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Interactive comment on "Energetic electron enhancements under radiation belt ($L < 1.2$) during nonstorm interval on August 1, 2008" *by* Alla V. Suvorova et al.

Alla V. Suvorova et al.

suvorova_alla@yahoo.com

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Dear Referee1,

Thank you very much for your comments and suggestions. We revised the Discussion and provided additional solid arguments and some quantitative estimation to support our suggestions. Here we try to address all your concerns.

General comments by Referee1:

"This manuscript reports a series of >30 keV electron flux enhancement events that happened at L<1.2 observed by POES satellites, and massive related observations

from THEMIS, ground magnetometer, ACE, etc. These events are likely to be a subset of the events analyzed in Suvorova (2017) and this study is a follow-up work related to Suvorova (2017). In the present study, the authors propose that the magnetic perturbation near the magnetopause causes a mixture of magnetosheath plasma and magnetospheric plasma to precipitate in high latitude (high L regions) which further induce a large transient electric field that could transport the electrons to L<1.2. However, there is no solid evidence reported to prove that the flux enhancements at L<1.2 are caused by magnetic perturbation near the magnetopause, nor analysis on the possibilities that this proposed chain of processes could work. The reviewer suggests to at least add in some more solid arguments or simulation results to prove that the proposed processes are reasonable before the paper can be published. The reviewer also suggests the authors to be more concise on some part of the paper, to avoid extra confusions of the readers."

Reply:

We thank the reviewer for the suggestion which help to improve the manuscript. We provide some additional observations and estimations in Discussion. We revised some descriptions in the paper in order to make them shorter.

In our study, we did not state or suggest that the magnetic perturbations cause the electron enhancements at low L-shells and plasma precipitations at high L-shells. Addressing to the comment 2, we will clarify this crucial point, which is important for overall understanding of our concept.

Specific Comment 1

(1.1) The authors presented the >30 keV electron flux measurements by POES satellites in Figure 1. In Figure 1, it is clear that electron fluxes are enhanced in the quasitrapped region (outside of SAA), but the fluxes in SAA that are more stably-trapped almost remain the same.

Reply:

Actually, electron fluxes did increase in the SAA region. However, the background fluxes in SAA were already high (several units of 105 (cm2 s sr)-1). The fluxes of FEE were mostly less than 105 (cm2 s sr)-1. Hence, they produce a little increase of the flux in SAA which is hard to be seen in the logarithmic scale. However, this effect is beyond the scope of our study.

(1.2) The authors refer to those events as injections in many places in the paper (e.g., line 202, 208). However, if those electrons are injected from higher L, they are supposed to become more 90 degree peaked in pitch angle, which means they are more likely to be stably-trapped and more enhancements in the SAA region are expected. From Figure 1, the slot region is not filled, which is supposed to be seen in an typical injection event that penetrates down to L=1.2. In fact, previous studies such as Li et al (2017, titled "Measurement of electrons from albedo neutron decay and neutron density in near-Earth space") reported events that enhanced stably trapped electrons are observed due to geomagnetic activities while the quasi-trapped electron fluxes stay the same. Moreover, people would easily link the enhancements in the quasi-trapped electrons to enhanced pitch angle scattering. The authors should show more detailed observations of these events and explain why these events are injections.

Reply:

We thank the reviewer for the comment. In order to clarify this crucial issue we revised Figure 2 (see below) in order to show the time profiles of intensities and L-shells of FEE enhancements. As we wrote, we use measurements from the vertically oriented detector (“0-detector”) of electrons with local pitch angles of 90° at the equator (quasi or locally trapped electrons). Another detector measured precipitating electrons at the equator. The electron precipitations did not arise. The observed time profiles of quasi-trapped electrons are proper for injections.

We revised the text accordingly:

“Figure 2 and Table 1 present main characteristics of 15 FEE enhancements detected along equatorial passes of POES satellites (P2, P5, P6, P7, P8). We analyze the peak fluxes in the FEE enhancements (time, local time, longitude, and L-shell). ” “As seen in Figure 2a,b, the FEE enhancements peak at minimal L-shells, i.e. at the equator. The fluxes decrease quickly with growing L. This pattern corresponds to a fast radial transport (injection) of electrons from the inner radiation belt. Note that pitch-angular scattering of electrons gives different profiles: the fluxes should be minimal and the equator and grow with L-shell.”

Concerning to the albedo neutron mechanism. First of all, that paper is about relativistic electrons (∼500 keV) during a geomagnetic storm. We think it has a little relation to our study of low-energy (>30 keV) electrons during nonstorm conditions. Next, it is impossible to apply this mechanism to the FEE enhancements because of the following well known facts: (1) The fluxes of albedo neutrons at equatorial latitudes are much lower (order of magnitudes) than the fluxes of FEE. (2) During magnetic quiet, the latitudinal profile of secondary particles (generated in decay) is positive, i.e. the flux of secondary particles increases with latitude due to a decrease of the cut-off rigidity of incident cosmic rays. Figure 2 demonstrates totally different pattern.

(1.3) The author should also specify the looking direction of the detector in the caption of Figure 1.

Reply:

In the caption of Figure 1 we add the following sentences: “The electrons are detected in vertical direction. In the forbidden zone, those electrons are quasi-trapped.”

Specific Comment 2

(2.1) As is stated in the general comments, the authors have not present any solid evidence that the electron enhancements at L=1.2 could be caused by magnetic perturbations near the magnetopause which is at quite large L. Only coincidences in time are shown in the present study. The reviewer suggests to show more solid arguments or some simulation results to prove this possibility.

Reply:

We thank the reviewer for the comment, which help to improve the manuscript.

We want to clarify that we did not state that the observed magnetic perturbations near the magnetopause or inside the outer magnetosphere, at large L, can cause such a mixture of plasma at high latitudes and electron enhancements at the equator. These perturbations had small amplitudes of about of several to tens of nT [e.g., line 332]. We wrote [line 513] “A series of night injections of >30 keV electrons could be associated with transient magnetospheric magnetic field perturbations.” We wrote about the association in other parts of text also. Note that the association is not a causality.

In Discussion we add:

“The amplitude of geomagnetic pulses is not very high: from few nT at ground to a few tens of nT at THEMIS. It should be noted that such magnetic perturbations are too weak to produce deep injections of >30 keV electrons below the radiation belt.”

These magnetic perturbations are only a response of the geomagnetic field on occasional pressure pulses produced by magnetosheath plasma jets at the magnetopause. In the study, we emphasized an important role of transient subsolar foreshock condition, under which plasma jets are generated, for the magnetosphere–ionosphere coupling, particularly for non-storm events. The transient subsolar foreshock was only recently recognized as a major driver for a throat aurora at high latitudes, as we mentioned in the study.

In revised Discussion, we emphasize the importance of jets for the magnetosphere-ionosphere coupling under conditions of stable solar wind dynamic pressure and northward IMF:

“The interaction of jets with the magnetopause results in geomagnetic pulses and penetration of the magnetosheath plasma inside the magnetosphere (Figure 8). Note that the upstream conditions observed by THEMIS-C during both time intervals (from 12 to 16 UT and from 16 to 18 UT) were similar in that the quasi-radial IMF appeared. Hence, it is reasonable to suggest that the geomagnetic pulses occurred from 12 to 16 UT were also produced by jets because there were no strong enhancements in the solar wind dynamic pressure Pd. Indeed, as one can see in Figure 1 and 8, gradual tenuous variations of Pd do not exceed a few tenths of nPa and, thus, they cannot produce sharp geomagnetic pulses with amplitudes of ∼10 nT.

Also, in the revised manuscript, we provide additional arguments in favor to jet impact on the magnetosphere-ionosphere system. It was established that the impact results in magnetosheath particles precipitations at high latitudes near local noon. We present observations of hot plasma precipitations to the latitude ionosphere during the event:

“The energy fluxes of hot plasma (from 50 eV to 10 keV) are measured by POES/TED plasma spectrometer. We conducted an additional analysis of hot plasma precipitations in the auroral region at L-shells from 7 to ∼15 during time interval from 11 to 18 UT on 1 August 2008. Figure 11 demonstrates magnetic observations by THEMIS-D and GOES-12, the energy fluxes of auroral precipitations, and FEE injections. We consider intense precipitations with the threshold of 0.5 (erg cm-2 s-1), which is several times higher than the background. One can see that from 11 to 16 UT, the hot plasma precipitates mainly on the dayside (12 – 16 LT) while after 16 UT, the precipitations occur practically at all local times both on the day and night sides. The first FEE injection (F1) at ∼1250 UT was preceded by several geomagnetic pulses observed by GOES-12 from 1100 to 1230 UT. The pulses were not very prominent because, at that time, GOES-12 was located in the morning sector. One can see that some of pulses were accompanied by dayside auroral precipitations of the hot plasma. Note that POES satellites have 100 min orbital period and, hence, they can miss some of localized precipitations. On the other hand, when a jet hits the magnetopause, the magnetosheath plasma is not necessarily penetrating into the dayside magnetosphere and, hence, precipitating at high latitudes [Dmitriev and Suvorova, 2015]. Nevertheless, in Figure 11, we find two cases of geomagnetic pulses followed by intense dayside precipitations of the hot plasma at 1105 UT and 1144 UT. Energetic electrons take a certain time dT to drift from the inner radiation belt edge (at L-shell L1 = 1.2) to the heights of $\sim$900 km (L-shell L2 = 1.1$\sim$1.15):

$dT(s) = 6380 * (L1 - L2)/VDE$ (1)

where the ExB drift velocity is determined as

$VDE = 0.032 * L3 * E$, (2)

where L the average L-shell in the first approach and E is azimuthal electric field in mV/m. From equations (1) and (2), we estimate that the earthward drift of energetic electron across the magnetic field lines from L = 1.2 to L = 1.1 takes up to 40 min under local electric field of $\sim$5 mV/m. Note that E $\sim$ 5 mV/m was obtained in simulations of energetic electron injections at L < 1.3 [Selesnick et al., 2016].

In our case of non-storm conditions, it is hard to imagine that the strong azimuthal E can persist for so long time. Previously, simulations by Su et al. (2016) have showed that it is not necessary for electrons to be transported earthward all the way during a single injection. Hence, we can consider a multi-step radial transport produced by a number of short pulses of E. In this case, the drift from L=1.2 to L=1.1 requires two or more pulses of $\sim$10 min duration that is comparable with the duration of jet-related disturbances. The multi-step process is limited by the time, during which a particle stays in the region of injection. The >30 keV electrons have a long period of azimuthal drift and, thus, they can stay in the region for hours. In contrast, the >100 keV electrons with the azimuthal period of $\sim$6 h leave quickly the injection region and, thus, do not have enough time to penetrate to the forbidden zone. This effect can explain the absence of high-energy electrons in the FEE enhancements presented.

We can suggest that the first FEE injection required a long time ($\sim$hour and longer) and

several pulses of E in order to transport energetic electrons from undisturbed edge of the inner radiation belt to L$\sim$1.1. Then, >30 keV electrons populate L-shells from 1.15 to 1.1 that makes possible to transport electrons to 900 km heights for a short time of $\sim$10 min by one pulse of strong E. The latter pattern is applicable for the FEE injection F2 and subsequent others. As one can see in Figure 11, each FEE injection after 13 UT is preceded within <30 min by intense auroral precipitations of the hot plasma. The latter is accompanied with geomagnetic pulses produced by the interaction of jets with the magnetopause. It is important to remind that tenuous variations of the solar wind dynamic pressure could not produce the geomagnetic perturbations occurred during the interval considered. We associate the dayside precipitations at high latitudes with the effect of jets piercing the magnetopause. The jets provide penetration of hot plasma from the magnetosheath to the magnetosphere. Dmitriev and Suvorova (2015) have found that the average rate of jet-related penetration of the magnetosheath plasma into the magnetosphere is about 1029 particles per day. The penetrated hot ions move quickly (within a few minutes) along the magnetic field lines to high-latitude regions of the dayside ionosphere. We can estimate the flux of precipitating ions of $\sim$107 to 108 (cm2 s)-1 if we assume that particles precipitate on the dayside arc of 3° width at 70° latitude. This particle flux corresponds well to the energy fluxes of precipitating ions (>0.5 erg cm-2 s-1) measured by POES/TED at high latitudes (see Figure 11). Hence, the jet-related magnetosheath plasma can produce significant additional ionization and increase conductivity of the high-latitude ionosphere on the dayside. An enhancement of electric currents in the dayside ionosphere should induce an enhancement of the electric field on the nightside and especially in the predawn sector, where the conductivity is weak. The nightside electric field might penetrate from high to low latitudes and produce ExB drift of electrons from the inner radiation belt to lower heights."

(2.2) In Li et al (2017), which is mentioned above, they also state that the large electric field can only cause an L shell distortion of 0.01 and this process is energy-dependent. Please comment on it and the possibility that the electric field moves the electrons to L<1.2 in this case.

Reply:

We note that Li et al. indicated the L-shell distortion of 0.01 for the relativistic electrons but not for the low-energy of 30 keV. In this concern, they cited the studies by Selesnik et al (2016) and Su et al. (2016), where observations of electron injections below L = 2 were compared with simulations. According to Su et al., “the electric field does not have a significant impact for electrons with energy >400 keV in the inner belt” (on page 8520), and “an enhanced large-scale electric field can be responsible for injection of ∼100 keV electrons in the inner radiation belt” (on page 8521). Also, it is important that they emphasized that “it is thus not necessary for electrons to be transported all the way from the outer zone during a single injection.” Hence, as followed from this, the slot region is not necessary to be filled by enhancements (see Referee’s comment 1). Selesnik et al. investigated various models of electric fields in applicability for deeper injections at L<1.2. Their conclusion is “Injection to L<1.2 is demonstrated in both observations and simulations by the end of 23 June, but the simulated injection is smaller because the model Ec (electric field) was reduced to zero for L<1.17”.

The simulations showed that at L<1.3 during quiet condition, an average electric field is weak (∼0.4 mV/m), but for deep injections the field should be strong ∼5 mV/m. Hence, the simulation studies had to admit that strong electric fields could penetrate and cause deep injections at L<1.3, but mystery of a penetration mechanism was not disclosed.

We put attention that, in our “quiet” case the penetration electric field could not be generated in a storm/substorm process. What process could provoke such a strong electric field at L<1.3? The both studies pointed out that none of the existing models can accurately describe the penetration electric field and, hence, deep injections at L<1.2. Su et al. (2016) : “An accurate global electric field model is a necessary requirement in order to correctly capture the non-diffusive radial transport in the inner radiation belt.” Our paper presents new experimental results, which help to develop a new model. The new model should be a subject of another study.

Specific Comment 3

(3) In Table 1, the authors list a series of flux enhancement events observed by POES. The author should specify the criteria used to select those events, and show some detailed electron flux profile of those events, such as how long the enhancements last, specific L shell of each event or how many data points are included in each event. The reviewer also suggests to use more commonly used names for POES satellites such as POES-15/18. . .instead of P2/P5. . .

Reply:

In the revised Figure 2, the intensity and L-shells of enhancements are shown. In the revised manuscript, we specify the criteria more precisely:

“. . . the forbidden zone extends at L < 1.2 in the latitudinal range from -20° to +30° and in the longitudinal range from 0° to 260°E (or 100°W) that is beyond the South Atlantic anomaly (SAA). . . . Figure 1b shows the interval 12 - 24 UT, when fluxes of >30 keV quasi-trapped electrons in the forbidden zone increased by 3 orders of magnitude above a background of ∼102 (cm2 s sr)-1 and kept at the enhanced level for several hours. We have selected FEE enhancements with intensity >103 (cm2 s sr)-1. ”

We think that abbreviation P2, P5 etc. are more convenient for presentations in Figures and Tables. Moreover, we would keep the abbreviations, which we used in our previous papers.

Specific Comment 4

(4) Line 210-227: the authors intend to prove that each flux enhancement event is individual and not caused by any other event, for example, F2 is not caused by F1. However, this analysis is based on the presumption that the event is really transient. The authors should show some evidence to argue such as F1 could not have been enhanced 100 min before the observation of F1. Also, please explain why this is important. The reviewer does not find it very essential to the analysis later and suggests

to be more concise on this problem.

Reply:

In the original manuscript, we have already clarified this important issue: “Figure 1a shows the observations of the >30 keV electrons at 0 - 12 UT, before the enhancements occurred.”

In the revised manuscript we provide an additional explanation:

“At that time, the satellites passed the same regions but they did not detect any FEE enhancements.” The suggestion of multiple injections is important because several injections are accompanied by several jets. We find correspondence between the jets/pressure pulses and injections (Figure 11). Note that there were no substorm-associated injections in the present case.

Specific Comment 5

(5) Line 227: Please specify if these events are a subset of Suvorova (2017) event list. If so, the authors should make a clarification before stating that the characteristics agree with those in Suvorova (2017), otherwise it is misleading.

Reply:

This event (15 peaks in one day) is a subset (1%) of the total statistics of 2465 peaks at the equator within 530 days. Examples of storm and nonstorm enhancement events (including the interval of 1 - 3 August 2008) were presented in Figure 1 of the paper by Suvorova (2017). We mention it in Introduction of the revised manuscript:

“Note that this event is a subset (1%) of the total statistics collected by Suvorova (2017) during various conditions, from magnetic quite to extremely strong geomagnetic storms.” Generally speaking, an individual event could be different from the overall statistics regarding the location of injections (local time and longitude ranges), especially for such specific conditions. Indeed, this particular event occurred under very

quiet geomagnetic condition, while the vast majority of events with similar parameters, such as multiple peaks or long durations of >4 h and high peak intensity > 104 - 105 (cm2 s sr)-1 occurred mainly during storms/substorms. Nevertheless, the electron enhancements during the August 1, 2008 event are in well agreement with those found from statistics as we concluded in the original manuscript (lines 223 – 227), namely: “specific longitudinal and local time distributions of the enhancements indicate multiple injections during about 4.5 h in the sector of 0 - 6 LT, and the injection region was confined within 3 h of local time over central and eastern Pacific. In general, these characteristic of injections are in well agreement with those found from statistics (Suvorova, 2017).”

Specific Comment 6

(6) Figure 3: Since the authors show that L1 is not a preferable location for observations of the magnetic perturbations as compared to Themis, this figure is not necessary. The reviewer suggests to combine some of the information in Figure 3 into Figure 4 and be more concise on the text as well, in order to help the readers to focus on the important part, Themis observations.

Reply:

The Figure 3 is important at least because of the comment by Referee 2, who believes that variation in the solar wind dynamic pressure could cause these magnetospheric compressions. The Figure clearly demonstrates that variations are tenuous. Additionally, a discussion of the OMNI data is important due to its wide use.

Specific Comment 7

(7) Line 611: Please use explicit number of the latitude of throat aurora instead of “lower latitude” here. It is misleading because this study is talking about phenomena at L=1.2 (<30 deg in latitude), while the throat aurora in a series of Han et al papers is still located at >70 deg in latitude (or please correct this number).

Reply:

Thank you for the important comment. We revised the text accordingly:

“Sometimes, the dayside aurora penetrates to lower geomagnetic latitudes of ∼72° from the discrete aurora oval at geomagnetic latitude ∼76°, so-called throat aurora.”

Sincerely, Alla Suvorova

Please also note the supplement to this comment:
https://www.ann-geophys-discuss.net/angeo-2019-5/angeo-2019-5-AC1-supplement.pdf

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Interactive comment on Ann. Geophys. Discuss., https://doi.org/10.5194/angeo-2019-5, 2019.

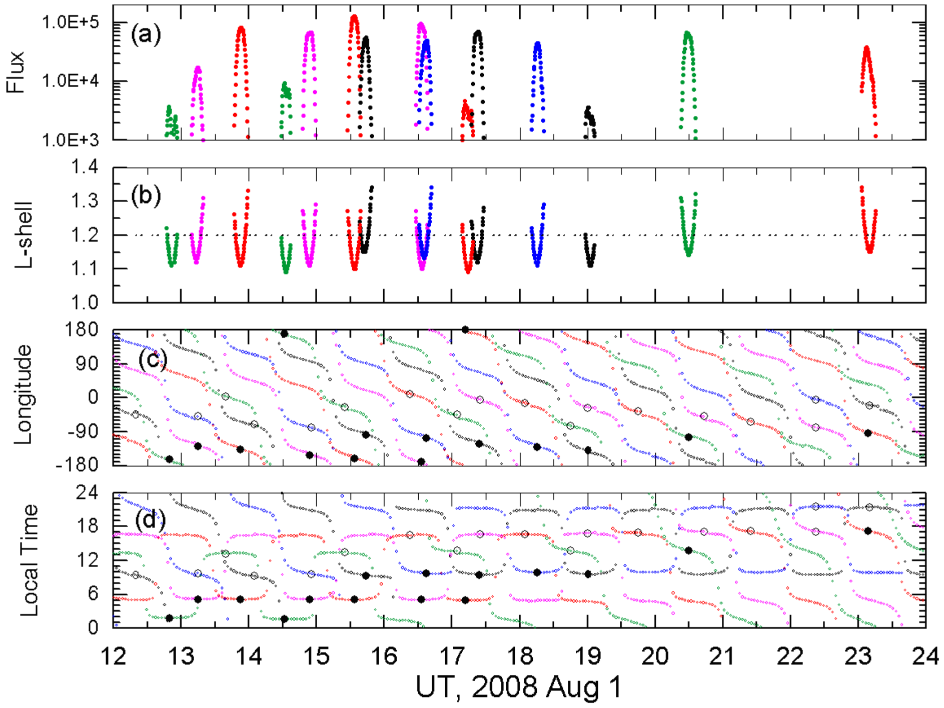

Fig. 1. Figure 2

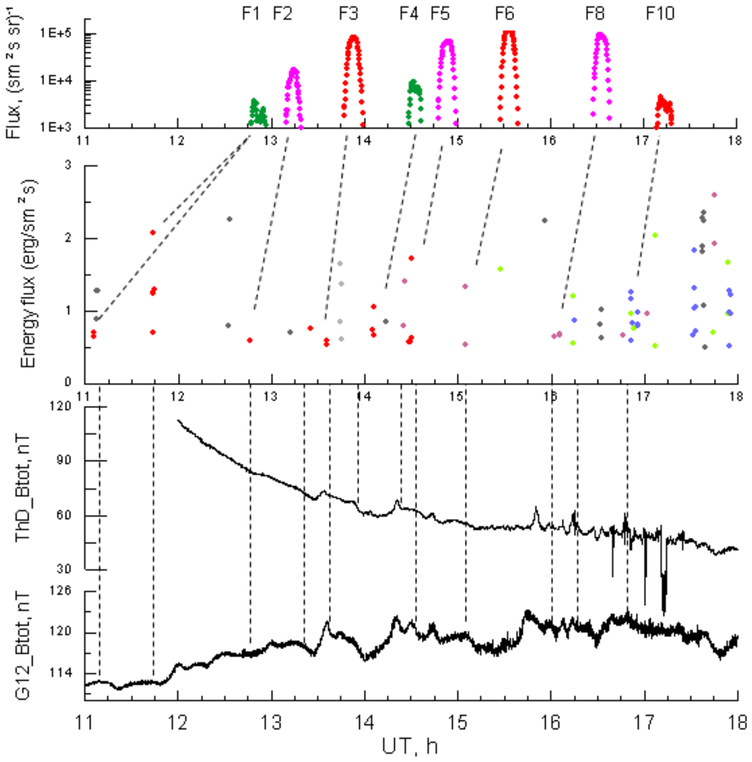

Fig. 2. Figure 11