]. The mechanism of "shock" injection of particles under the influence of a sudden bipolar pulse of the magnetic field (SSC) made it possible to explain the data of the *CRRES* spacecraft on March 24, 1991 on the formation within ~1 min of a radiation belt of electrons with an energy of ~15 MeV with a maximum at L = 2.2–2.6 [14].

Experimental confirmation of the dependence of the dynamics of the flux of relativistic electrons in the Earth's outer radiation belt on variations in the magnetic field during storms was first presented in [15]. Using data from low-altitude polar satellites, an empirical dependence of the position of the maximum of the belt of relativistic electrons injected during magnetic storms (L_{max}) on the maximum amplitude of the storm was obtained: $|Dst|_{max} = 2.75 \times 10^4\ L_{max}^{-4}$. The results of a study of magnetic storms with an increase in electron fluxes during the recovery phase based on data obtained in the core of the outer radiation belt on the *Van Allen Probes* spacecraft showed agreement with this empirical dependence [5]. The theoretical justification for the empirical dependence was presented in [16].

Several mechanisms have been proposed to replenish the radiation belt with new accelerated particles. "Storm" injection is a process consisting of two stages and accelerating populations of plasma layer particles under the influence, first, of substorm activity (up to a few hundred kiloelectronvolts) and, then, due to interaction with waves up to subrelativistic and relativistic energies (see, for example, review [17] and links therein). The main mechanisms for accelerating electrons to relativistic energies are considered resonant interaction between electrons and very-low-frequency (VLF) waves (see, for example, [18, 20]) and radial diffusion of electrons under the influence of ultra-low-frequency (ULF) waves (see, for example, [20]). Ideas of local acceleration of electrons by waves of the "chorus" type are being developed (see, for example, [20]).

The main mechanisms of particle loss during the main phase of a geomagnetic storm are considered to be particle precipitation during interaction with waves due to pitch-angle diffusion and electron loss during magnetopause displacement [7]. As a result of resonant interaction with waves of different natures, a change in the pitch-angle distribution of trapped particles occurs, leading to their precipitation into the atmosphere from the loss cone [8, 9]. An increase in solar wind pressure can lead to compression of the magnetosphere, and the outer part of the population of trapped electrons can end up in open L-shells. The result of this process is the exit of energetic electrons beyond the magnetosphere [21].

The purpose of this work is, based on the results of the analysis of experimental data from spacecraft, to provide an explanation for variations in the fluxes of relativistic electrons in the region of geostationary orbit (GSO), which can be initiated by the dynamic impact of the magnetospheric magnetic field changing during a storm.

SOURCES OF EXPERIMENTAL DATA

The work is based on the results of the analysis of experimental data on the fluxes of relativistic electrons from the Earth's outer radiation belt with energy (E) >2 MeV and measurements of the magnetic field of the SEM (Space Environment Monitor) instrument on the *GOES-15* satellite (http://www.ngdc.noaa.gov/stp/satellite/goes). The *GOES-15* satellite is in geostationary orbit at 120° west longitude.

To study the state of the interplanetary medium, experimental data from the *ACE* spacecraft were used (https://izw1.caltech.edu/ACE/ASC/).

The Earth's magnetospheric activity was characterized by magnetic indices: *Dst* variation and *AE* and *AL* indices (http://wdc.kugi.kyoto-u.ac.jp/wdc/Sec3.html).

The figures for the article were created on the website of the Space Monitoring Data Center (SMDC) of

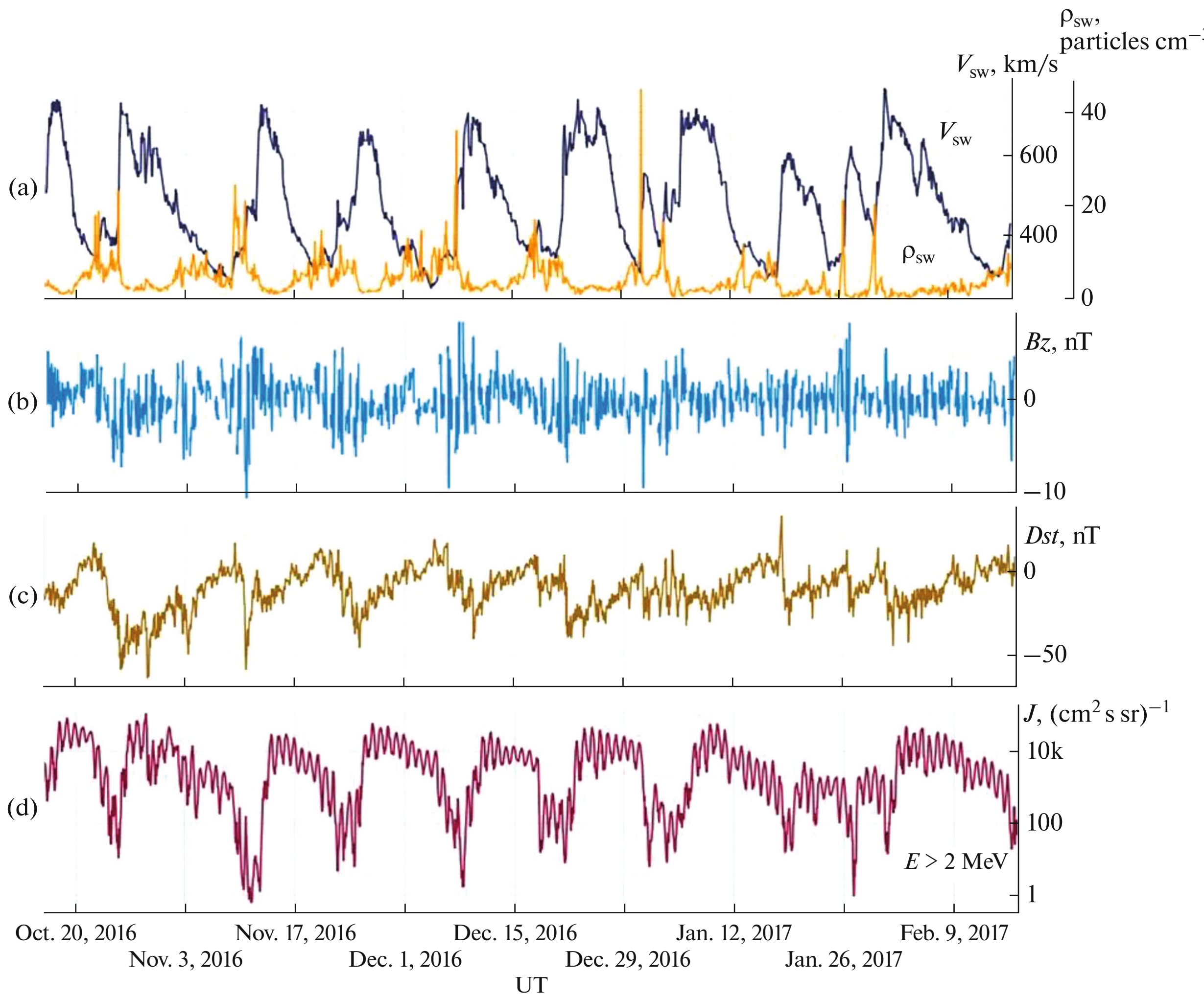

Fig. 1. Time profiles of velocity (V_{sw}) and density (ρ_{sw}) of (a) the solar wind, (b) the *Bz* component of the interplanetary magnetic field according to *ACE* spacecraft data, (c) *Dst* variation, and (d) electron flux with $E > 2$ MeV according to data from the *GOES-15* satellite (October 16, 2016–February 16, 2017).

the Skobeltsyn Institute of Nuclear Physics of Moscow State University (SINP MSU), which provides access to operational data from space experiments and models for operational forecasting of space weather phenomena. The SMDC website of Space Weather (https://swx.sinp.msu.ru/) collects the data necessary for assessing and analyzing the radiation situation not only in near-Earth space, but also in the interplanetary environment. Improved graphical applications enable comparative analysis of both experimental data and simulation results.

EXPERIMENTAL RESULTS

The dynamics of the Earth's radiation belts depend on the state of the magnetospheric magnetic field, which is influenced by the interplanetary medium, which varies depending on solar activity and the phase of the solar cycle. During a decline in solar activity, the observed variations in the fluxes of relativistic electrons in the outer radiation belt are, as a rule, associated with magnetic disturbances developing under the influence of high-speed solar wind streams [13, 22].

The time interval from October 16, 2016, to February 16, 2017 falls on the late phase of the decline of the 24th solar activity cycle (2019 is the last year of the cycle) and is interesting for studying the dynamics of relativistic electrons in the Earth's outer radiation belt because during this period, the magnetosphere was affected by several high-speed solar wind streams, the response to which was magnetic disturbances and strong variations in relativistic electron fluxes, in particular in geostationary orbit. Time profiles of some key parameters that play major roles in the impact of the interplanetary medium on the Earth's magnetosphere are presented in Fig. 1: solar wind speed and density (Fig. 1a) and the IMF *Bz* component (Fig. 1b). During the period under study, the evolution of several coronal holes, coronal mass ejections, and the development of sporadic phenomena in the interplanetary medium, which caused high-speed solar wind flows, were observed [23]. The impact of the interplanetary medium in the form of shock waves, SW pressure pulses, mainly with the southern orientation of the IMF, causes a strong reaction in the magnetosphere. During the period under study, the response of the magnetosphere to strong variations in the interplanetary medium was a sequence of geomagnetic disturbances of varying strength. At the beginning of the period, three moderate magnetic storms with $|Dst|_{\max} \geq$ 50 nT were observed, subsequent disturbances were weaker (Fig. 1c). Figure 1e shows the time profile of electron fluxes in the Earth's outer radiation belt with $E > 2$ MeV according to data from the *GOES-15* geostationary satellite. In all subsequent figures, this particular energy channel will be presented for measuring the electron flux according to the *GOES-15* satellite data. It can be seen that variations in electron fluxes with $E > 2$ MeV are pronounced, correlating with the arrival of high-speed flows, and the maximum electron flux, in almost all cases, exceeded 10^4 $(\text{cm}^2\ \text{s sr})^{-1}$. The cause-and-effect relationships of phenomena in the interplanetary medium and magnetospheric processes are clearly manifested in the obvious correlations of parameters presented in Fig. 1. Most often, the arrival of high-speed solar wind streams is preceded by an increase in the solar wind density (Fig. 1a) and, consequently, pressure pulses (not shown in Fig. 1), as well as a reorientation of the IMF *Bz* component to the south (Fig. 1b). The result of the impact of each high-speed stream is a depression of the magnetospheric field—a decrease in *Dst* (Fig. 1c) and, as a consequence, first a decrease and then an increase in the fluxes of relativistic electrons, in particular, in geostationary orbit (Fig. 1d). In this case, there is no direct proportionality between the value of $|Dst|_{\max}$ and the minimum and maximum values of electron fluxes in geostationary orbit. This effect is present both in the studied time interval (Fig. 1) and according to the results of a study of 22 magnetic storms in [24]. Comparing the time characteristics of the observed parameters, one can see that periods with increased solar wind plasma density and, accordingly, pressure, as well as with large negative values of the IMF *Bz* component, are significantly shorter than periods when the solar wind speed is close to maximum values. Each new structure of the interplanetary medium affects the magnetosphere, transferring energy to it and being a trigger for the development of magnetic disturbance. The response of the magnetosphere can be traced by the time course of the *Dst* variation, which has its own special profile that differs from the time profiles of the parameters of the interplanetary medium (Fig. 1).

Let us try to compare some time characteristics inherent in the parameters under study. One panel of Fig. 2a shows time profiles of solar wind speed and electron fluxes in geostationary orbit. The time correction associated with the propagation of the solar wind stream from the *ACE* spacecraft orbit at a distance of 1.5 million km from the Earth to the Earth orbit (approximately 1 hour) was taken into account. Calculation of the parameters of the solar wind in Earth orbit is carried out at the OSMDC of SINP MSU (https://swx.sinp.msu.ru/apps/solar_wind.php?gcm=1) in real time. Comparing the time profiles of the solar wind speed and electron fluxes in the GSO (Fig. 2a), one can see that, although each high-speed stream corresponds first to a decline and then an increase in the electron flux, the profiles differ significantly: the time of decline, minimum and increase of the electron flux, and time of growth of the SW in each case differs. Sinus-shaped, fast (compared to the studied variations of electron fluxes) variations in the values of electron fluxes are daily variations characteristic of experimental data obtained in geostationary orbit. Diurnal variations in the geostationary orbit are due to the difference in the magnitude of the magnetic field on the day and night sides of the orbit: more during the day, less at night.

The duration of periods of increasing electron fluxes exceeds the corresponding duration of periods of recording high-speed SW streams. The steepness of the declines of the compared values is completely different. We can conclude that an increase in the solar wind speed is only one of the triggers for the development of processes in the magnetosphere leading to an increase in the electron flux, but the shape of the time profile of the electron flux and, consequently, the dynamics of the electron flux can be determined by others, including intramagnetospheric parameters. Among them, we can highlight both those associated with the state of magnetospheric current systems, and factors associated with the acceleration and loss of particles under the influence of wave activity. Our research shows that the first set of factors can play a dominant role against the background of wave activity.

One of these parameters is *Dst* variation—a geomagnetic index formed from measurements of the magnetic field on the Earth's surface and used to characterize the magnetic perturbation in the magnetosphere. At the same time, the shapes of the electron flux profiles and *Dst* variations differ very significantly (Fig. 2b). It should be noted that a steep rise in the electron flux is observed near the minimum of *Dst* variation; for a long time (several days), the value of the electron flux decreases slightly, after which a sharp decline occurs, coinciding with the beginning of a new geomagnetic disturbance, a new depression of the magnetic field (Fig. 2b). Thus, during the period under consideration, quasi-periodic variations in the solar wind speed, the value of magnetic index *Dst*, and the flux of relativistic electrons in the GEO are observed. Despite the obvious interrelation of these processes, one can see significant differences in the behavior of the time profiles of the parameters under study.

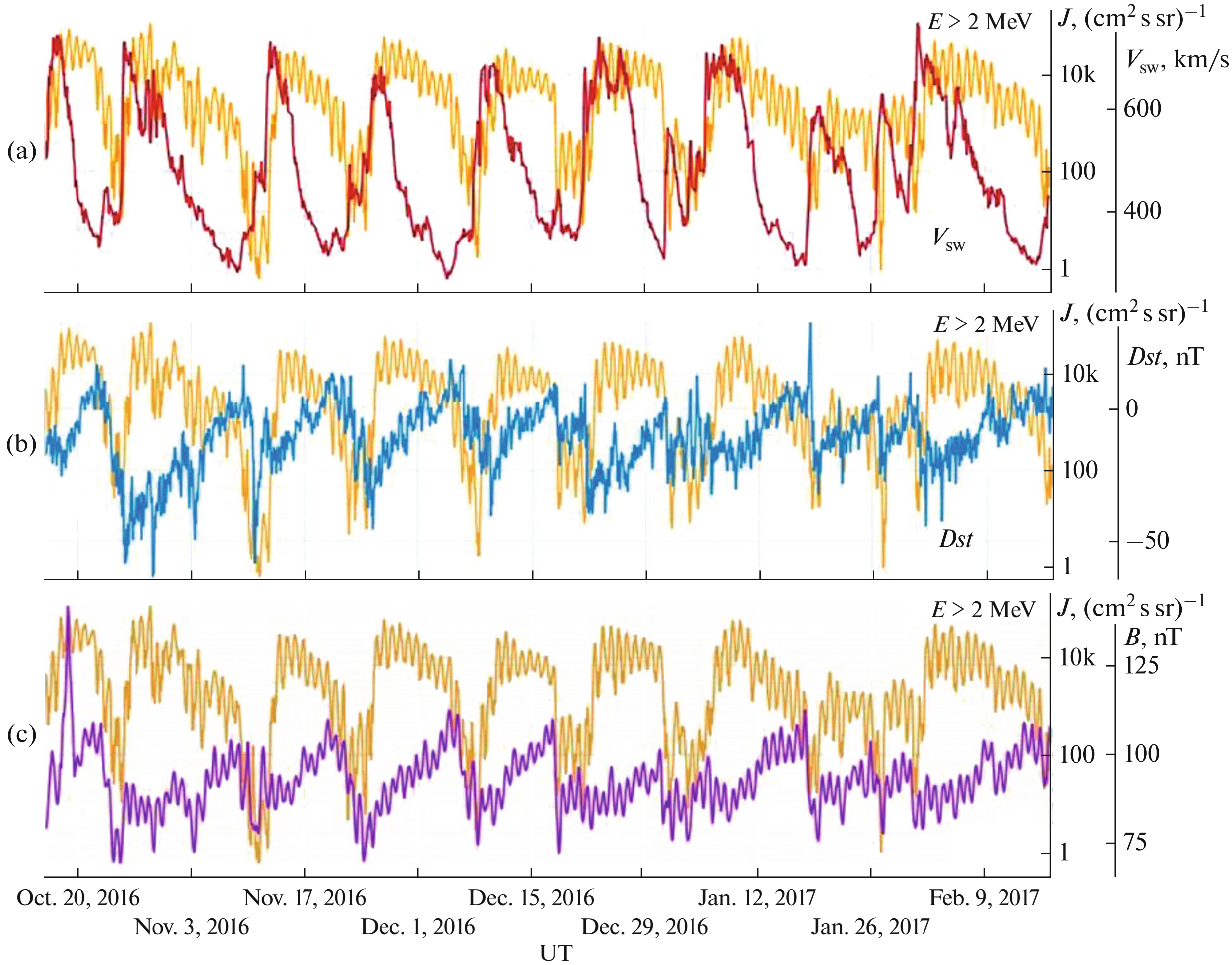

Fig. 2. Time profiles of electron flux and parameters: (a) solar wind speed, (b) *Dst* variations, (c) averaged magnitude of the magnetic field modulus during the period October 16, 2016–February 16, 2017.

The work used experimental information on measurements of magnetic field components in the Earth's magnetosphere by the *GOES-15* satellite and in the interplanetary medium by the *ACE* spacecraft. To isolate long-term variations in magnetic fields, data averaging was used applying the moving average method: the value at each point was calculated as the arithmetic mean of the values at ten previous and ten subsequent points. Figure 2c presents simultaneous data on electron fluxes and averaged values of the magnetic field modulus according to the *GOES-15* satellite data. It can be seen that the characters of the time profiles of electron fluxes and the magnetic field modulus differ approximately in the same way as when compared with *Dst* variation (Fig. 2b), which is natural: the magnitude of the magnetic field in the geostationary orbit decreases during the main phase of the storm and, then, gradually increases during the recovery phase, until the arrival of the next structure of the interplanetary medium, causing the next disturbance. In this case, the electron flux drops sharply along with the module of the magnetospheric magnetic field in the GEO, after which it quickly recovers and remains almost at the same level, usually decreasing slightly, until there is a rapid drop with the development of the next storm.

Along with the magnitude of the magnetic field at the GEO, we will consider variations in the direction of the field vector. *GOES* satellites measure the *Hp*-, *Hn*-, and *He*-components of the field, directed, respectively, perpendicular to the GEO plane, in the azimuthal (eastward) and radial (toward the Earth) directions in the plane of the geographic equator. Since the *Hp* component makes the main contribution to the magnitude of the magnetic field modulus in geostationary orbit, the conclusions when comparing the dynamics of electron fluxes and the magnetic field modulus (Fig. 2c) can be completely attributed to the *Hp* component. The ratio of the values of the *Hp* and *He* components characterizes the degree to which the magnetic field in the geostationary orbit differs from the dipole one. The profiles of the *Hp* and *He* components of the magnetic field presented in one panel

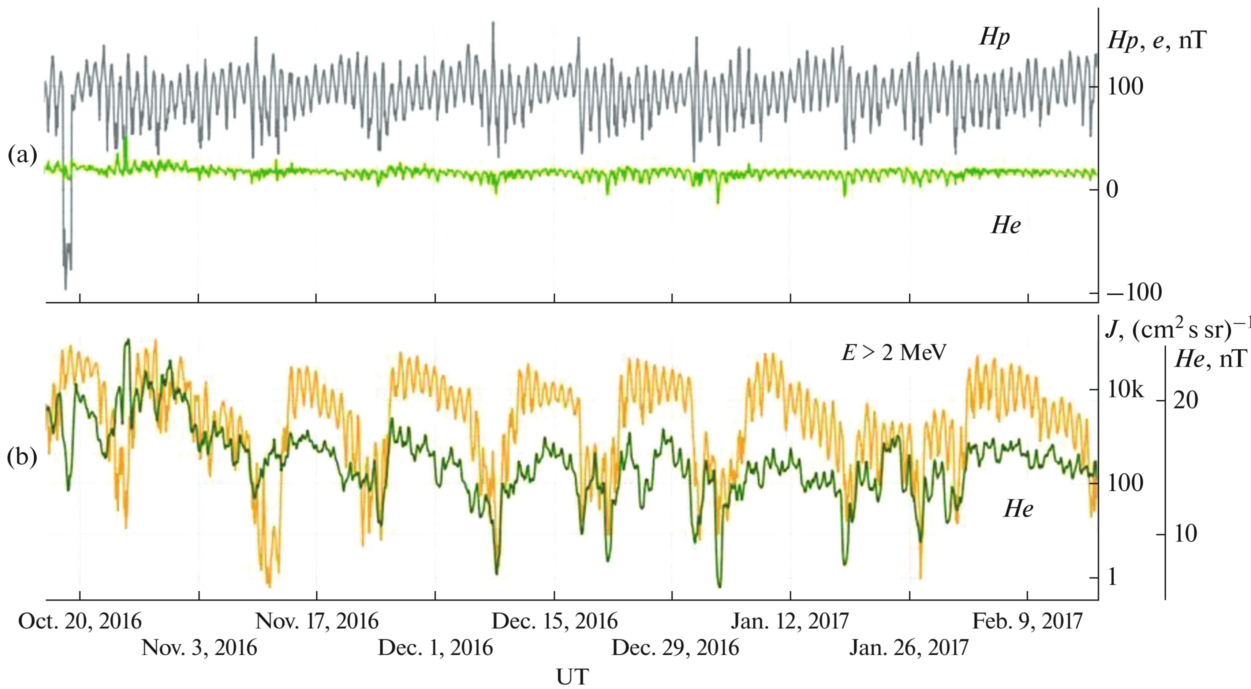

Fig. 3. Time profiles of the *Hp* and *He* components of (a) the magnetic field and (b) the electron flux and the averaged value of the *He* component of the magnetic field according to the *GOES-15* satellite data during the period October 16, 2016–February 16, 2017.

(Fig. 3a) demonstrate different dynamics. The *He* component has a significantly smaller absolute value, but its role becomes significant during magnetic disturbances and especially in the night sector of the magnetosphere. Here, the *He* component is directed approximately along the X_{GSM} axis and characterizes mainly the intensity of the current system of the magnetotail. Time profiles of electron fluxes and the averaged value of the *He* component are presented in Fig. 3b. It can be seen that, in contrast to variations in the speed and density of the solar wind, the *Dst* index and the magnetic field modulus in the GEO, long-term variations in the averaged *He* component correspond to changes in electron fluxes. During the period under study, at the beginning of each magnetospheric disturbance (storm), the value of the *He* component begins to decrease and reaches its lowest value, approximately at the maximum of the storm, after which it quickly recovers. Having reached a maximum, the value of the *He* component gradually decreases. The profiles of the *He* component of the magnetic field and electron flux presented in one panel indicate the presence of general patterns in their time evolution.

DISCUSSION

The foundations of knowledge about the structure and dynamics of the Earth's radiation belts and, in particular, the outer electron radiation belt were laid quite quickly after the discovery of the radiation belts, to a large extent, thanks to experimental data obtained from satellites of the *Electron* series, which were launched into an elliptical orbit [25]. The very title of the review by S.N. Vernov et al.—"Particle Fluxes in the External Geomagnetic Field" [25]—speaks of a priority factor influencing the dynamics of electron fluxes of the external radiation belt. The results of the analysis of the dynamics of electron fluxes of the outer radiation belt during individual magnetic storms depending on variations in the parameters of the solar wind and IMF indicate the repeatability of the processes, which can be clearly seen in the time interval chosen for the study: October 16, 2016, to February 16, 2017 (Fig. 1). The most significant effect on the magnetosphere is exerted by variations in the solar wind speed (see, for example, [26]). The IMF *Bz* component and its variations are a key factor determining the state of the magnetosphere: IMF turn to the south is one of the main conditions for the development of a magnetic storm [27]. The southern component of the IMF characterizes the rate of reconnection at the magnetopause and the intensity of global plasma convection from the magnetotail to the trapping region. In turn, the dynamic pressure of the solar wind affects the position of the magnetopause; an increase in pressure and the southern direction of the IMF ensures a more efficient transfer of mass–energy–momentum from the solar wind to the magnetosphere.

Experimental confirmation of the currently existing ideas about the influence of the state of the interplanetary medium on the magnetosphere is presented in Fig. 1 in the form of time profiles of solar wind and IMF parameters, as well as *Dst* variations and magnetospheric field components in Fig. 3 (October 16, 2016, to Febru-

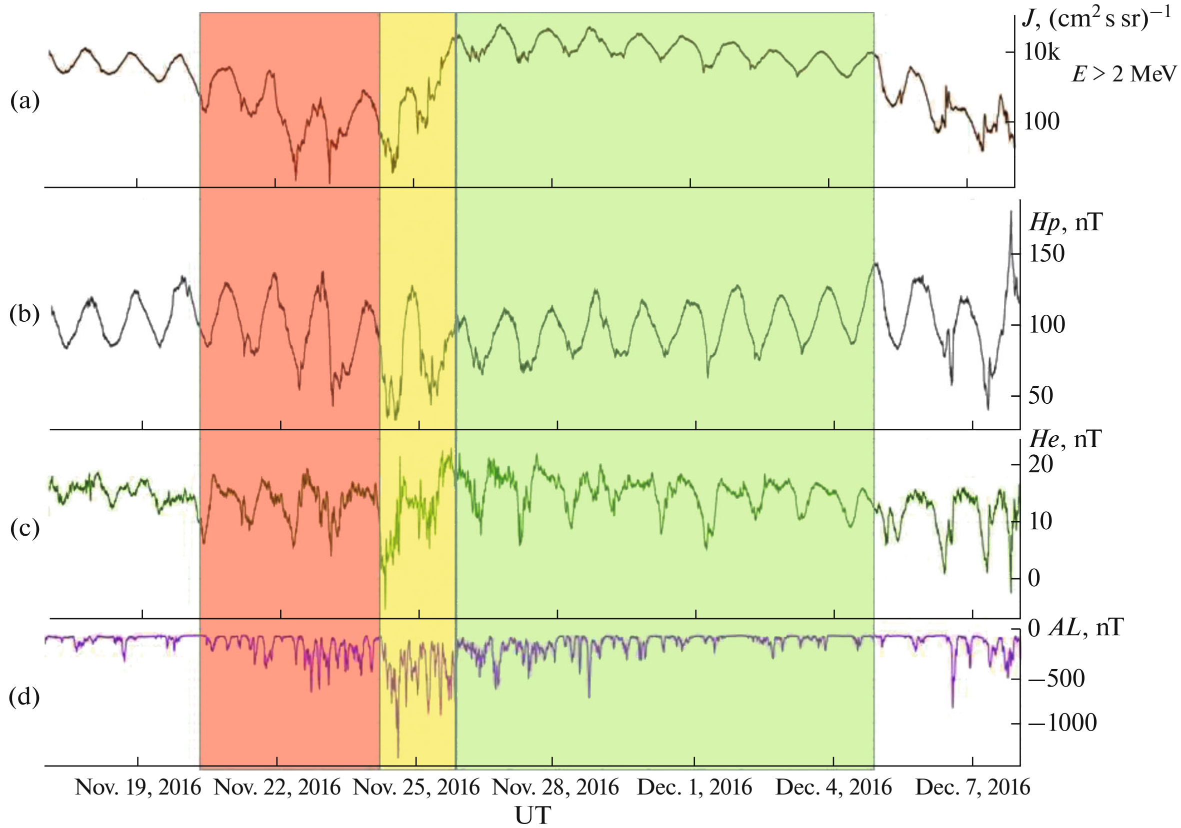

Fig. 4. Time profiles of the (a) electron flux, (b) *Hp* and (c) *He* components of the magnetic field, and (d) *AL* index during the period November 17–December 7, 2016.

ary 16, 2017). A comparative analysis of the profiles of electron fluxes and the magnitude of the magnetic field and its components in geostationary orbit demonstrates a clear correlation of the studied parameters under conditions of repeated magnetic disturbances.

One of the first articles on a statistical study of the dynamics of relativistic electron fluxes in the Earth's outer radiation belt based on data from geostationary satellites shows that usually during a storm the electron flux decreases and, then, either recovers or exceeds the prestorm level, or the flux remains unchanged at a low level [4]. A magnetospheric storm has several phases in its development. Let us consider one of the storms (November 25, 2016) shown in Fig. 1 in more detail (Fig. 4). On the time profiles, three intervals with different dynamics of the electron flux are highlighted in color: a decrease in the flux during the main phase of the storm (red), minimum flux value and rapid increase at the storm maximum and at the very beginning of the recovery phase (yellow), a roughly constant flux value, and then a slow decrease in flux during the recovery phase of the storm (green). Periodic oscillations of the electron flux, *Hp* and *He* components of the magnetospheric field (Figs. 4a–4c) are a diurnal variation of the tail-like magnetic field lines in the night sector, which ensures the minimum values of the measured quantities.

The first interval, during which the electron flux decreases, coincides with the main phase of the magnetic storm. The rapid decrease in the electron flux almost simultaneously with the decrease in the magnetic field can be explained by the adiabatic effect associated with the expansion of *L*-shells—the *Dst* effect [6]. It was noted in [7] that, as the solar wind stream increases, large-scale convection intensifies in the magnetotail. The electric field of convection and currents across the magnetotail increase, which noticeably deform the field lines, extending them to the night side. The flux of low-energy particles injected from the magnetotail penetrates into deeper regions of the inner magnetosphere. The length of the field lines increases noticeably, and the field strength in the equatorial region decreases. As a result, during the first phase of a magnetic storm, when plasma penetrates the periphery of the region of trapped radiation and extends the field lines into the tail, at appropriate distances from the Earth a sharp drop in the intensity of high-energy particles should be observed due to the adiabatic deceleration of particles and an increase in the volume of the field tubes by a factor of 10^2–10^3.

The results presented in our work are consistent with the conclusions made in [28] based on multipoint observations using data from the *Van Allen Probes* spacecraft and modeling the decrease in the flux of relativistic electrons with a decrease in the magnetic field associated with proton injection. The relation between the radiation belt and the ring current during the main phase of the storm on May 27, 2017, is described. The simulation results indicate that the magnetic field lines stretch outward in the equatorial region by ~0.5 R_E and that the field weakens by approximately four times within a few minutes. Due to betatron and Fermi slowdown, while preserving the first and second adiabatic invariants, the flux of relativistic electrons with an energy of several megaelectronvolts decreases by from two to three orders of magnitude with a change in the pitch-angle distribution from almost flat at the maximum to a distribution with maxima at ~30° and ~150°.

Other mechanisms for the influence of the topology of the magnetospheric field on the dynamics of electron fluxes during a storm are also proposed. Thus, in work [19], the following explanation is given for the decrease in the electron flux during the main phase of the storm on September 7, 2002: a partial ring current can lead to such a change in the topology of the magnetic field, as a result of which a trap for electrons is formed on the dayside, in which electrons can be stably captured for more than 11 h. The decay of the partial ring current leads to the disappearance of the trap and the restoration of the movement of electrons around the Earth. The presented results indicate a redistribution of electron fluxes in energy and space during the main phase of a magnetic storm.

Let us conduct a comparative analysis of the dynamics of electron fluxes and magnetic field variations at the maximum and in the early recovery phase of the storm on November 25, 2016 (Fig. 4, yellow area). A slight increase in the *Hp* component of the magnetic field is observed mainly in the night sector of the magnetosphere, with an increase in minimum values (Fig. 4b), while a rapid increase is visible in the electron flux profile (Fig. 4a). After the minimum values at the storm maximum, the value of the *He* component of the magnetic field in the early recovery phase shows a rapid increase (Fig. 4c), synchronous with the electron flux (Fig. 4a). As noted above, in almost all magnetic disturbances observed during the studied interval, the rapid recovery of the electron flux in the early phase of storm recovery coincides with a rapid increase in the *He* component of the magnetic field (Fig. 3c). An increase in the *He* component of the magnetic field after disturbances means a weakening of the effect of tail currents, so that the field lines elongated into the tail are drawn into the magnetosphere, and according to [7], particles experience strong adiabatic acceleration, and the stronger the disturbance, the deeper shells are affected by this process. The increase in the amplitude of rapid variations in the magnitude of the *He* component of the magnetic field during this period is associated with substorm activity, which in this storm was precisely at its maximum and in the early phase of storm recovery (Fig. 4d).

To explain the fluxes of energetic electrons in the outer radiation belt, including relativistic electrons that appear sporadically in the magnetosphere, a mechanism was proposed for the acceleration of these electrons by short-term electric field pulses that arise on the night side during substorm disturbances [29]. In [30], this mechanism is significantly specified taking into account modern concepts of fast plasma flows in the geomagnetic tail, the emergence of dipolization fronts, as well as the excitation of local-time localized longitudinal-resonant poloidal Alfven oscillations containing a strong electric field component in the direction morning–evening. It is shown that, in one act of adiabatic acceleration of electrons with an energy of ~1–2 MeV, the energy increment can be ~200–500 keV and the flux increase can be ~100–300% with an exponential spectrum shape with E_0 ~ 0.3 MeV. The conclusions presented in articles [29, 30] are consistent with the results of this work, but we assume that, during the dipolization process, predominantly electrons that were slowed down during the main phase of the storm are accelerated.

It is assumed in [31] that a very rapid (stepwise) increase in electron fluxes almost simultaneously in a wide energy range is associated with substorm dipolizations of the magnetic field in the magnetotail. Publication [32] concludes that a necessary condition for increasing the fluxes of relativistic electrons is an increase in the *AE* index. Time profiles of the electron flux and magnetic indices characterizing substorm activity in the magnetosphere (*AL* and *AE* indices) during the period under study (October 16, 2016, to February 16, 2017) are presented in Fig. 5. It can be seen that substorm activity accompanies each decrease in the *Dst* variation (Fig. 5a). Moreover, the maximum activity (Figs. 5b, 5c) is observed mainly at the maximum and/or at the early stage of storm recovery, coinciding with a rapid increase in the electron flux (Fig. 5c).

At the late phase of magnetic storm recovery (Fig. 4, green area), a process of gradual (over several days) restoration of the quiet structure of the magnetic field in the region of trapped radiation, in particular, geostationary orbit, occurs: the value of the *Hp* component of the magnetic field increases (Fig. 4b), and the *He* component decreases (Fig. 4c). A smooth decrease in the electron flux is observed, which can be explained by a change in the ratio of the *Hp* and *He* components of the magnetic field and the diffusion of particles into the radiation belts.

Review [33] shows that, based on the empirically obtained dependence of the position of the maximum of the belt of relativistic electrons during the recovery phase of a magnetic storm on the amplitude of this storm ($|Dst|_{max}$) [15], one can predict to what latitudes many "critical," from the point of view of space weather, magnetospheric plasma structures—such as the boundary of a region of trapped radiation, night equatorial boundary of the auroral oval, center of the

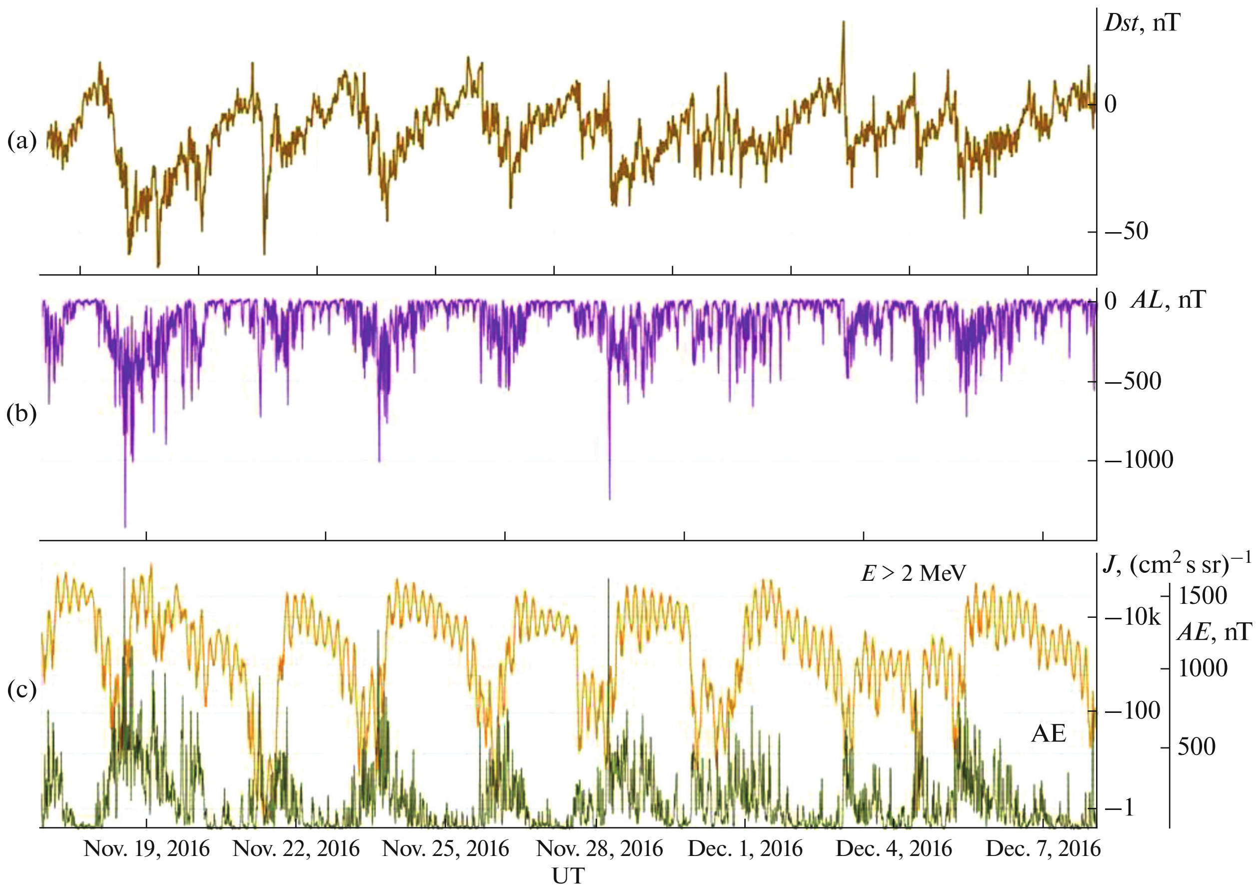

Fig. 5. Time profiles of (a) *Dst* variation, (b) *AL* index, and (c) electron flux and *AE* index during the period October 16, 2016–February 16, 2017.

western electric jet, and maximum ring current plasma pressure—will approach the Earth during the storm. This proves that the increase and decrease in electron fluxes is a repeating regular process that occurs along with changes in the magnetosphere as a whole.

CONCLUSIONS

The results of a study of the dynamics of relativistic electron fluxes in the geostationary orbit region depending on magnetic field variations under the influence of heliospheric structures with high solar wind speed on the Earth's magnetosphere on October 16, 2016, to February 16, 2017, are presented. As a result of a comparative analysis of variations in electron fluxes and parameters of the solar wind and interplanetary magnetic field and components of the magnetospheric field, the following is shown.

— High-speed solar wind streams are one of the factors determining the flow of energy from the interplanetary medium into the magnetosphere and a trigger for the development of magnetospheric disturbances.

— The decrease in the electron flux of the Earth's outer radiation belt during the main phase of a magnetic storm is mainly associated with a decrease in the magnetic field (adiabatic slowdown of particles and an increase in the volume of magnetic field tubes [7]).

— The increase in electron fluxes at the maximum and in the early recovery phase of a magnetic storm is predominantly associated with a change in the topology of the magnetospheric field, namely, with a significant increase in the radial component of the magnetospheric field (adiabatic acceleration, retraction of field lines inward [7]), as well as with substorm activity [29, 30].

— The dynamics of electron fluxes in the late phase of magnetic storm recovery correlates with the gradual restoration of the topology of the magnetospheric field lines (an increase in the vertical and a decrease in the radial component of the magnetic field), as well as due to the diffusion of particles inside the radiation belts [7].

The results of the study indicate a strict cause-and-effect relationship between processes in the heliosphere and magnetosphere of the Earth and their recurrence during the period under consideration (from October 16, 2016, to February 16, 2017). The Earth's radiation belts are a structural formation in the magnetosphere that exists due to the presence of a sufficiently strong quasi-dipole magnetic field. The dynamics of electron fluxes is a process that occurs together with variations of the magnetosphere as a whole. The dominant factor influencing electron dynamics is variations and changes in the magnitude and structure of the magnetospheric field.

The results obtained indicate the dominant influence of the magnetospheric field structure on the dynamics of relativistic electron fluxes in the geostationary orbit region. Along with this, there are undoubtedly processes that lead to real losses and replenishment of the outer electron radiation belt with new particles, but they occur against the background of global changes in the outer radiation belt associated with the development of large-scale storm current systems, leading to changes in the structure of the magnetosphere.

ABBREVIATIONS AND NOTATION

SW	solar wind
IMF	interplanetary magnetic field
AES	artificial Earth satellite
EMIC	electromagnetic ion cyclotron
VLF	very low frequency
ULF	ultra low frequency
GSO	geostationary orbit

SUPPLEMENTARY INFORMATION

The online version contains supplementary material available at https://doi.org/10.1134/S0010952524600410.

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CONFLICT OF INTEREST

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

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