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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.

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Dear Referee2,

Thank you very much for your comments and suggestions. We revised the Discussion and provided additional solid arguments and some quantitative estimations to support our suggestions.

General Comments by Referee2:

This paper reports energetic (>30 keV) electron flux enhancement at L<1.2 measured by the NOAA/POES satellites and relate it to the transient injection of magnetosheath

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plasma into the dayside magnetopause region, which is measured by the THEMIS satellite, and global geomagnetic pulses, which are measured by ground INTERMAGNET magnetometers and GOES satellites. The authors propose a scenario of possible association between these dayside magnetopause phenomena with the deep injection of >30keV electrons at L<1.2 by the penetration of localized electric field. The electron flux enhancement at L<1.2 is well described including its research history which is very interesting. Looking through this paper, however, I think the connection between the observed phenomena occurring in the dayside magnetosheath/magnetopause region and the electron flux enhancement at L<1.2 is weak and not well validated by the observations reported in this paper. These two phenomena occur in the same half day of 12-24 UT on August 1, 2008. But there is a significant possibility that they occur in the same day “by chance”. I think it is necessary to provide some more concrete evidence including some quantitative estimation that can explain the observed L<1.2 electron enhancement.

Reply:

We thank the reviewer for the suggestion which help to improve the manuscript. In the revised manuscript, we add some estimation on ExB drift. We provide additional arguments in favor to jet impact on the magnetosphere-ionosphere system. We present observations of hot plasma precipitations to the high-latitude ionosphere during the event in a new Figure 11. It was established that the jet impact results in magnetosheath particles precipitations at high latitudes near local noon.

In Discussion we add:

“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 ∼900 km (L-shell L2 = 1.1∼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 ∼5 mV/m. Note that E ∼ 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 ∼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 ∼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 (∼hour and longer) and several pulses of E in order to transport energetic electrons from undisturbed edge of the inner radiation belt to L∼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 ∼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 ∼107 to 108 (cm2 s)-1 if

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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."

Specific Comment 1

1. The descriptions of OMTI, THEMIS, GOES and ground magnetometers are fair and easy to understand, although they can be shorter. The authors propose a scenario that dayside magnetopause phenomena cause magnetosphere compression, and associated magnetosheath / magnetospheric plasma precipitation to the dayside ionosphere at high latitudes that result in a local increase of the ionospheric conductivity. This in turn promotes generation of transient localized electric fields, which are able to penetrate from high latitudes to very low latitudes to accelerate energetic electrons at L<1.2. However, in the nightside auroral zone we have normal aurora and associated ionospheric conductivity change which can be much larger than those in the dayside aurora. If the scenario proposed by the authors works, why we do not have L<1.2 acceleration during ordinary (non-storm time) substorms which occur almost every day and cause strong aurora and associated conductivity change in the nightside high latitudes? If L<1.2 electron flux enhancement does not occur during ordinary substorms, I think it indicates that the proposed scenario does not work in the actual magnetosphere.

Reply:

Indeed, a typical substorm produces an increase of conductivity on the nightside. In

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contrast, our scenario is proposed for the magnetic quiet (no substorm!) and it is based on the change of dayside conductivity, which should be larger then the nightside one. The scenario explains qualitatively the induction of electric field on the nightside.

It is true that not every substorm results in FEE enhancement. It means that substorm activity alone is insufficient for induction and penetration of electric field to low latitudes on the nightside. We also pointed out this important issue in Introduction of original manuscript [lines 137-146]. Namely, the FEE events account for only 8% of the total time from 1998 to 2016 (Suvorova, 2017). Most of FEE events are accompanied by substorm activity, but we have found “three dozen days without essential substorm activity”. Hence, it should be something else. Here, we totally agree with the Reviewer. It seems the factor controlling the occurrence of FEE enhancements might be different for storm-time and non-storm conditions. In the previous study, we have found that the illumination of the dayside auroral zone plays the key role, because its dependence on tilt angle explains perfectly the annual variation of FEE occurrence with a main maximum during the northern summer period, from May to September (see Figure 13 in Suvorova, 2017).

In order to clarify this important issue, we have revised the end of Introduction accordingly:

“External drivers from the solar wind should trigger some processes in the magnetosphere-ionosphere system that might result in the electron injections into the forbidden zone. However, the external drivers are necessary but often not sufficient for FEE enhancements to occur. If the auroral ionosphere is sunlit, then impact of external drivers more likely results in the electron injections into the forbidden zone. In this case, the factor of the dayside auroral ionosphere conductivity is sufficient, and it comes to the fore during weak geomagnetic activity. The relevant processes in the magnetosphere-ionosphere chain during magnetic quiet are still unclear.”

In order to clarify the role of the dayside conductivity in the auroral zone, we add Figure

11 (see above). As known, the initial response to the solar wind impact is particle precipitations to the high-latitude ionosphere at the dayside, particularly within the cusp region. For example, impact of high solar wind pressure under northern IMF Bz. It is a very common case to observe dayside aurora and intense particle precipitations in the cusp. Under non-substorm condition, intense dayside particle precipitations in sunlit auroral zone can provide a temporal condition for a higher conductivity at the dayside. In such condition, the electric field is induced in the nightside ionosphere (where the conductivity is relatively lower) and then the induced electric field might penetrate to low latitudes providing the earthward transport of particles. Hence the additional ionization of sunlit auroral zone is a very important condition in the proposed scenario. We have to remind that the mechanism of the electric field penetration is still unresolved problem of the magnetospheric physics.

Specific Comment 2

2. As shown in Figures 7 and 8 the THEMIS satellites shows repeating motion in and out from the magnetosphere to the magnetosheath. Such in and out features are very often seen when THEMIS is approaching to the magnetopause region, because the magnetopause location is not fixed and changes due to dynamic pressure change in the magnetosheath and/or surface waves caused by Kelvin-Helmholz instability in the magnetopause. In the present case, since compressional wave signatures are seen in GOES and ground magnetometers, it is likely that the dynamic pressure variation outside the magnetosphere is the cause of this motion of THEMIS in/out from the magnetosphere. But I think such compressional wave with an amplitude of a few nanotesla is not unusual and occur frequently. Then how often does the authors find L<1.2 electron acceleration? Is this a frequent phenomenon occurring associated with the frequently-occurring compression of the magnetosphere with the amplitude of a few nano-tesla on the ground magnetometers? How the authors can prove that these two phenomena occurs in the same time not by chance? Maybe the authors can check correspondence of timing between each magnetospheric compression and the elec-

tron flux enhancement at L<1.2.

Reply:

We have partially replied to this comment above (see Reply to General comment). Concerning to the magnetopause motion and magnetic variations in our case, the weak magnetic pulses do not affect the FEE enhancements. They are just signatures of jets impacting the magnetopause. In the scenario proposed, the key effect is the jet-related penetration of the magnetosheath plasma inside the magnetosphere and its precipitation to the dayside auroral ionosphere. Actually, only a small portion of jets ($\sim$10%) pierces the magnetopause. In the revised manuscript, we mention: “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].”

This is why not every magnetic pulse is followed by FEE enhancement. Considering Figure 11 in the revised manuscript, we demonstrate the direct relationship between jets, magnetosheath plasma penetration/precipitation and FEE injections.

Specific Comment 3

3. The authors show magnetic field pulses observed by GOES and ground magnetometers. If the penetrating electric field is propagating in the magnetosphere, it should be related to the observed magnetic field variations by the Maxwell’s equation of dB/dt = -rot E. One can argue that the observed magnetic field variation (dB/dt) can be used to estimate electric field by taking only one component of the rotation, e.g., dB/dt = dEx/dy (dEx = dB/dt * dy). The GOES magnetic field amplitude is _5 nT and the time scale was _500 s. If we take a localized scale size of dy = 1000 km, it gives the electric field intensity of 0.01 mV/m (=1000 x 10ËĘ3 x 5 x 10ËĘ-9 / 500). This value seems to be too small to cause the electron flux enhancement at L<1.2, because this value is two orders smaller than the prevailing electric field in the ionosphere by the thermospheric neutral wind through F-region dynamo. Thus, electric field associated with the

observed magnetospheric compression seems not to work for the present case.

Reply:

We agree that the magnetic filed pulses were too weak to provide the FEE injections. To make the text clear, 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.”

Specific Comment 4

4. In Figure 2b, I noticed that not only the electron flux at L<1.2, but also the electron flux at high latitudes above +-60 degree increases, particularly at negative longitudes in the norther hemisphere and positive longitudes in the southern hemisphere. Thus the electron acceleration seems to be not confined at L<1.2. Why the authors neglect this clear enhancement of electron flux about +-60 degrees? It is not clear whether the flux at middle latitudes increased or not in this color scale. If possible, it would be better to show the latitudinal profile of electron flux changes at some particular longitudes (e.g., at -120 degree) in a separated figure. Such figure may be useful to discuss how the electric field penetration suggested by the authors affect from high to low latitudes.

Reply:

We thank the Referee for the valuable comment. Concerning the mechanisms of radial transport, we wrote in Introduction [lines 55-61] that studies (e.g., Turner, 2015) showed that mechanisms of injections and dynamics of energetic electrons at low L-shells (inside the plasmasphere, L<4) are different from those at higher L-shells (outside the plasmasphere). Nevertheless, we have checked > 30 keV electron fluxes at high latitudes using data from both detectors measured precipitating and trapped populations of the outer radiation belt. We found that the fluxes of the radiation belt electrons increased after 16 UT. Note that increases of electron fluxes at high latitudes observed at low-earth's orbits are rather caused by pitch-angular scattering of trapped electrons into the loss cone due to wave activity rather than due to the effect of electric field.

From 12 to 16 UT the electron fluxes at high latitudes were not disturbed in contrast to FEE at low latitudes. Note that at middle latitudes, the satellites measured the background intensity of precipitating electrons from the inner radiation belt, while trapped population was observed in the SAA region (L<2). As seen in Figure 1 (a, b), the background fluxes in SAA were already high (several units of 105 (cm2 s sr)-1), and the fluxes of FEE were mostly less than 105 (cm2 s sr)-1. Hence, they produce a little increase in the flux at L<2.

At higher L-shells, the increase could be even less. Let assume that the induced electric field accelerates electrons in the radiation belt. In this case, the electrons should stay in the acceleration region for a certain time, which should be sufficient for effective acceleration. In Discussion we consider this situation for >100 keV electrons in the inner radiation belt:

"In contrast, the >100 keV electrons with the azimuthal period of ∼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."

Similarly at high latitudes, i.e. for the outer radiation belt (L-shells ∼ 4), we can find that ∼30 keV electrons have azimuthal period of ∼6 h and, thus, they leave quickly the acceleration region and gain not too much energy. So the flux increase (if any) is hard to be seen in the logarithmic scale. In the original manuscript we have already discussed how the electric field penetration affects from high to low latitudes. Namely, penetration of electric field is still a serious problem, and modern models can not provide strong electric field at L<1.3 in order to explain observation of deep injections (e.g., Su et al., 2016; Selesnick et al., 2016). In Introduction and Discussion [lines 122-128; 647-652] we emphasized that:

“and most of researchers consider and model an electric drift of electrons in the ExB fields, even though the electric field must be very high (e.g., Zhao and Li, 2013; Turner et al., 2015; Lejosne and Mozer, 2016; Selesnick et al., 2016; Su et al., 2016; Zhao et al., 2017a). There is no explanation for penetration of a strong electric field to such low L-shells. . . .. . . empirical electric field models are limited and do not provide the results below L$\sim$2 (e.g., Rowland and Wygant, 1998; Matsui et al., 2013). The most modern research suggests that the actual strength of penetration electric fields can be stronger than any existing electric field model at $L < 2$ (Su et al., 2016).”

“Another serious problem is the generation/penetration of electric fields in the inner magnetosphere, which is far from complete understanding. Numerical estimations show that the anomalous (fast) radial transport of particles observed in the inner magnetosphere can be produced by the electric field up to 5 mV/m (Selesnick et al., 2016; Suvorova et al., 2013). At the present time, there are no models predicting strong electric fields in the inner radiation belt and below.”

Specific Comment 5

5. Sorbo et al. (GRL, 2006) indicated the >30keV electron flux enhancement in the NOAA/POES data at the equator caused by precipitation of energetic neutral atoms (ENAs). Although their events are mainly during magnetic storms, we can expect some amount of ENA flux even during quiet times, because ring current is a persistent feature in the magnetosphere. Is there any possibility that the present L<1.2 electron flux enhancement is related to the ENAs from the magnetosphere? Sørbø, M., F. Søraas, K. Aarsnes, K. Oksavik, and D. S. Evans (2006), Latitude distribution of vertically precipitating energetic neutral atoms observed at low altitudes, Geophys. Res. Lett., 33, L06108, doi:10.1029/2005GL025240.

Reply:

The ENA mechanism cannot explain very strong (3 order of magnitude) enhancements of the count rate in the channel of >30 keV electrons, which was observed during magnetic quiet (!) in a wide range of latitudes (∼40 deg) and in a restricted range in longitudes. In particular, it is impossible to explain why almost whole Eastern hemisphere (longitudes from 0 to 160E) is free from ENA. We even do not see there a small-amplitude equatorial maximum of ENA from the quiet ring current. Hence, this is certainly not the ring current effect.

Technical Corrections

6. line 120-122: Please provide the values of the electric field suggested by these references.

Reply:

We add the following : "According to simulation results of Selesnick et al. (2016), the electric field of ∼5 mV/m can provide deep injections at L<1.3."

7. line 182 (kept at the enhanced level for several hours): Readers cannot understand how the authors obtain the information "several hours" from Figure 1b. Please explain.

Reply:

We add this information in the next paragraph: "Figure 2 and Table 1 present main characteristics of 15 FEE enhancements detected along equatorial passes of POES satellites (P2, P5, P6, P7, P8). The fluxes kept at the enhanced level for several hours. We analyze the peak fluxes in the FEE enhancements (time, local time, longitude, and L-shell)."

8. line 349-350 and line 462: I think we cannot exclude the possibility of solar wind dynamic pressure variations, since the OMNI solar wind dynamic pressure in Figure 3a shows small variations with time scales well less than 1 hour throughout the plotted interval.

Reply:

The OMNI data are obtained from measurements by the ACE and Wind upstream

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monitors. The ACE data were shown in Figure 8. The both datasets showed tenuous solar wind pressure variations of a few tenths of nPa around an average value 1.2 - 1.8. Figure 8 (b1, b2, b3) allow estimating the pressure variations more accurately (< 0.2 nPa). They cannot produce magnetic pulses with amplitude of ∼10 nT. We check the both data further and find fast ∼10% fluctuations of pressure with a quasi-period varying from ∼2 to 10 min. The timescale of the magnetic pulses is much longer, from 15 min to ∼1-1.5 h (Table 2). Hence, it is hard to connect fast pressure variations with the occasional magnetic pulses and shallow valleys presented in Figure 6. Moreover, small-scale fluctuations of the solar wind pressure could not produce intense precipitations observed in the cusp region (see Figure 11).

In the revised manuscript we add:

"Indeed, as one can see in Figures 1 and 8, 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."

9. lines 528-529: Why the authors focus only on night injections occurring occasionally from ∼1300 to ∼1700UT at 2-5 LT in Figure 2? There is a continuous injection at nearby 06 LT.

Reply:

We replace "night" to "nightside" to avoid misunderstanding. Actually the "continuous injection at nearby 06 LT" occurred at around 5 LT (see Table 1). We analyzed 8 peak fluxes on the nightside at 1.8, 1.6, 5.1, 5.0 and 4.9 LT. They were listed as F1-F6 and F8, F10 in Table 1.

We revised the text accordingly:

"With analysis of longitudinal and local time distributions of the enhancements we identified a series of nightside injections occurred in the sector of 2 - 5 LT during the period from ∼1300 to ∼1700 UT (Figure 2)."

10. Figure 3: I cannot see shaded box at 13-23 UT, which is mentioned in the figure caption.

Reply:

We correct the Figure 3.

Figure 11. Dynamics of the geomagnetic field and particles on 1 August 2008: (a) FEE enhancements, (b) plasma precipitation at high latitudes, and dayside magnetic field perturbations observed by (c) GOES-12 and (d) THEMIS-D. The numbers indicate the FEE injections at ∼2 and ∼5 LT (see Table 1), colors for POES satellite are the same as in Figure 2. Plasma precipitations are shown for the energy flux above the threshold of 0.5 (erg/sm2 s) and are grouped in LT: 23 – 24 LT (light gray), 0 – 2 LT (gray), 5 – 6 LT (blue), 12.5 - 15 LT (red points), 15 – 16 LT (violet), and 19.5 – 21.5 LT (green).

Sincerely,

Alla Suvorova

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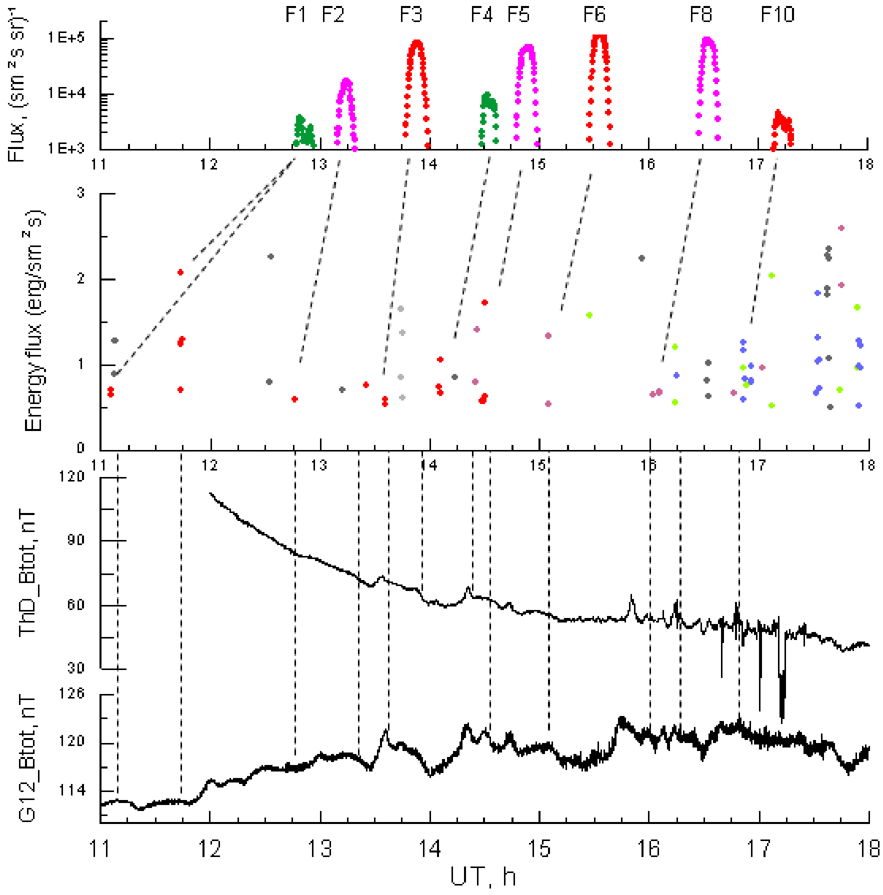

Fig. 1. Figure 11

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