

FLUXES OF 40–500 keV ELECTRONS AT THE GEOSTATIONARY ORBIT WITHOUT STRONG GEOMAGNETIC DISTURBANCES, AND INTERPLANETARY MEDIUM PARAMETERS

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Abstract. The study is focused on 40–500 keV electron flux enhancements at the geostationary orbit, which occur without strong geomagnetic disturbances. We use data on the differential-energy electron flux recorded by the magnetospheric satellite GOES-15. Electron flux enhancements occurring without magnetic storms and strong substorms are selected for analysis. The superposed epoch method is employed to examine interplanetary medium and solar wind parameters during the enhancement intervals, as well as during the preceding several hours, which are compared with intervals lacking enhancements but exhibiting similar geomagnetic

and auroral activity indices. We also compare the energy spectra of electrons averaged over the selected event groups. We demonstrate that differences in solar wind speed are observed for at least 6 hours prior to the onset of enhancements, and the immediate precursor to the enhancement emerging 1–2 hours before a selected flux local maximum is a rise in solar wind dynamic pressure.

Keywords: sub-relativistic electrons, space weather, magnetosphere.

INTRODUCTION

Fast charged particle fluxes in the magnetosphere are an important element of solar-terrestrial relations. The most energetic particles — cosmic rays — penetrate the magnetosphere from the interplanetary medium [Murzin, 2007], but most of the energetic charged particles present in the magnetosphere accelerate inside the magnetosphere. Their study provides valuable information about magnetospheric plasma, plasma instabilities, and, above all, wave—particle interactions [Klimushkin et al., 2021].

Spatial and energy distribution of particle fluxes is of great practical importance, since fast electrons, primarily of relativistic energies, cause satellite equipment failures [Baker, 2000; Pilipenko et al., 2006], and precipitation of softer auroral electrons is associated with the excitation zone of intense geomagnetically induced currents, which are the most dangerous terrestrial manifestation of space weather disturbances [Boteler et al., 1998; Boteler, 2019; Pilipenko, 2021; Pilipenko et al., 2024].

The impact of solar wind (SW) and interplanetary magnetic field (IMF) parameters on fast magnetospheric electron flux is realized not directly, but through intramagnetospheric mechanisms. The relevance of studying the statistical relationships of IMF and SW parameters with the electron flux is related to the availability of monitoring data on extra-magnetospheric parameters. For example, for more than 30 years, IMF, velocity, density, ionic composition, temperature, and a number of other SW parameters and fast electron and ion fluxes have been contin-

uously measured at the libration point. The measurement data and the most important derived parameters, such as the SW dynamic pressure, the Alfvén Mach number, etc. are available on the website [<https://cdaweb.gsfc.nasa.gov/>].

Among the SW parameters, a stable positive correlation is observed between electron flux and velocity. An important and not yet fully solved problem is the prediction of the electron flux, especially its enhancements to values dangerous for satellites. The fundamental possibility of the prediction is related to the non-zero delay time between an external impact on the magnetosphere and a change in the electron flux.

The predictions are made using regression models as well as more complex methods, including machine learning [Simms, Engebretson, 2020]. An overview of the basic principles of prediction and works devoted to this problem can be found in [Potapov, 2017]. The paper systematizes the main factors used for the prediction, including SW and IMF parameters, geomagnetic indices, and ultralow-frequency (ULF) waves. Potapov et al. [2016] have developed a predictive model based on multifactorial linear regression analysis with data windowing for dynamic correction of regression coefficients. This made it possible to increase the accuracy of the prediction of relativistic electron fluxes with a 1–2 day horizon as compared to traditional methods.

Myagkova et al. [2020, 2021a] have fulfilled the prediction of the relativistic electron flux at $E > 2$ MeV in Earth's outer radiation belt (EORB) with machine learning algorithms. In [Myagkova et al., 2020], it is shown that the inclusion of the SW velocity predicted from the area of

coronal holes in the model improves the medium-range forecasting (3–4 days). In their next work, Myagkova et al. [2021a] handle the problem of short-term forecasting (1–24 hrs). The influence of the inclusion of precursor electrons in the model (channel $E > 800$ keV) on the prediction quality for $E > 2$ MeV is also analyzed. It is concluded that such a modification has negligible effect on the prediction quality. Furthermore, the prediction quality in this channel is worse than in $E > 2$ MeV.

Analysis of statistical relationships between external factors and electron flux, carried out by different authors, differs in input parameters of the model, averaging time, consideration of time delays, and as to whether the objective is set to identify closer relationships and direct factors. One of the most comprehensive series of papers to date, in which these issues are raised and consistently addressed, is ([Simms et al., 2024] and references therein).

In a number of studies, parameters of wave disturbances are directly included in the factors that are used to make electron flux models and related prediction. Thus, Degtyarev et al. [2009] examined the correlations of Pi1 and Pc5 geomagnetic pulsation parameters with relativistic electron fluxes $E > 2$ MeV in geostationary orbit during the recovery phase of magnetic storms. The authors performed a comparative analysis of the pulsation parameters and compared them with SW parameters and *Dst*. Special attention is paid to how the joint manifestation of “seed” electrons (indicated by Pi1 pulsations) and high-amplitude global Pc5 affects the relativistic particle flux. The authors conclude that the mid-latitude Pi1 pulsations can serve as a near-real-time indicator of the ability of a geomagnetic storm to generate intense relativistic electron fluxes, and the inclusion of geomagnetic pulsation parameters in input parameters can improve the accuracy of models of predicting radiation conditions in near-Earth space.

In [Sakaguchi et al., 2015; Simms et al., 2018], along with IMF, SW parameters and geomagnetic activity indices, wave disturbances in the magnetosphere in the ranges from ULF (< 1 Hz) to VLF ($\sim 10^3$ Hz) are taken into account. Belakhovsky et al. [2020] have analyzed the contribution of ULF and VLF disturbances to the acceleration of electrons to relativistic energies in EORB. The analysis showed that a necessary condition for acceleration of electrons to relativistic energies is the long-term substorm activity accompanied by 50–100 keV electron injection.

The most probable position of the EORB maximum fast electron flux near the equatorial plane of the magnetosphere is at radial distances $(4\div 5)R_E$ (see, e.g., [Mauk et al., 2012]). Accordingly, electron fluxes in the geostationary orbit are on average lower than in the outer radiation belt maximum. Nonetheless, during disturbances, the flux maximum can markedly shift about the mean [Boyd et al., 2016; Reeves et al., 2016].

Fast electron fluxes in geostationary orbit are actively studied due to the extensive technical use of this orbit (see, e.g., [Thomsen et al., 2013; Ganushkina et al., 2021] and references therein). Moreover, data analysis is technically easier for the geostationary orbit than for

other regions of the magnetosphere, since a satellite constantly observes one point of the magnetosphere. As a result, there is no problem of separating temporal and spatial variations, which makes processing geostationary observation data similar to processing ground-based observations. On the other hand, since the magnetosphere in general and the radiation belt in particular are not rigid systems, flux variations can be associated not only with acceleration/deceleration processes, but also with the displacement of the magnetopause and/or intramagnetospheric boundaries.

Reeves et al. [2003] analyze relativistic electron fluxes, using long-term observations in geostationary orbit from LANL satellites and in the L -shell range from 4 to 7 from the POLAR satellite, which allows us to separate the effects of acceleration and displacement. The paper indicates that during magnetic storms a relativistic electron flux can both increase and decrease, and some storms are not accompanied by any noticeable change in the flux. At the same time, electron variations, at least up to $L < 6$, are similar, i.e. the detected effects generally characterize accelerations.

Fundamentally, new possibilities for separating spatial and temporal variations arise when analyzing fluxes at different heights on the same L -shell. Low-altitude measurements of relativistic and subrelativistic electron fluxes are made by small ionospheric satellites such as Vernov [Panasyuk et al., 2016]. Myagkova et al. [2016] report the results of recording of variations in relativistic and subrelativistic electron fluxes by the RELEK equipment on board the Vernov satellite in July–December 2014. The paper has examined electron flux intensity bursts with an energy of hundreds of keV at auroral and middle latitudes. It is shown that isotropization of the flux occurs on the OERB boundary at $L = 6\div 6.5$.

The possibility of comparing data on fast electron fluxes measured simultaneously by geostationary and low-orbit satellites is discussed in [Myagkova et al., 2021a]. The authors studied electron fluxes with energies from 100 keV to several MeV during moderate disturbances at solar minimum. The peculiarities of measurements with low-orbit satellites make it impossible to constantly compare fluxes in two orbits, but the possibility of such a comparison even for individual events is of fundamental importance.

Electron fluxes with energies of tens to hundreds of keV are an intermediate link between auroral (from a few to several keV) and relativistic (of the order of and above several MeV) electrons. Fewer studies have been devoted to supra-auroral and subrelativistic electrons than to slower auroral and faster relativistic electrons. Such electrons in the inner magnetosphere are the seed population for OERB relativistic electrons [Jaynes et al., 2015]. Furthermore, non-relativistic electrons have higher fluxes than relativistic ones, and the total effect of their impact on satellites proves to be significant. The main process determining the effect of electrons that cannot pass through the skin is differential charging followed by a breakdown [Gussenhoven et al., 1987; Garrett, Whittlesey, 2000; Thomsen et al., 2013].

Electrons with energies of tens to hundreds of keV form high-energy tails of auroral electron distributions. Variations in their flux modulate ionosphere and upper atmosphere parameters and represent a link between space weather and ordinary weather [Vokhmyanin et al., 2023]. Artemyev et al. [2022] has explored the nature of intense subrelativistic electron precipitation into Earth's atmosphere. It was shown that intense subrelativistic microbursts can be generated by nonlinear Landau resonance for electrons with strongly oblique whistling waves. It was suggested that such subrelativistic microbursts occur due to capture of plasma sheet electrons (0.1–10 keV) into the nonlinear Landau resonance, which leads to their acceleration to energies $\lesssim 200$ keV.

In recent decades, interest in electrons of this energy range has increased with the amount of satellite data available for analysis. For example, Li et al. [2005] examined the dependence of electron fluxes in geostationary orbit on SW parameters. The energy range from 50 keV to 6 MeV was analyzed, and it was found that for all energies the main contributing factor is the SW velocity. For energies below 200 keV, the IMF B_z effect is also pronounced.

The conclusion about the importance of the same two parameters is drawn in other works too, but the energy ranges for which the effect of one of the parameters prevails differ from author to author. Analysis of GOES-13 and MAGED satellite measurements for 2011–2015 has revealed a moderate correlation between SW velocity and 30–200 keV electron flux, whereas B_z has a major effect, especially in the 0–12 MLT sector [Sillanpää et al., 2017]. Katsavrias et al. [2021], using nine-year GOES measurements, explored interplanetary parameters correlating with 30–600 keV electrons. Their analysis shows that electron fluxes up to 100 keV are mainly controlled by auroral activity, and at 100–350 keV the SW velocity contribution becomes predominant.

The work [Shi et al., 2009] delves into the effect of magnetosphere compression on the electron flux in geostationary orbit. The same energy range as in [Li et al., 2005] is analyzed. The analysis draws on measurement data from LANL satellites for 2000–2003. The selection was made from abrupt changes in the SW dynamic pressure before a shock wave. It was found that the main reaction of 50–75 keV electrons is flux enhancement, whereas in the case of relativistic electrons, the flux decreases.

Christodoulou et al. [2025] have investigated correlations of 50–500 keV electron fluxes in the inner magnetosphere ($L < 6$) with SW parameters and geomagnetic indices. The analysis used data from approximately seven-year RBSP and MMS satellite observations. It was found that the substorm activity is a key factor determining 10–100 keV electron fluxes. Moreover, subrelativistic electron fluxes are controlled not only by the auroral activity level, but also by magnetospheric convection.

Thus, previous studies have demonstrated that among the extramagnetospheric factors affecting electron fluxes the main ones are the SW velocity, IMF B_z , and SW dynamic pressure variations. Among the mag-

netospheric factors, wave disturbances have a direct effect on electron fluxes; and among the non-wave factors inside the magnetosphere, the auroral activity and magnetospheric convection are the most crucial.

The influence of B_z is associated with the leading role of this parameter in reconnection and development of a substorm [Lyons, 1995]. The correlation between the flux and SW velocity is indirect evidence of the role of ULF waves, since it is the SW velocity that determines the amplitude of geomagnetic pulsations in a wide frequency range [Yedidia et al., 1991; Engebretson et al., 1998].

Quantitative differences in the works by different authors may be related to different levels of solar and geomagnetic activity during the periods of interest, as well as to differences between processing techniques. The presence of diurnal variations and other quasi-periodic variations results in the fact that they have to be accounted for in analysis results [Simms et al., 2022a]. Due to the fact that the response time of the electron flux to an external disturbance depends on energy [Li et al., 2005; Wang et al., 2024; Simms et al., 2022b, 2023], statistical analysis results vary with the averaging time in use.

A number of studies observe weaker correlations of electron fluxes having energies of tens to hundreds of keV with parameters outside and inside the magnetosphere as compared to both faster and slower electrons [Simms et al., 2024], as well as worse predictive models for this energy range [Myagkova et al., 2021b].

Sufficiently rapid electron flux enhancements without magnetic storms and strong substorms are still the least understood. This paper deals with these enhancements. From five-year GOES-15 observations, fairly rapid (with a noticeable flux enhancement within an hour) electron flux enhancements are selected. For the selected events, we compare SW and IMF parameters with the intervals chosen during the same period without significant flux enhancements.

1. DATA AND PROCESSING

Geostationary Operational Environmental Satellites (GOES) operate in geostationary orbit ($6.6R_E$ geocentric distance), which ensures their permanent position relative to the Earth surface and continuous monitoring of a given magnetospheric region. As of 2025, 22 satellites of different generations had been launched under the GOES program.

This work uses data on the energy differential electron flux measured by GOES-15 in 2013–2017. The observation is made in five energy channels of 40, 75, 150, 275, and 475 keV, approximately evenly distributed on a logarithmic scale and in several (up to 9) directions (telescopes).

Analysis of the electron flux with energies of tens to hundreds of keV has revealed that the response time of the flux to external disturbances increases with energy [Simms et al., 2022a]. As the analysis of [Li et al., 2005] has shown, the maximum correlation between variations in the flux of relativistic electrons and electrons with energies below 400 keV is observed at a delay time < 10 hrs, and for faster electrons it is in the order of a day. Thus,

the boundary between relatively soft electrons, which are characterized by a short response time of the flux to an external disturbance, and subrelativistic ones, for which it is of the order of a day, passes at ~ 300 keV. Among the GOES energy channels available for analysis, the 275 keV channel is closest to the boundary.

This determined the choice of energy for studying the enhancements. Electrons with energies of several hundred keV are the immediate precursor to the most dangerous relativistic electrons. At the same time, due to the noticeable time delay between the external impact and the reaction of the flux of these electrons to it, we can, in principle, predict the enhancements.

The events were selected in two stages: first, episodes with an electron flux enhancement were identified, then a control sample of events with similar geomagnetic indices, but without detected flux enhancements, was formed.

To select rather sharp flux enhancements, an algorithm is adopted for finding maximum of the envelope of local flux maxima on the interval $[-3, +1]$ hr from t_0 of each local maximum. In addition, on the selected maximum the condition was imposed of exceeding the flux at a maximum $J_{\max} = J(t_0) \geq 1.5 J_{\text{prv}}$, where J_{prv} is the logarithmic average of the flux on the interval $[t_0-3, t_0-1]$ hr. This ensures that the flux changes significantly within an hour. The condition $J_{\max} > J_{\text{qt}}$ was also imposed on $J_{\max}$, where J_{qt} is the quiet-day logarithmic mean flux at the same time. Thus, the diurnal variation is suppressed and small fluxes are excluded. As a result, a single maximum or a series of local maxima is selected during flux enhancement. In this case, the minimum time between adjacent maxima is ~ 1 hr, and the time of the first maximum of the series corresponds to the first excess of the quiet-day average flux, caused by substantial flux enhancement within ~ 1 hr.

The background conditions were determined from the data for days without significant flux enhancements (quiet days): 5, 6, 9–11, 24–27 February and 5, 6, 8, 10, 11, 13 March 2013. When enhancement times coincided at several telescopes, the largest of the enhancements was selected for analysis. A mixed criterion was used for the selection, which takes into account both the logarithm of the maximal flux $J_{\max}$ and the logarithm of the ratio $R_{\max} = J_{\max}/J_{\text{prv}}$, to which the sum of squares normalized to the variance of the logarithms $J_{\max}$ and $R_{\max}$ determined from quiet days was applied. Thus, the group of events with enhancements (group A) is finally formed.

The condition for choosing intervals without enhancements was the absence of flux values exceeding J_{qt} at t_0 on the interval $[t_0-3, t_0+3]$ hr. The initial selection yields intervals without enhancements from which a list of events (group N) is compiled.

The condition for the absence of adjacent storms and strong substorms was created on the basis of the *AE* (Auroral Electrojet) and *Dst* (Disturbance Storm Time) indices [Bergin et al., 2019]. *Dst* measures the intensity of geomagnetic storms from data collected by four magnetic stations located near the equator. *AE* is determined by a high-latitude chain of stations

and measures the activity of auroral currents (electrojets) making up the main current system of a magnetospheric substorm.

To suppress the effect of strong storms, the condition $Dst > -100$ nT was imposed on the interval $[-120, 1]$ hr, since the recovery phase can last several days, and the condition for weaker storms $Dst > -50$ nT was imposed on $[-24, 1]$ hr.

For *AE*, the problem was to exclude strong substorms, the interval $[-3, 1]$ hr was considered, and the $AE_{\max}$ parameter — maximum *AE* in the interval — was used for selection. The inclusion of not only the maximum and the preceding period, but also the hour interval after the maximum in the analyzed time interval is associated with the need to exclude the initial phase of geomagnetic disturbances from consideration.

For the selected events, we analyze conditions in the interplanetary medium and electron spectra at the moment of enhancement and in the preceding period. We apply the following interplanetary medium and SW plasma parameters that most strongly affect the magnetosphere: the IMF B_y and B_z components in the GSM (Geocentric Solar Magnetospheric) system, the SW velocity modulus V_x , and the SW dynamic pressure P_{sw} . While this parameter is not measured, but is found from velocity and density, its use is justified by the fact that it is responsible for the position of the subsolar point of the magnetopause.

To identify the differences between the two event groups, the Superposed Epoch (SPE) method is adopted. For zero of the time axis, the moments of maxima chosen according to the described criteria and the time points for whole hours were selected from the given intervals without enhancements.

When calculating the time variations averaged over a group of events, a common one-minute time step was used for all parameters. For each reading, the averaging was made over intervals when data did not contain instrumental outliers and gaps if the number of values was not less than the threshold one. Given the number of gaps, the threshold was set at 0.7, the maximum possible for the IMF components, and at 0.5 for V_x and P_{sw} . For events within the intervals without enhancements, averaging was first performed for each $AE_{\max}$ bin, and then their weighted average was computed. Furthermore, due to the strong effect of substorms on electron flux variations, $AE_{\max}$ distributions were plotted for each sample and equalized by weight functions when *N* group parameters were averaged.

Figures illustrating individual events show the IMF B_y and B_z components, and the averaging technique in the SPE method was chosen in view of the effect of the IMF components on SW energy transfer to the magnetosphere. The possibility of magnetic reconnection and the geomagnetic activity level depend on the sign of B_z , since negative B_z (southerly direction) stimulates energy exchange between SW and the magnetosphere, and positive (northerly) one eliminates it. The Akasofu parameter ϵ , which estimates the rate of SW energy transfer to the magnetosphere, takes this asymmetry into account [Akasofu, 1981]. The B_z averaging was therefore performed with the sign unchanged.

Most of the selected events occur under low geomagnetic activity, which is typical of near-zero and positive B_z . In this case, the convection pattern changes, reconnection shifts from the subsolar point, and energy transfer is significantly affected by B_y , while estimating the energy transfer rate generally requires numerical calculations (see [Zhang et al., 2023] and references therein). In this paper, the averaging is based on the square of IMF B_y which contributes to B_N ($B_N^2 = B_y^2 + B_z^2$), normal to the SW velocity, which is included in the estimate of the electric field at the magnetopause $\mathbf{E} = [\mathbf{v} \times \mathbf{B}]$. The SW velocity is considered separately, since it is almost constant on the time scales under study, and short-term variations depend primarily on IMF variations.

Data processing was conducted in Python with SciPy and NumPy libraries.

2. RESULTS

2.1. Event selection and AE condition optimization

The time t_0 was included in the event group A (enhancements) if at that moment at least one of the directions (telescopes) had a local flux maximum at 275 keV that met the selection conditions. To identify intervals without enhancements, the condition was set that in none of the directions (telescopes) on $[t_0 - 3, t_0 + 3]$ hr there were values satisfying the condition for selecting group A events. Thus, continuous intervals without flux enhancements exceeding 6 hrs were formed from which events can be randomly selected to create a control sample.

To single out factors not directly related to storms and substorms, the same index restrictions were placed on the intervals of events with and without enhancements, and for $AE_{\max}$, the choice of threshold was governed by a compromise between the number of events in two samples and the possibility of introducing a weight function through linear interpolation within each bin.

Before index selection, the total duration of the intervals without enhancements was ~ 4500 hrs. From them, events without enhancements (group N) with 1 hr step were chosen. The step was taken so that the total number of selected readings exceeded the number of

chosen maxima in the first group and would allow correction for the difference in $AE_{\max}$ distributions. The full number of events for both groups before and after index selection is given in Table. Mind that the group N events are at least 3 hours away from the end of the interval, and hence the total duration of intervals in column 3 in Table is smaller than that without enhancements.

For each selected time point t_0 of the two groups, we determined the number of events in each of the disjoint bins 100 nT wide and the ratio W_{AN} of the percent of events with flux enhancements (group A) to events without enhancements (group N), which define the weight function for considering one group N event.

Empirical probability density functions *PDFs* for the $AE_{\max}$ distribution of events of the two groups and the weight functions W_{AN} are presented in Figure 1. For the two event groups, *PDFs* have, as expected, an opposite dependence on $AE_{\max}$. This causes an increase in W_{AN} with $AE_{\max}$. The weight function is represented as logarithms to illustrate its relative changes at boundaries between bins. Maximum relative variations in W_{AN} are observed at low $AE_{\max}$: the height of the steps at 100 and 200 nT is the same; at $AE_{\max} = 300$ nT, the growth slows down, and the step at 400 nT is slightly higher than the previous one. This is due to a marked decrease in the number of events in the control sample.

The technique of accounting for the $AE_{\max}$ distribution for the N group is exhibited in Figure 2. B_z averaged over each of the $AE_{\max}$ bins and their weighted means are presented. There is a decrease in B_z with increasing $AE_{\max}$ and the predominant contribution to the final curve of intervals with large $AE_{\max}$ in accordance with their weight functions. Since low $AE_{\max}$ prevails for intervals without flux enhancements, the curves for these bins are quite smooth. For a bin with $AE_{\max} \geq 300$ nT, the level of fluctuations rises and they are also visible on the averaged curve.

With the number of events and the weight function type, the interval $AE_{\max} = 0 \div 400$ nT was taken for further analysis. The inclusion of the lowest bin $A_{\max} < 100$ nT, despite the small number of events, is justified by the fact that they make a small contribution to the final statistics and the effect of random fluctuations in the parameters on the weighted average is insignificant in this case.

The number of events selected from electron flux parameters before and after imposing index restrictions

	Enhancements		Without enhancements	
	Number of events	percent, %	Number of events	percent
No.	1	2	3	4
All	6651	100	3715	100
<i>Dst</i> , $AE < 500$	1593	24	3138	84
0–100	62	1	1123	30
100–200	163	3	853	23
200–300	348	5	558	15
300–400	474	7	390	10
<i>400–500</i>	<i>546</i>	<i>8</i>	<i>214</i>	<i>6</i>
<i>Dst*</i>, $AE_{\max}$: 0–400	1047	16	2924	78

*Data for the final selection of the $AE_{\max}$ interval is highlighted in bold; and the 400–500 nT bin excluded from further analysis, in italics

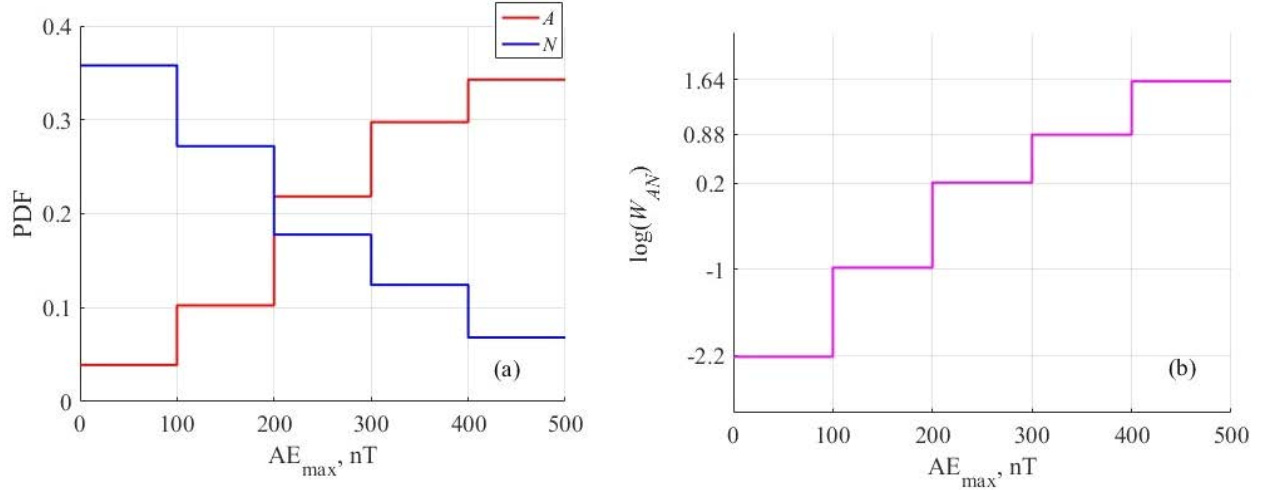


Figure 1. Empirical probability functions for events with (group A) and without (group N) flux enhancements according to $AE_{\max}$ — maximum AE in the interval $[t_0-3, t_0+1]$ hr (a) and weight functions of a group N event to equalize distributions according to $AE_{\max}$ (b)

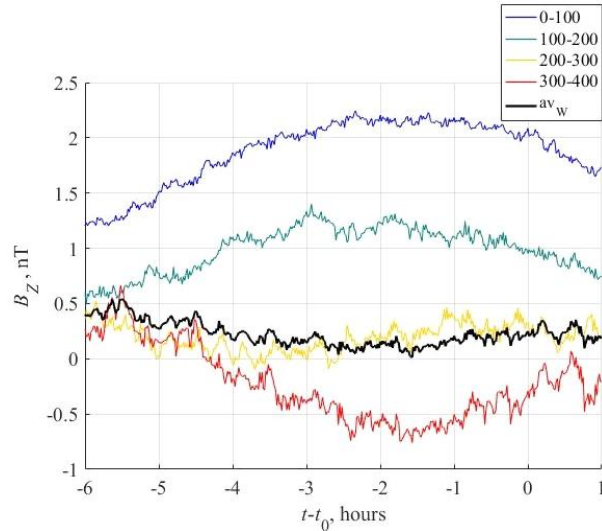


Figure 2. B_z averaged over $AE_{\max}$ bins (bin boundaries are shown in the legend) and over the entire $AE_{\max}$ interval (black curve) for group N events

Since this work deals with flux enhancements without strong disturbances, the enhancements under the strictest restrictions on the geomagnetic activity level are of the greatest interest. Some events of this type are discussed in the next subsection.

2.2. Examples of selected events

Enhancements without strong geomagnetic disturbances comprise a relatively small part of all enhancements (16 % for the 5-year interval examined). With such enhancements, no extreme values of the electron flux are detected. Their importance is determined by the fact that in the absence of strong disturbances it is easier to isolate individual factors affecting the flux, whereas under strong disturbances, several mechanisms operate at once, for example, during a magnetic storm both wave and non-wave acceleration mechanisms are activated.

Especially noteworthy are rare cases when enhancements occur under the most stringent selection

conditions. Below are examples of events for which the following restrictions hold: $Dst > -50$ nT during the last five days, $AE < 100$ nT during the last three hours.

One of the scenarios of such an enhancement is illustrated in Figure 3 by the example of event 1 occurring on November 4, 2014 (day 308). Panel a depicts electron flux variations in all energy channels from 40 to 475 keV. According to the selection condition, a maximum at 00:07 UT is taken as 0 on the time axis. Up to -4.5 hr, the average flux values at low energies are almost constant; and at 275 and 475 keV, the flux monotonously increases, slightly faster at 475 keV. At $\tau = t - t_0 = -4$ hr, there is a weak maximum after which a slow decrease begins in the flux at all energies, which is followed by a smooth enhancement at $\tau = -2.7$ hr. At -1.4 hr, the flux at all energies rises step-wise (step in panel a). The relative step is almost the same at all energies. At 275 keV, the flux at $t = t_0$ is ~ 3.5 times larger than the flux on the left boundary of the interval and 2 times greater than during the local minimum at $\tau = -2.7$ hr. The flux enhancement occurred under quiet conditions: Dst did not fall below -25 nT for at least five days, and the last moderate substorm with maximum $AE = 125$ nT was recorded at $\tau = -10$ hr. That said, a weak maximum of the flux at $\tau = -4$ hr before the onset of fall and rise at $\tau = -1.4$ hr are also noted for low AE maxima, i.e. activations of the current system at auroral latitudes.

Conditions in the interplanetary medium are shown for this event in Figure 4. The SW velocity on the entire interval is ~ 400 km/s. At $\tau < -4$ hr, B_y and B_z are close to 0, and the SW dynamic pressure is low ($P_{SW} < 1.5$ nPa).

The step in the electron flux at $\tau \sim -1.4$ hr occurs almost simultaneously with a step-wise, almost twofold, increase in P_{SW} from 2.9 nPa. From -2.7 hr there are also fluctuations in B_z with a maximum peak-to-peak amplitude up to 5 nT; and in ~ 10 min after the pressure jump, the field changes direction: average B_y changes from near-zero to negative with minimum $B_y \sim -10$ nT, and B_z shifts to positive values with maximum $B_z \sim 6$ nT. Thus, in this event, the flux enhancement takes place against a moderate SW

velocity and is preceded by ~ 1.5 -hour interval of B_z fluctuations. The abrupt flux enhancement at $\tau \sim -1.4$ hr occurs simultaneously with the P_{SW} jump and is probably related to it. Conceivably, a trigger in this case might be compression of the initially expanded magnetosphere.

Let us consider another scenario, using event 2 on August 14, 2013 (day 226) as an example. Figure 5 displays flux variations and geomagnetic indices for this event. After a series of substorms with a prolonged rise in AE to ~ 500 nT, which ended at -6 hrs, the electron flux decreased significantly, especially at the upper boundary of the energy range. At 475 and 275 keV, the flux values were $1\text{--}10$ $(\text{keV sr s})^{-1}$, which is an order of magnitude lower than that in event 1. Notice that the flux values at energies to 100 keV are approximately the same as in the previous case. As a result, the minimum flux at 475 keV before enhancement at -4.2 hr is 3 orders of magnitude less than at 40 keV. After the minimum, the flux begins to increase, especially rapidly for

high energies. Hence, the local maximum of the flux at $t=t_0=12:04$, observed during the flux enhancement phase, corresponds to selection conditions. It is important that the flux values at $E \geq 150$ keV exceed those at the left end of the interval considered, i.e. the flux not only recovers, but also further increases. For 275 keV at $\tau \sim -3$ hr, the flux reaches the initial level; and at -0.6 hr, the maximum level for the entire interval, recorded at $\tau \sim -6$ hr, at the end of the series of substorms observed at the beginning of the interval. This enhancement develops without magnetic storm under low auroral activity.

Interplanetary medium conditions for this interval are shown in Figure 6. After -4.2 hr, small (in modulus) B_y and weakly positive B_z are observed. The SW velocity at the beginning of the interval is ~ 400 km/s. From about $\tau = -8$ hr, the velocity begins to rise, and by -4 hr its average value exceeds 440 km/s. The SW dynamic pressure over the entire range does not exceed 3 nPa, and at $\tau = -4.2$ hr P_{SW} falls from 2.4 to 1.6 nPa within an hour.

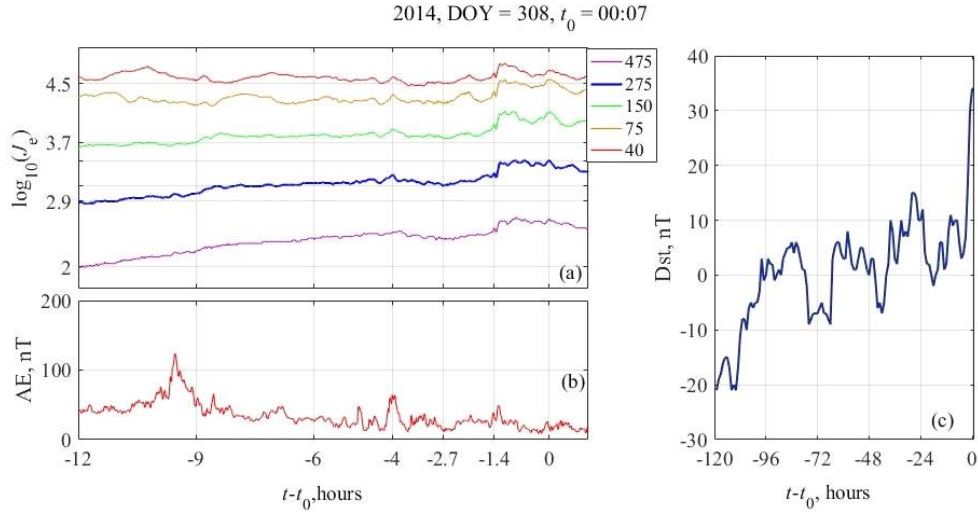


Figure 3. Electron flux variations in five energy channels (a). Central energies in keV are given in the legend; in panels b, c are AE and Dst variations. The moment $t_0=00:07$ UT on November 4, 2014 (day 308) is taken as 0 of the time axis

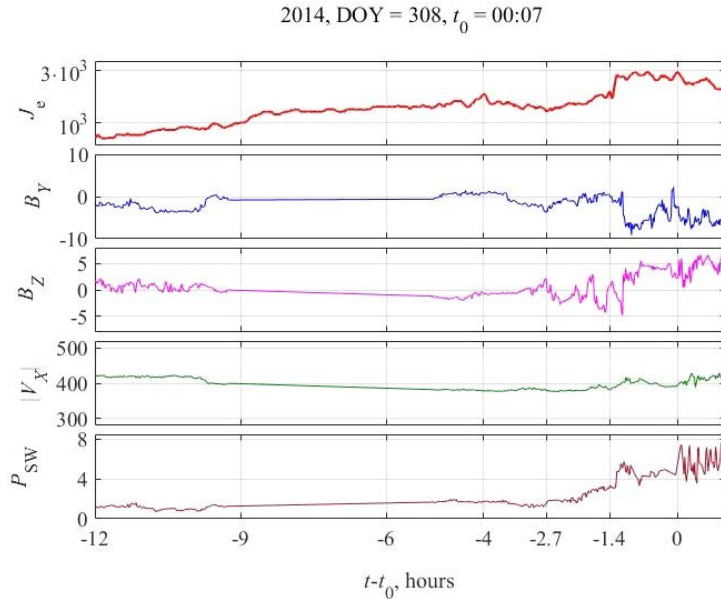


Figure 4. Variations in the 275 keV electron flux and IMF/SW parameters for the same event as in Figure 3. From top to bottom: 275 keV electron flux $(\text{keV sr s})^{-1}$; B_y (nT); B_z (nT); $|V_x|$ (km/s); P_{SW} (nPa)

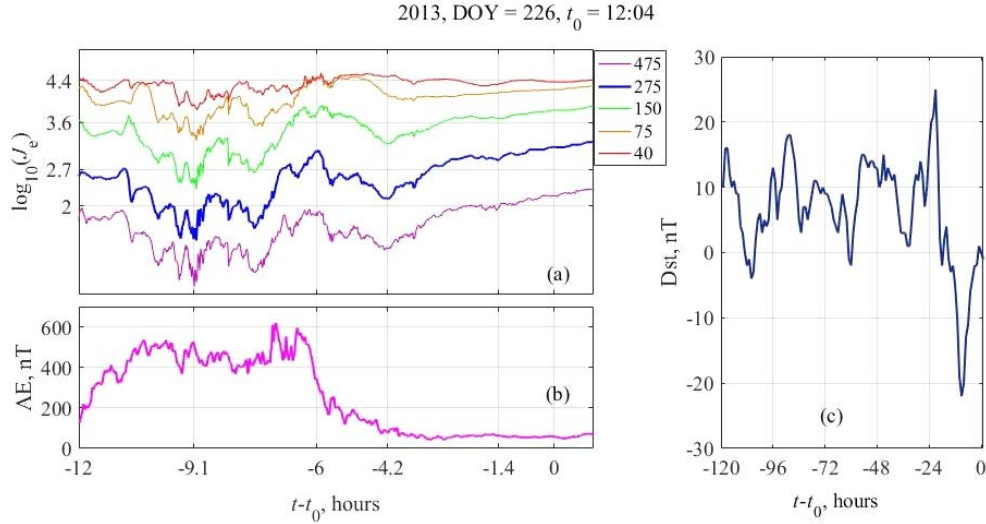


Figure 5. Variations in the electron flux, AE , and Dst for $t_0=12:04$ UT on August 14, 2013 (day 226). The format is the same as in Figure 3

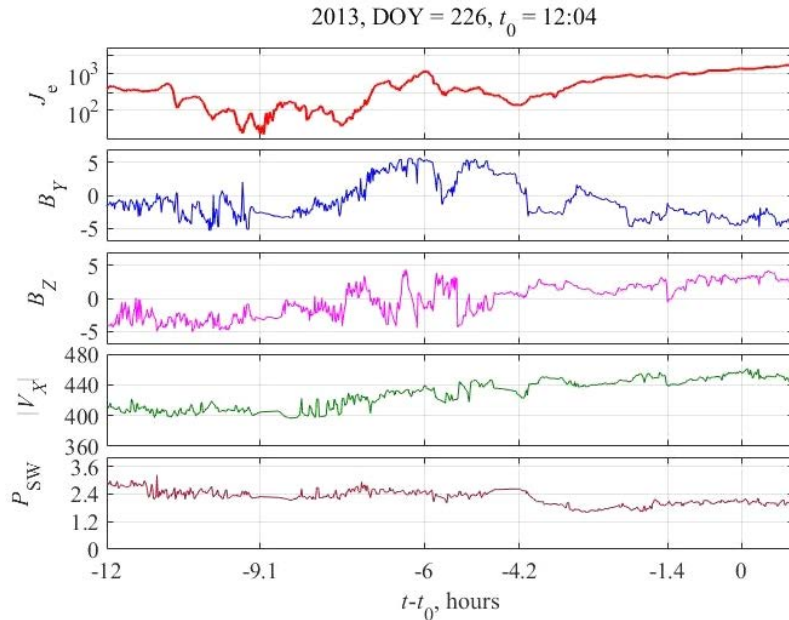


Figure 6. Variations in 275 keV electron flux and IMF/SW parameters for the same event as in Figure 5. The format is the same as in Figure 4

Thus, for event 2, the electron flux at $E \geq 150$ keV increases quite rapidly. For example, for 275 keV (see Figure 6) an enhancement by an order of magnitude occurs for the first two hours after the minimum ($\tau = -4.2$ hr) and doubles on $\tau [-1.4, 0]$ hr when the flux reaches the threshold level. Unlike event 1, neither a sharp step in the electron flux variations nor an obvious trigger in the interplanetary medium can be detected for event 2.

2.3. The superposed epoch method

Below, we present the results of application of the superposed epoch (SPE) method to intervals with (group A) and without (group N) over-threshold flux enhancements at 275 keV in the absence of significant magnetic storms and strong substorms ($Dst > -100$ nT, $AE_{\max} < 400$ nT). For the enhancement intervals, the distribution was constructed without correction; and for the control sample, with correction of the distribution ac-

cording to the $AE_{\max}$ discrete distribution in increments of 100 nT.

Figure 7 illustrates electron flux and IMF/SW parameter variations average with respect to the event groups. In the top panel are electron flux variations. For the intervals preceding enhancements, the flux varies slightly within $\tau [-6, 1]$ hr and amounts to ~ 1500 (keV sr s) $^{-1}$. Near -1 hr, the flux begins to increase, reaching ~ 3000 (keV sr s) $^{-1}$ at its maximum ($t=t_0$), and then gradually decreases at a rate lower than the rate of increase within $\tau [-1, 0]$ hr. The group N average flux is ~ 150 – 200 (keV sr s) $^{-1}$, which is by an order of magnitude lower than the group A average one, and this difference is observed over the entire time interval of interest.

The second panel displays mean square of IMF B_y . For both groups, B_y^2 vary from 16–17 to 21 nT 2 . Up to -2 hr, B_y^2 are close for two groups of events and change

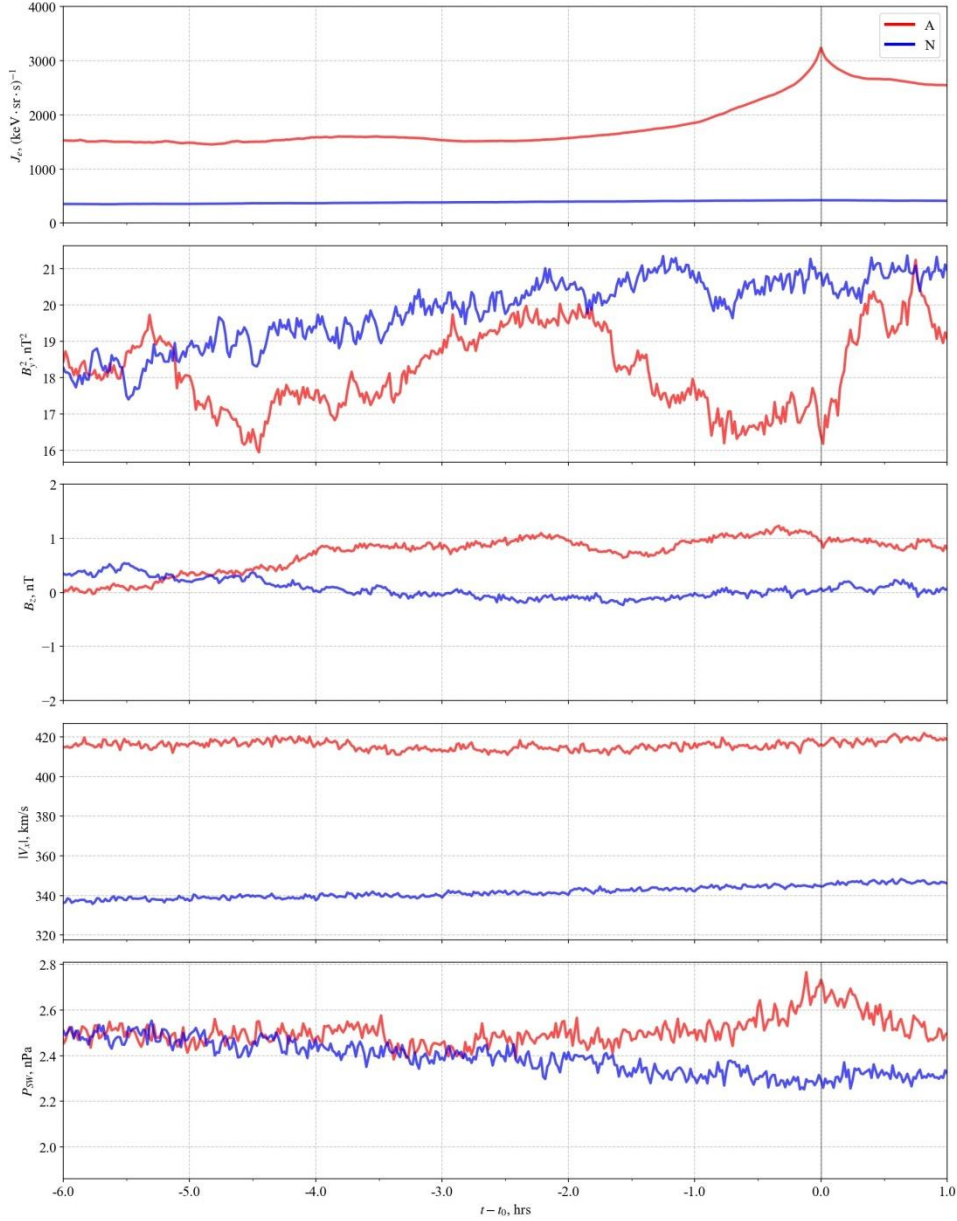


Figure 7. Parameter variations average over events of the two groups. From top to bottom: 275 keV electron flux, B_y^2 , B_z , $|V_x|$, P_{SW}

slightly with time, and at $t > -2$ hr B_y^2 decreases for group A and reaches a minimum at -1 hr. There is also a maximum difference between B_y^2 values for the two groups, which is ~ 3 nT².

The third panel shows B_z . For both groups, it is in the range of near-zero and positive values, which corresponds to the conditions of weak disturbances, from which the intervals were selected. The curve for group A from -4 hr lies in the range of positive values by ~ 1 nT higher than for group N.

The fourth panel displays $|V_x|$. Both curves lie in the region of low SW velocities — from ~ 300 to 450 km/s. For all t , the velocity for group A is higher than for group N. The average for group A is ~ 420 km/s; and for group N, 340 km/s. The bottom panel shows P_{SW} . For both groups, P_{SW} does not exceed 3 nPa. For group N,

P_{SW} ranges from 2.2 to 2.4 nPa, and for group A up to -1.5 hr it is ~ 2.5 nPa, after which it begins to rise with a maximum of ~ 2.8 nPa at zero. Mind that for group A P_{SW} and electron flux variations before the zero mark are similar.

Let us assess the significance of the results. Figure 8 depicts IMF/SW parameter distributions for the two groups of events. For B_z , we examine the distribution of the component itself; and for the remaining parameters (they are always positive), logarithms. For all group N values and for all group A parameters except $\log(B_y^2)$, distributions were plotted for $t=t_0$; and for $\log(B_y^2)$, for $t=t_0-0.8$ hr when the difference between the averages of the two groups is maximum (see Figure 7). The normal distributions for each parameter are also shown with averages and variances derived

from the empirical distribution. Since the differences between empirical and normal distributions are not too large, the standard error of the mean can be approximated using the formula $\sigma/N^{1/2}$, where σ is the standard deviation and N is the sample number.

Averages (expectations) and errors of expectation according to the sample mean are also given for the distributions of both groups. For B_z , the intervals for expectations, in view of the errors, overlap, i.e. the differences between averages of the two distributions cannot be considered significant. For average $\log(B_y^2)$, the intervals do not overlap, but the distance between their adjacent boundaries is about the width of the interval for group A, and the significance of the differences we have found requires further examination. For velocity and P_{sw} , the distance between the averages of the two groups far exceeds the width of the intervals, i.e. for these parameters, the differences between the two groups confirm their significance.

Referring to Figure 7, at the 275 keV energy used for the selection, the average electron flux for group A is higher than for group N, not only at the time zero (this directly follows from the selection condition), but also during at least previous 6 hrs. The question arises whether there are differences between particle spectra at

this time. Figure 9, *a* displays energy spectra averaged over the two groups of events at the time zero and for several earlier time points. In the entire energy range, spectra of group A lie above those of group N. Since the group N spectra on the scale of figure coincide for the entire interval from -6 hr to 0, there is one curve for them in Figure 9, *a*. For group A, spectra are almost equal for $\tau = -6$ and -3 hr; flux enhancement begins between -3 and -1 hr, and the enhancement rate is maximum during the last hour.

All spectra on a doubly logarithmic scale are visually close to linear, which, with a negative slope, corresponds to an inverse power-law dependence of the flux on energy, but in the middle of the energy range the slope is smaller, i.e. it is unstable in the energy range of interest. To more clearly illustrate this difference and the spectrum change with time, Figure 9, *b* plots the dependence of logarithmic flux on logarithmic energy after subtracting the linear trend. Since the selection for the two groups was made according to 275 keV energy, the curves for the time zero for the two event groups have respectively a convexity and a concavity at this energy for groups A and N.

At $t < t_0$, group A spectra are enriched with 75 and 150 keV energies, as compared to the spectrum at $t = t_0$,

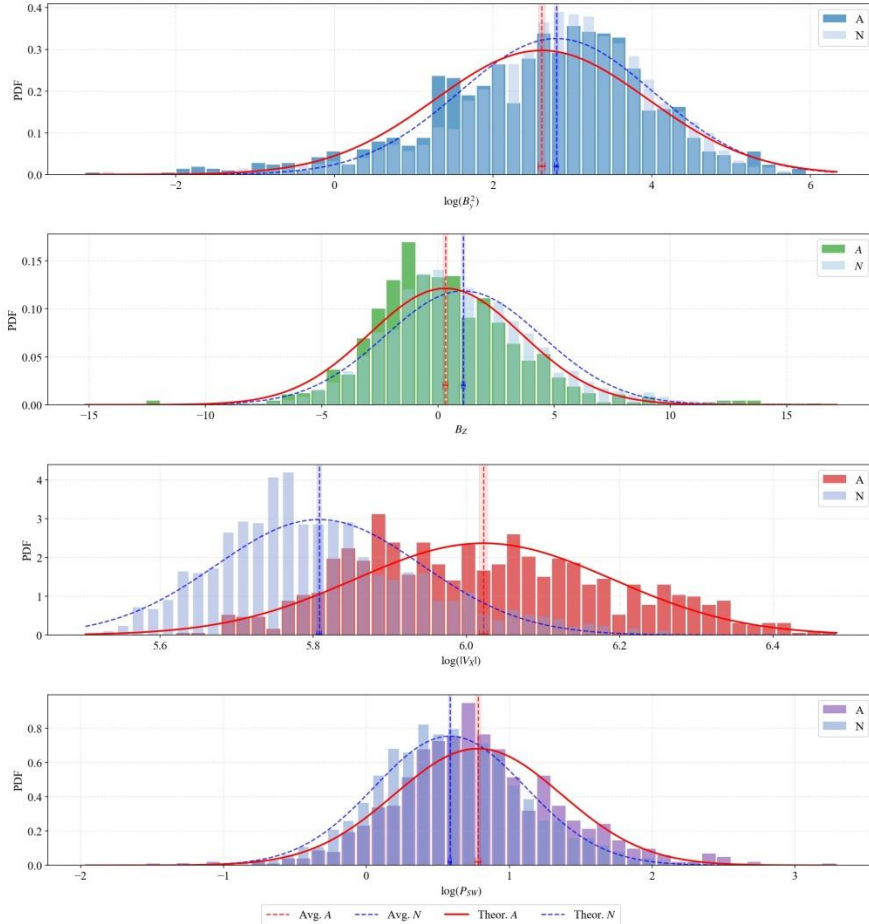


Figure 8. Comparison between IMF/SW parameter distributions for two groups of intervals. Histograms show empirical probability density functions (PDFs); lines are normal distributions with the mean and variance determined from corresponding PDFs. Vertical dotted lines indicate sample averages, the fill denotes intervals for expectations in view of the error in their determination from the sample average. Solid red lines are results for group A; dotted blue lines, for group N

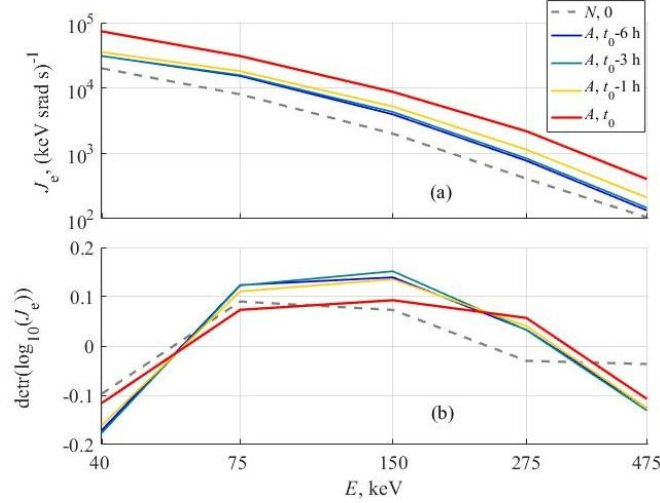


Figure 9. Energy spectra averaged for group N for $t=t_0$ and for group A at different time points (a); logarithmic spectra after removing the linear trend (b)

due to both lower and higher energies. Differences between the spectra for $t=t_0$ and the previous ones are also observed on the left edge of the spectrum. For $t < t_0$, the slope in the 40–75 keV range is larger than for $t=t_0$ and group N. Thus, in the last hours before the selected time points, the spectra are enriched with lower energies (75–150 keV) compared to both the spectra at the time of the selected local maxima and the background spectra on intervals without enhancements.

3. DISCUSSION

Flux enhancements without strong geomagnetic disturbances are still poorly understood due to smaller flux values than during strong disturbances and due to the fact that most works first analyze disturbances and then fluxes. In this paper, an attempt was made to select enhancements according to preassigned criteria by recording intervals of variations in the Dst and AE indices characterizing magnetic storms and substorms. In our study, the obtained distributions were additionally fitted by the AE index, which has the strongest effect on the flux level. Thus, the relationship between input (interplanetary medium parameters) and output (flux enhancement) parameters is taken into account in the "purest" conditions. Furthermore, the selection scheme adopted allows us to include in analysis those events that may be overlooked during reverse selection.

Both groups of intervals were selected at 275 keV, and the following differences in average parameters were found between them. Differences in flux levels at the sampling energy are observed for at least 6 hrs, and group A average flux enhancement began 2 hrs before the selected local maximum t_0 . For several hours before t_0 , the spectra are enriched with 75 and 150 keV energies, lower than the sampling energy (see Figure 9, b). This difference is seen both for the spectrum at $t=t_0$ and for the intervals lacking enhancements. This suggests that one of the flux enhancement conditions without strong disturbances is a sufficient number of precursory electrons.

In the general case, an electron flux enhancement in geostationary orbit can be caused both by acceleration or by radial displacement of the radiation belt. The differences found in the spectra are indirect evidence for the presence of acceleration.

The main results for the interplanetary medium parameters are as follows. For several hours before the selected events of both groups, B_z averages are close to zero or positive, which corresponds to a closed magnetosphere, and the differences between the two groups of intervals are minor. Formally, this result contradicts the conclusion on the contribution of B_z to electron flux variations [Li et al., 2005, Sillanpää et al., 2017]. The most likely reason for this is the suppression of the AE effect carried out in this work, which led to the suppression of the flux dependence on B_z .

B_y (directly or as a component of B_N normal to the flux velocity) affects the energy input to the magnetosphere, especially at near-zero and positive B_z . For the selected intervals with enhancements, average B_y^2 begins to decrease at $t \approx t_0 - 2$ hr and reaches a minimum at $t \approx t_0 - 0.8$ hr. At a constant SW velocity, a decrease in B_N^2 reduces the input of SW energy into the magnetosphere, which under conditions of a closed magnetosphere causes either a weak substorm or convection enhancement without substorm [Lyons, 1995]. Average B_y^2 at minimum is by ~ 3 nT² smaller than the average over the group N intervals and before the onset of the decrease. The significance of this effect requires further investigation.

Differences between the two groups of events are most pronounced in SW parameters: the average SW velocity for enhancements is ~ 420 km/s, which exceeds that for the intervals without enhancements by ~ 80 km/s. The difference in the average SW velocity between the intervals of the two groups exists for at least 6 hrs and is statistically significant. The selected local flux maxima are preceded by ~ 1.5 hr rise in P_{SW} by ~ 3 nPa from the initial level of 2.5 nPa. The difference in average P_{SW} between the two groups at t_0 is statistically significant.

For most events considered, a jump in P_{SW} causes a weak substorm or does not promote development of a substorm. Thus, changes in magnetospheric convection are probably the common cause of flux enhancements for the events considered [Christodoulou et al., 2025]. Analysis of variations in IMF/SW parameters for event 1 has revealed that even at the lowest geomagnetic activity levels a P_{SW} rise is of concern.

Event 2 demonstrates a different flux enhancement scenario, possibly related to waves. In this case, a fairly rapid flux enhancement in the absence of an external trigger may be associated with a reversible transfer of energy from particles to waves during a series of auroral activations that ended 6 hrs before the selected local maximum of the flux, followed by a reverse process that caused a significant flux enhancement within a few hours.

In some events similar to event 1, IMF and P_{SW} fluctuations are also recorded before enhancements. These factors are an indirect argument for the contribution of large-scale ULF waves to electron acceleration; and episodes similar to event 2, of smaller-scale inner magnetospheric ULF waves. We plan to verify this assumption, using GOES magnetic measurement data.

In this work based on data from one geostationary satellite, it is impossible to separate the effects of electron acceleration and flux variations associated with the displacement of the magnetopause and inner magnetospheric structures. At least for some of the selected events, this analysis can be made with data from geostationary satellites located at other longitudes, as well as from MMS or Van Allen Probes satellites [Mauk et al., 2012] passing through lower L -shells, including the region of maximum electron flux in the middle of the radiation belt. The most reliable separation of spatial and temporal variations, as well as reversible and irreversible electron losses, can be carried out through simultaneous measurements of electron fluxes from magnetospheric and ionospheric satellites, adopting the approaches described in [Myagkova et al., 2021a].

CONCLUSIONS

Selection of electron flux enhancements at 275 keV has shown that they can occur without a storm and at all levels of auroral activity.

Comparison of electron flux, IMF, and SW parameters between intervals with and without enhancements by the superposed epoch method has indicated that average B_z for both groups lies in the range of near-zero and positive values. We have found the following differences between the groups.

- For the intervals with enhancements the average flux is higher than that for the intervals without enhancements for at least 6 hrs, and the energy spectrum is enriched with 75–150 keV energies.
- The enhancements takes place at an average SW velocity of ~ 420 km/s, which is higher than for the intervals without enhancements.
- A flux enhancement occurs simultaneously with a rise in P_{SW} with its noticeable change within ~ 1 hr.

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Data sets on electron fluxes from GOES and on IMF/SW parameters are available on the website [<https://cdaweb.gsfc.nasa.gov/>]; and on the Dst and AE indices, at [<https://wdc.kugi.kyoto-u.ac.jp/wdc/Sec3.html>].

REFERENCES

- Akasofu S.I. Energy coupling between the solar wind and the magnetosphere. *Space Sci. Rev.* 1981, vol. 28, pp. 121–190. <https://doi.org/10.1007/BF00218810>.
- Artemyev A.V., Zhang X.-J., Zou Y., et al. On the nature of intense sub-relativistic electron precipitation. *J. Geophys. Res.: Space Phys.* 2022, vol. 127, e2022JA030571. <https://doi.org/10.1029/2022JA030571>.
- Baker D.N. The occurrence of operational anomalies in spacecraft and their relationship to space weather. *IEEE Trans. Plasma Sci.* 2000, vol. 28, pp. 2007–2016. <https://doi.org/10.1109/27.902228>.
- Belakhovsky V., Pilipenko V., Mioshi E. Contribution of ULF and VLF wave disturbances to the growth of relativistic electron fluxes. *Proc. XLIII Annual Seminar “Physics of Auroral Phenomena”*. Apatity, 2020, pp. 43–46. <https://doi.org/10.37614/2588-0039.2020.43.010>.
- Bergin A., Chapman S., Gjerloev J. AE , Dst , and their SuperMAG counterparts: The effect of improved spatial resolution in geomagnetic indices. *J. Geophys. Res.: Space Phys.* 2019, vol. 125, e2020JA027828. <https://doi.org/10.1029/2020JA027828>.
- Boteler D.H. A 21st century view of the March 1989 magnetic storm. *Space Weather*. 2019, vol. 17, pp. 1427–1441. <https://doi.org/10.1029/2019SW002278>.
- Boteler D.H., Pirjola R.J., Nevanlinna H. The effects of geomagnetic disturbances on electrical systems at the Earth’s surface. *Adv. Space Res.* 1998, vol. 22, pp. 17–27. [https://doi.org/10.1016/S0273-1177\(97\)01096-X](https://doi.org/10.1016/S0273-1177(97)01096-X).
- Boyd A.J., Spence H.E., Huang C.-L., et al. Statistical properties of the radiation belt seed population. *J. Geophys. Res.: Space Phys.* 2016, vol. 121, pp. 7636–7646. <https://doi.org/10.1002/2016JA022652>.
- Christodoulou E., Katsavrias C., Kordakis P., Daglis I.A. Influence of solar wind driving and geomagnetic activity on the variability of sub-relativistic electrons in the inner magnetosphere. *Universe*. 2025, vol. 11, 101. <https://doi.org/10.3390/universe11030101>.
- Degtyarev V.I., Chudnenko S.E., Kharchenko I.P., et al. Forecast of maximum daily means of relativistic electron fluxes at the geostationary orbit during the magnetic storm recovery phase. *Sol.-Terr. Phys.* 2009, iss. 13 (126), pp. 34–42.
- Engelbreton M.J., Glassmeier K.H., Stellmacher M., Hughes W.J. The dependence of high-latitude Pc5 wave power on solar wind velocity and on the phase of high-speed solar wind streams. *J. Geophys. Res.: Space Phys.* 1998, vol. 103, pp. 26271–26283. <https://doi.org/10.1029/97JA01343>.
- Ganushkina N.Y., Swiger B., Dubyagin S., et al. Worst-case severe environments for surface charging observed at LANL satellites as dependent on solar wind and geomagnetic conditions. *Space Weather*. 2021, vol. 19, e2021SW002732. <https://doi.org/10.1029/2021SW002732>.
- Garrett H.B., Whittlesey A.C. Spacecraft charging, an update. *IEEE Trans. Plasma Sci.* 2000, vol. 28, pp. 2017–2028.
- Gussenhoven M.S., Mullen E.G., Filz R.C., et al. New low-altitude dose measurements. *IEEE Trans. Nucl. Sci.* 1987, vol. 34, pp. 676–683. <https://doi.org/10.1109/TNS.1987.4334701>.

- Jaynes A.N., Baker D.N., Singer H.J., et al. Source and seed populations for relativistic electrons: Their roles in radiation belt changes. *J. Geophys. Res.: Space Phys.* 2015, vol. 120, pp. 7240–7254. <https://doi.org/10.1002/2015JA021234>.
- Katsavrias Ch., Aminalragia-Giamini S., Papadimitriou C., et al. On the interplanetary parameter schemes which drive the variability of the source/seed electron population at GEO. *J. Geophys. Res.: Space Phys.* 2021, vol. 126, e2020JA028939. <https://doi.org/10.1002/essoar.10504803.1>.
- Klimushkin D.Yu., Mager P.N., Chelpanov M.A., Kostarev D.V. Interaction between long-period ULF waves and charged particles in the magnetosphere: theory and observations (review). *Sol.-Terr. Phys.* 2021, vol. 7, iss. 4, pp. 33–66. <https://doi.org/10.12737/stp-74202105>.
- Li X., Baker D.N., Temerin M., et al. Energetic electrons, 50 keV to 6 MeV, at geosynchronous orbit: Their responses to solar wind variations. *Space Weather*. 2005, vol. 3, S04001. <https://doi.org/10.1029/2004SW000105>.
- Lyons L.R. A new theory for magnetospheric substorms. *J. Geophys. Res.: Space Phys.* 1995, vol. 100, pp. 19069–19081. <https://doi.org/10.1029/95JA01344>.
- Mauk B., Fox N., Kanekal S., et al. Science Objectives and Rationale for the Radiation Belt Storm Probes Mission. *Space Sci. Rev.* 2012, vol. 179. <https://doi.org/10.1007/s11214-012-9908-y>.
- Murzin V. *Astrophysics of Cosmic Rays: A University Textbook*. Moscow: Universitetskaya Kniga; Logos, 2007, p. 488. (In Russian).
- Myagkova I., Panasyuk M., Svertilov S., et al. Electron flux variations at altitudes of 600–800 km in the second half of 2014. Preliminary results of an experiment using RELEC equipment onboard the satellite Vernov. *Kosmicheskie issledovaniya [Cosmic Research]*, 2016, vol. 54, no. 1, pp. 67–75. (In Russian). <https://doi.org/10.7868/S0023420616010131>.
- Myagkova I.N., Shugai Yu.S., Kalegaev V.V., et al. Medium-term prediction of relativistic electron fluxes on a geostationary orbit via machine learning based on observation data on coronal holes. *Geomagnetism and Aeronomy*, 2020, iss. 3, pp. 293–304. <https://doi.org/10.1134/S0016793220030123>.
- Myagkova I.N., Bogomolov A.V., Ereemeev V.E., et al. Dynamics of the radiation environment in the near-Earth Space in September–November 2020 according to the Meteor-M and Electro-L satellite data, *Cosmic Research*, 2021a, vol. 59, iss. 6, pp. 433–445. <https://doi.org/10.1134/S001095252106007>.
- Myagkova I.N., Shirokii V.R., Shugau Yu.S., et al. Shortland and medium-range prediction of relativistic electron flux in the Earth's outer radiation belt by machine learning methods, *Meteorologiya i Gidrologiya (Meteorology and Hydrology)*. 2021b, iss. 3, pp. 47–57. (In Russian). <https://doi.org/10.52002/0130-2906-2021-3-47-57>.
- Panasyuk M.I., Svertilov S.I., Bogomolov V.V., et al. Experiment on the Vernov satellite: Transient energetic processes in the Earth's atmosphere and magnetosphere Part I: Description of the experiment, *Cosmic Research*. 2016, vol. 54, iss. 4, pp. 261–269. <https://doi.org/10.1134/S0010952516040043>.
- Pilipenko V.A. Space weather impact on ground-based technological systems. *Sol.-Terr. Phys.* 2021, vol. 7, iss. 3, pp. 68–104. <https://doi.org/10.12737/stp-73202106>.
- Pilipenko V., Yagova N., Romanova N., Allen J. Statistical relationships between the satellite anomalies at geostationary orbits and high-energy particles. *Adv. Space Res.* 2006, vol. 37, pp. 1192–1205. <https://doi.org/10.1016/j.asr.2005.03.152>.
- Pilipenko V.A., Kozyreva O.V., Belakhovsky V.B., et al. What should we know to predict geomagnetically induced currents in power transmission lines? *Russian J. Earth Sciences*. 2024, vol. 24, pp. 1–15. <https://doi.org/10.2205/2024ES000954>.
- Potapov A.S. Relativistic electrons of the outer radiation belt and methods of their forecast (review), *Sol.-Terr. Phys.* 2017, vol. 3, iss. 1, pp. 57–72. https://doi.org/10.12737/article_58f9703837c248.84596315.
- Potapov A.S., Ryzhakova L.V., Tsegmed B. A new approach to predict and estimate enhancements of “killer” electron flux at geosynchronous orbit. *Acta Astronautica*. 2016, vol. 126, pp. 47–51. <https://doi.org/10.1016/j.actaastro.2016.04.017>.
- Reeves G.D., McAdams K.L., Friedel R.H.W., O'Brien T.P. Acceleration and loss of relativistic electrons during geomagnetic storms. *Geophys. Res. Lett.* 2003, vol. 30, 1529. <https://doi.org/10.1029/2002GL016513>.
- Reeves G.D., Friedel R.H.W., Larsen B.A., et al. Energy-dependent dynamics of keV to MeV electrons in the inner zone, outer zone, and slot regions. *J. Geophys. Res.: Space Phys.* 2016, vol. 121, pp. 397–412. <https://doi.org/10.1002/2015JA021569>.
- Sakaguchi K., Nagatsuma T., Reeves G.D., Spence H.E. Prediction of MeV electron fluxes throughout the outer radiation belt using multivariate autoregressive models. *Space Weather*. 2015, vol. 13, pp. 853–867. <https://doi.org/10.1002/2015SW001254>.
- Shi Y., Zesta E., Lyons L.R. Features of energetic particle radial profiles inferred from geosynchronous responses to solar wind dynamic pressure enhancements. *Ann. Geophys.* 2009, vol. 27, pp. 851–859. <https://doi.org/10.5194/angeo-27-851-2009>.
- Sillanpää I., Ganushkina N.Y., Dubyagin S., Rodriguez J.V. Electron fluxes at geostationary orbit from GOES MAGED data. *Space Weather*. 2017, vol. 15, pp. 1602–1614. <https://doi.org/10.1002/2017SW001698>.
- Simms L.E., Engebretson M. Classifier neural network models predict relativistic electron events at geosynchronous orbit better than multiple regression or ARMAX models. *J. Geophys. Res.: Space Phys.* 2020, vol. 125, e2019JA027357. <https://doi.org/10.1029/2019JA027357>.
- Simms L.E., Engebretson M., Clilverd M., et al. A distributed lag autoregressive model of geostationary relativistic electron fluxes: Comparing the influences of waves, seed and source electrons, and solar wind inputs. *J. Geophys. Res.: Space Phys.* 2018, vol. 123, pp. 3646–3671. <https://doi.org/10.1029/2017JA025002>.
- Simms L.E., Engebretson M., Reeves G. Removing diurnal signals and longer term trends from electron flux and ULF correlations: A comparison of spectral subtraction, simple differencing, and ARIMAX models. *J. Geophys. Res.: Space Phys.* 2022a, vol. 127, e2021JA030021. <https://doi.org/10.1029/2021JA030021>.
- Simms L.E., Ganushkina N.Yu., van de Kamp M. et al. Using ARMAX models to determine the drivers of 40–150 keV GOES electron fluxes. *J. Geophys. Res.: Space Phys.* 2022b, vol. 127, e2022JA030538. <https://doi.org/10.1029/2022JA030538>.
- Simms L.E., Engebretson M.J., Reeves G.D. Determining the timing of driver influences on 1.8–3.5 MeV electron flux at geosynchronous orbit using ARMAX methodology and stepwise regression. *J. Geophys. Res.: Space Phys.* 2023, vol. 128, e2022JA030963. <https://doi.org/10.1029/2022JA030963>.
- Simms L.E., Ganushkina N.Y., Dubyagin S. Comparing influences of solar wind, ULF waves, and substorms on 20 eV – 2 MeV electron flux (RBSP) using ARMAX models. *J. Geophys. Res.*

- ophys. Res.: Space Phys.* 2024, vol. 129, e2024JA032458. <https://doi.org/10.1029/2024JA032458>.
- Thomsen M.F., Henderson M.G., Jordanova V.K. Statistical properties of the surface-charging environment at geosynchronous orbit. *Space Weather*. 2013, vol. 11, pp. 237–244. <https://doi.org/10.1002/swe.20049>.
- Vokhmyanin M., Asikainen T., Salminen A., Mursula K. Long-term prediction of sudden stratospheric warmings with geomagnetic and solar activity. *J. Geophys. Res.: Atmospheres*. 2023, vol. 128, e2022JD037337. <https://doi.org/10.1029/2022JD037337>.
- Wang J., Xiang Z., Ni B., et al. Influences of solar wind parameters on energetic electron fluxes at geosynchronous orbit revealed by the Deep SHAP method. *Space Weather*. 2024, vol. 22, e2024SW003880. <https://doi.org/10.1029/2024SW003880>
- Yedidia B.A., Vellante M., Villante U., Lazarus A.J. A study of the relationship between micropulsations and solar wind properties. *J. Geophys. Res.: Space Phys.* 1991, vol. 96, pp. 3465–3470. <https://doi.org/10.1029/90JA01992>.
- Zhang H.X., Lu J.Y., Wang M. Energy transfer across magnetopause under dawn–dusk IMFs. *Sci Rep.* 2023, vol. 13, pp. 7409. <https://doi.org/10.1038/s41598-023-34082-2>
- URL: <https://cdaweb.gsfc.nasa.gov/> (accessed October 10, 2025).
- URL: <https://wdc.kugi.kyoto-u.ac.jp/wdc/Sec3.html> (accessed October 7, 2025).

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