ISSN 0040-2508

TELECOMMUNICATIONS AND RADIO ENGINEERING

Volume 75 Issue 9 2016

begell house, inc. publishers

TELECOMMUNICATIONS AND RADIO ENGINEERING

Volume 75, 2016 **Number 9**

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ELECTRON DENSITY VARIATIONS IN MIDDLE-LATITUDE IONOSPHERIC D-REGION DURING THE GEOMAGNETIC STORM OF NOVEMBER 7-11TH, 2004 DUE TO SUNRIZE TERMINATOR

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The partial reflection technique was applied to experimentally investigate how the electron concentration in the middle-latitude ionospheric D-region varied at the sunrise terminator during the geomagnetic storm of November 7-11th, 2004. It was revealed that the electron concentration increased by 450-700% both immediately during the sunrise terminator passage and after it. The explanation to such phenomenon is based on the hypothesis about terminator-enhanced electron precipitation from the magnetosphere.

KEY WORDS: *partial reflection technique, electron concentration variations, middle-latitude ionospheric D-region, sunrise terminator, geomagnetic storm*

1. INTRODUCTION

It is a well-known fact that the sunrise terminator is a powerful natural source of various disturbances in the Earth atmosphere and ionosphere [1–3]. Vast majority of the recent publications are dealing with wave disturbance parameters in the ionospheric *E* and *F* regions as well as with generation of atmospheric turbulence (see reviews in [2,3]), while the influence of the terminator on the parameters of the lower part of the atmosphere, i.e., the *D*-region, remains poorly explored due to the complexity of long-term continuous (hours and days) systematic measurements and their heavy expenses. Experimental investigations are rather episodic (see [4–6]). In the morning, due to a rocketing flow of solar radiation, the passage of the sunrise terminator (ST) is accompanied by specific physical processes occurring in the atmosphere. Their energy is high enough [6], thus, during and after a ST, some characteristic changes in the ionospheric plasma are quite expectable not only in the shadow and semi-shadow zones, but much outside, which, depending on the ionospheric, atmospheric and magnetospheric conditions, are at large recurring day after day, occasionally varied with new features evoked by concurrent factors (e.g. repeated and sporadic changes of geomagnetic and solar activity, solar bursts, geomagnetic storms etc). The understanding of such variations in the ionospheric plasma is crucial for applied problems of radio wave propagation, radio navigation, radio communication etc., for studying physical and chemical processes in the plasma, since there is still a gap in the knowledge about this region of the ionosphere.

In this paper, we will discuss the partial reflection technique and its experimental results as for the electron concentration variation in the middle-latitude D-region at the ST passage during the geomagnetic storm that took place on November 7–11th, 2004, as well as consider a possibility of ST-enhanced electron precipitation from magnetosphere.

2. PRACTICAL AND THEORETICAL BASIS OF MEASUREMENT AND DATA PROCESSING

The sounding in the D-region was performed with a partial reflection (PR) radar provided by the V.N. Karazin Kharkiv National university [7] and situated at the radio physics observatory of the Kharkov National university (geographical coordinates: $\varphi = 49.5^{o}$N, $\lambda = 36.3^{o}$E). The amplitudes of the combined PR signal and noise of the ordinary and extraordinary polarization A_{mo}, A_{mx} (indices o, x) after digitization with a frequency of 10 Hz and altitude step of 3 km have been recorded on a magnetic storage medium. In order to discriminate signal amplitudes A_o, A_x from noise every time before sending sounding pulse, two noise samplings A_{no}, A_{no} were made in the frequency band of 50 kHz. The values of A_{mo}, A_{mx} and A_{no}, A_{no} were measured within the altitude range of 60 through 126 km during the geomagnetic storm of November 7–11th, 2004. The observations were being performed on 08.11.2004: 01.41. – 14.30. LT, on 09.11.2004: 01.50. – 24.00. LT, on 10.11.2004: 00.00. – 24.00. LT, on 11.11.2004: 00.03. – 00.00. LT, on 12.11.2004: 14.07. – 00.00. LT, and on 13.11.2004: 00.07. – 00.00. LT. For comparison, similar measurements have been performed by using the PR technique under undisturbed conditions on November 03rd, 17th and 24th, 2004. 7-hour periods of recording have been processes and analyzed: from 05.00 to 12.00 LT (recording started appr. 1–1.5 hour before the ST passage in the D-domain and lasted several hours after it). The mean values of the PR signal strength $\langle A^2_{o,x}\rangle$ and of the noise $\langle A^2_{no,nx}\rangle$ have been estimated by a total of 60 samples within a 60 s interval. The statistical error never exceeded 10%. Experimental data on $\langle A^2_{o,x}\rangle$ at fixed altitudes with a step of $\Delta z = 3$ km were used to calculate the altitude-time profiles of the electron density $N(z,t)$ (z is the altitude in kilometers above the Earth surface, and t is the time) after the technique suggested in [8]. Profiles $N(z)$ were calculated at the averaging intervals of 10 min with an error below 30%. The altitude-time variations of $\langle A^2_{o,x}\rangle(z,t)$, $\langle A^2_{no,nx}\rangle(z,t)$ and $N(z,t)$ have been analyzed.

3. ON THE SPACE WEATHER

Before the geomagnetic storm, during November 3 – 6th, 2004, according to the data provided by http://www.sec.noaa.gov/, they registered smooth variations in the solar wind parameters. The measured values of concentration, velocity and temperature of solar wind particles were within the range (0.7–11) cm^{-3}, (320 – 460) m/s and (1.7–2.3). The value of a vector of the magnetic field density B was within (1.4–8.1) nT, and the field component B_z varied between –7 and 6.5 nT. The mean-diurnal proton flows of the energy above 1, 10 and 100 MeV were $(2–7)\cdot 10^4$, $(2–4)\cdot 10^3$ and $(3–4)\cdot 10^2$ $m^{-2}c^{-1}stere^{-1}$, respectively, and electrons whose energy exceeded 2 MeV – $(1–5)\cdot 10^5$ $m^{-2}s^{-1}stere^{-1}$. The index K_p took on values from 0 to 4, and the values of the geomagnetic activity index D_{st} changed from –24 through 2 nT. During the time span in question, two most powerful geomagnetic storms have been observed, with their main phases on November 8th and 10th, falling within the waning 23-th cycle of solar activity: the first storm began at about 18.00. LT on 07.11.2004 and lasted till about 16.00. LT on 08.11.2004; the second one began at 22.00. LT on 08.11.2004 and subsided at about 14.00. LT on 11.11. 2004. During this time, the index Kp grew up to 8–9. The increase was accompanied by essential geomagnetic field variations, while the index D_{st} dropped from –24 to –400. The storm energy was close to the ultimate one. The magnetic storm energy E_m can be conveniently estimated by the lowest value of the geomagnetic activity index $D_{st\min}$ from the expression $E_{\mathrm{m}} = \frac{3}{2} E_M \frac{D_{st}^*}{B_0}$, where $E_M \approx 8\cdot 10^{17}$ J is the energy of a dipole geomagnetic field near the ground, $B_0 = 3\cdot 10^{-5}$ T is a value of the geomagnetic field density at the equator; the corrected value is $D_{st}^* = D_{st} - bp^{1/2} + c$. Here $p = N_p m_p v_{sw}^2$, N_p and m_p is proton concentration and mass, v_{sw}^2 is solar wind velocity, $b = 5\cdot 10^5$ nT/(J $m^{-3})^{-1/2}$, $c = 20$ nT. The geomagnetic storm as estimated by the formula for E_m was $E_1 \approx 1.7\cdot 10^{16}$ J for the first storm (total power $P_1 \approx 5.4\cdot 10^{11}$ W) and $E_2 \approx 1.4\cdot 10^{16}$ J for the second one ($P_2 \approx 1.3\cdot 10^{12}$ W). From November 7th on, the proton and electron flows became 2-3 orders stronger. The GOES–8 satellite registered larger, against the pre-storm time, proton precipitation flows till November 17th and that of electrons (by the GOES–12 satellite) – till November 20-th. The key data characterizing the space weather during this period are presented in Fig. 1 (obtained from www.solar.sec.noaa.gov): *a* – changes in the geomagnetic activity index D_{st} (http://swdcdb.kugi.kyoto-u.ac.jp/dstdir/dst1/final.html; *b* – 5-minute average of proton flows of 10, 50 and 100 MeV (proton/$cm^2\cdot s\cdot st$), measured by the GOES–8 satellite (W75); *c* – electron flows of the energy over 2 MeV, measured by the GOES–12 satellite; *d* – 5-min average of the *H*–component of the geomagnetic field measured by the GOES–12 satellite; *e* – values of the planetary geomagnetic Kp index. During the second phase of the storm on November 10th, the solar wind particle density did not exceed 15 cm^{-3}, their velocity and temperature decreased to 600 km/s and $3\cdot 10^4$ K, respectively. Most part of the day the value of B_z

was negative with a local minimum. Index K_p reached its peak of 9 at 09.00 – 15.00 LT, after which it was gradually falling down to 4 at the end of the day. The values of index D_{st} had their local minimum of –297 nT at 14.00 LT, then they started growing, thus indicating the onset of storm build up. In the following days, the parameters restored their undisturbed values (Fig. 1). After November 11th the key parameters of the solar wind and geomagnetic field corresponded to the undisturbed conditions, according to data from http://www.sec.noaa.gov/ (see also Fig. 1). Geomagnetic storms were accompanied by a series of powerful optical (class (1–3)n and 3b) and x-ray (class M(2.3 – 8.9) and X 2.5) bursts. Most interesting and most powerful one is the X2.5 class x-ray burst (followed by an optical burst of class 3b) of November 10th at 04.04. – 04.10.(max) – 05.15. LT in proximity of the ST (sunrise at the altitude of 85 km was registered at about 06.02. LT). For comparison let us consider the variations $N(z,t)$, determined experimentally using the same equipment under undisturbed conditions on November 03rd, 17th and 24th 2004 and during two other less powerful storms on 30–31.05.2003 (the highest values of geomagnetic activity index Kp were ≈5) and on 17.09.2003 (Kp = 5–7).

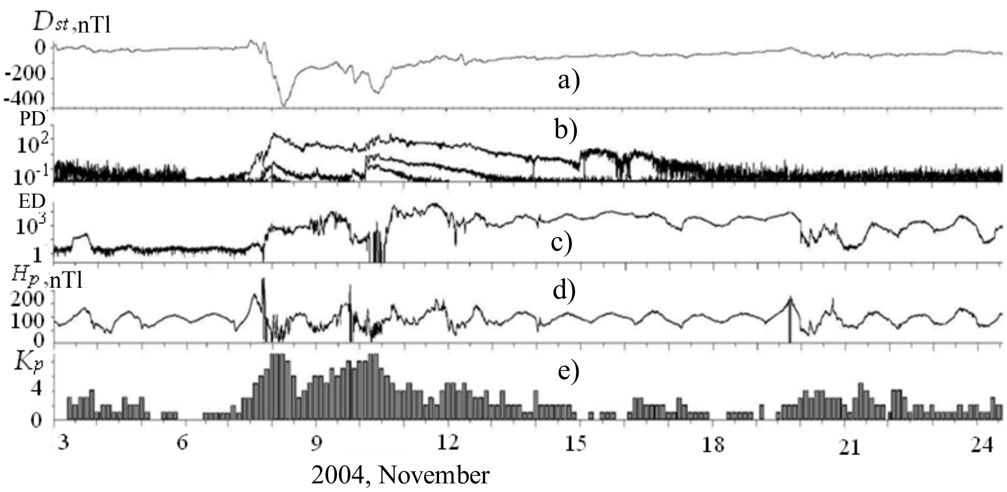

FIG. 1: Time records of the space weather during geomagnetic storms of November 07–12th, 2004

4. EXPERIMENTAL RESULTS

Figure 2 presents altitude-time variations of the electron concentration $N(z,t)$ during November 9 – 13th, 2004 (the curves correspond to the altitudes z: 1 – 78 km, 2 – 81 km, 3 – 84 km, and 4 – 87 km. The dashed region at the time axis marks the time of the x-ray burst X2.5. The arrows mark sunrise and sunset time at z = 85 km). Values of $N(z,t)$ were obtained for the altitude z = 78–87 km. Let us consider their main characteristics.

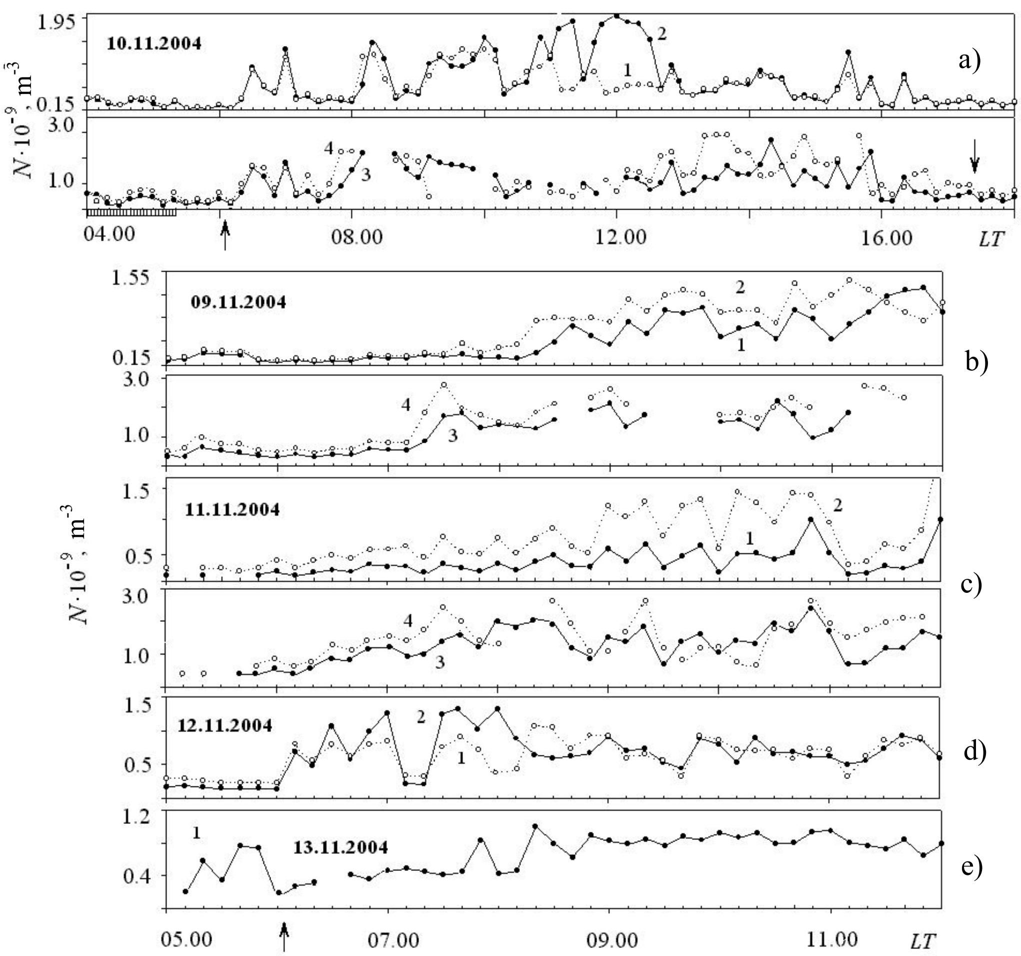

FIG. 2: Altitude-time variations of electron concentration at sunrise in the D-region during geomagnetic storms of November 09–13th, 2004

Figure 2(a) shows the variations of $N(z,t)$ on November 10th after the most powerful x-ray burst of class X2.5. It subsided 45–50 min before sunrise at the altitudes of the D-region (80–100 km). This means that during the burst this part of the ionospheric plasma was not sunlit yet and there was no direct solar irradiation there. Characteristic changes of $N(z,t)$ began 5–10 min after the terminator. The quasi-periodic growth of values N for 50–55 min was as high as 400 – 600%, and the peak disturbance amplitude N was 800–1600% at the altitudes of 78 and 81 km, and 450–550% at the altitudes of 84 and 87 km. It is worth noting that the quasi-periodic variations of N were observed in the same day through the whole observation period. During the experiments on November 9th, 11th and 13th there were no such variations of N registered, which is confirmed by the results from Figs. 2(b), 2(c) and 2(e). Here we noticed typical for the middle-latitude D-region variations of $N(z,t)$ at the time and after the terminator passage (smooth and quasi-periodic growth of values N in tens of minutes) [6]. In the experiment of November 12th the quasi-periodic variations of N in the lower part of the D-region began, as can be seen in Fig. 2(d), a few minutes after ST passage in the ionospheric region and lasted more than 180 minutes. PR signals were often registered at the altitudes of 78 km and higher (sometimes at 72 km and higher), which turned to be a specific feature of all the considered experiments, unlike measurements under undisturbed conditions at the same operating frequencies, with the measuring equipment being the same (this could be attributed to some characteristics of the middle-latitude D-region, namely, to quite small values of N at these altitudes). Possible reasons can be the growth of N and strong turbulization (and instability as well) of the ionospheric plasma in the D-region during the geomagnetic storm.

Figure 3 shows variations of $N(z,t)$ at the time of ST passage in the middle-latitude D-region before (November 03rd, 2004) and after (November 17th and 24th, 2004) of the storm in question. It can be clearly seen that the behavior of $N(z,t)$ on November 03rd and 24th is quite typical [5,6]. On November 17th, several minutes after the ST passage at the altitude of 84 km the value of N increased at an average of 100–200% (the peak disturbance amplitude N was about 400%), which lasted about 30 min together with the accompanying quasi-periodic variations.

5. NUMERIC RESULTS AND DISCUSSION

According to [6], in about 25% of all observed cases under undisturbed conditions the value of N was increased by 50 – 150% during the ST passage in the D-region or soon after it (in 30 – 60 minutes). In the experiment of November 17th, 2004 the growth of $N(z)$ was essential (~400%). Such behavior of $N(z)$ could be caused by precipitation of high-energy electrons from the Earth's radiation belt.

This hypothesis is supported by the fact that such precipitations can be observed during appr. 4–10 days after a storm [9,10]. An analysis of geophysical data (Fig. 1) reveals significant intensification of precipitated electron flows. It is well-known that radiation belts are more saturated with high-energy electrons during magnetic storms as they usually are. In this case a solar terminator is like a trigger initiating electron precipitation from the radiation belt. Such behavior of $N(z)$ can also be associated with disturbance propagation in space due to the terminator in the ionospheric plasma region preceding in time and space (latitude). In the experiment of November 13th the values of $N(z)$ before ST (Fig. 2e) in this region of ionosphere, in the lower D-region, were 200 – 400% higher as compared to the undisturbed conditions. Further on the behavior of $N(z)$ was the same as a typical undisturbed state. Like in the previous case, such behavior could be dictated by high-energy electrons precipitating from the Earth's radiation belt after a geomagnetic storm. The hypothesis is backed up by our observation of that day, when we on a periodical basis registered PR signals at the altitudes of 72–75 km and higher. While analyzing the variations of $N(z,t)$ during the two other storms (Fig. 4), we revealed that in one case, on September 17th, 2003, the variations in $N(z,t)$ in the D-region were quite typical, without noticeable changes during the terminator. In the other case, on May 31st, 2003, the value of $N(z,t)$ grew quasi-periodically for several hours, started 50 – 60 min before the ST passage. The maximum growth of $N(z)$ was 400 – 600%. It is worth noting that the increased N in the morning of November 10th after a powerful x-ray burst was several times higher than the increased $N(z)$ during other storms considered here, as well as than during the storm-free periods.

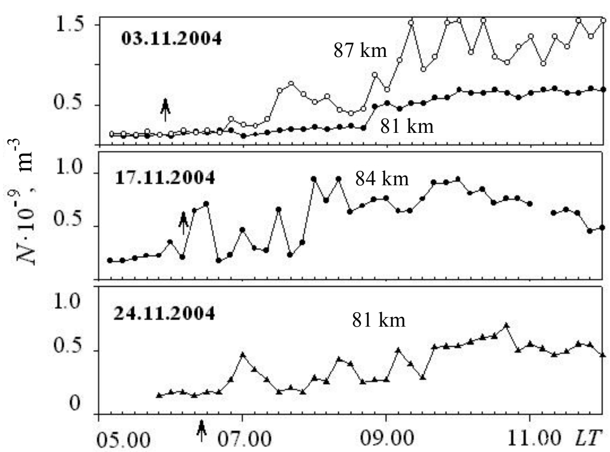

FIG. 3: Altitude-time variations of electron concentration during sunrise on November 03rd, 17th and 24th, 2004 in the middle-latitude ionospheric D-region. The arrows mark the time of sunrise and sunset at the altitude of 85 km

Thus, the main characteristics of variations of $N(z,t)$ in the middle-latitude D-region at the ST during a geomagnetic storm can be summarized as follows: 1) significant, as compared to undisturbed state, increase of N during the ST passage after a powerful x-ray burst: the value of N grew as high as 800–1700% at the altitudes of 78 and 81 km and 450–550% at the altitudes of 84 and 87 km; 2) values of N increased appr. 2–4 times during geomagnetic storms as compared to undisturbed conditions at the time of electron concentration variations typical for the terminator passage (when N increase lasts for tens of minutes).

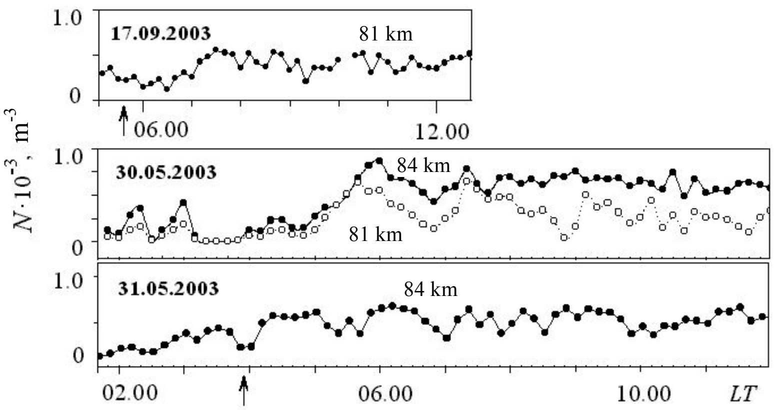

FIG. 4: Altitude-time variations of electron concentration at the sunrise during the geomagnetic storms of May 30th and 31st and September 17th, 2003 in the middle-latitude D-region. The arrows mark the sunrise and sunset time at the altitude of 85 km

Let us briefly discuss the processes occurring in the D-region during the terminator passage. The growth of N during and after the terminator passage can be caused by the following reasons: 1) ionization of NO molecules by the scattered radiation in the Lyman–α bands. In this case the variation of N is $\Delta N \leq 10^7 - 10^8$ m^{-3}, which gives no valid explanation to the observed growth of N; 2) ionization of molecules $O_2(^1\Delta_g)$ by scattered solar radiation at the wavelength of 102.7–111.8 nm. In this case the value of ΔN is $\leq 10^7$ m^{-3}, i.e., also too small; 3) motion of regions of steep atmospheric parameter gradients in the morning hours. In such a case the variation of N can be considerable, while the propagation rate of disturbances N in latitude is obviously not high enough to be responsible for the delays observed in the experiments; 4) interaction between the terminator and atmospheric inhomogeneities (this mechanism is rather inertial and can induce the registered disturbances of N with a big time delay of several tens or hundreds of minutes after the terminator passage. This mechanism requires a closer investigation); 5) radiation instability due to a large gradient of the radiation flow, which is a result of the flat-layered absorption coefficient; 6) increased Rayleigh-Taylor instability in the vicinity of the terminator; 7) a magnetoconjugate terminator inducing a photoelectron flow from the magnetoconjugate region; 8) ionization with high-energy electron flows. Taking into account the specific behavior of $N(z,t)$ discovered during the experiments, the most feasible reason among the listed above seems to be the electron flow escaping the radiation belt. The space weather data (Fig. 1) are in a good agreement with this hypothesis: during this time span, the flows of high-energy precipitating particles were several times higher than under undisturbed conditions. The role of the precipitation of middle-latitude charged particles from the magnetosphere has been widely discussed (for example [4–6]). There are no doubts left that, during geomagnetic storms and 5–14 days after them, electrons of the energy $\varepsilon \geq 40$ keV precipitating from the radiation belts induce additional ionization of the middle-latitude D-region up to the latitudes of 45–60^o (e.g. [4–6]). Another important ionization source at the middle latitudes are high-energy protons. The importance of the corpuscular ionization of the middle-latitude D-region has been proven experimentally (for example [4–6,10]). The contribution of electrons and protons into the ionospheric ionization at the altitude of 50–100 km at night and during disturbances of various kind, both natural and artificial, can be quite essential. Precipitation can be a result of pitch-angle redistribution of captured particles either because of distortions of the geomagnetic field lines or because of reduction of the "transverse" energy $\varepsilon_\perp$ of the particles. Moreover, during the onset and relaxation of disturbances of the ionospheric plasma conductivity tensor, the polarization field E_p has a vortex component E_r. Terminator passage can induce significant changes in the ionospheric plasma conductivity tensor and variations of the electric field components E_p and E_r, hence, of the component $\varepsilon_\perp$.

Let us now provide an estimation to the flow parameters in terms of the suggested mechanism of high-energy electron precipitation. By using the experimental values of $N(z,t)$ under undisturbed N_o and disturbed N conditions, estimate the ionization rate $q_o = \alpha_o N_0^2$ and $q = \alpha N^2$ (index "*0*" corresponds to undisturbed conditions). At the altitude $z > 75$ km in the D-region the parameter α varies approximately within the range from 10^{-11} to 2 10^{-13}m^{3}s^{-1} (further on assume that $\alpha \approx \alpha_o$ and neglect the atmospheric heating due to the electron precipitation). The density of the flow P_1 of the power P consisting of particles of the energy ε will be defined as $P_1 \approx 2\varepsilon_i \Delta z \Delta q = \varepsilon p$ ([4] as an example, where $\Delta q = q - q_o$, $\varepsilon_i \approx 35$ eV is the energy of one ionization event, Δz is the altitude range of an efficient absorption of the electron flow p with the given energy ε (while neglecting the energy distribution of precipitating electrons). The power P and energy E of electrons precipitating over the surface S for the time Δt can be estimated through the ratios $P = P_1 S$ and $E = P\Delta t$. The calculation was based on the analysis of PR signals and $N(z,t)$ under assumption that $S = 10^{14}$ m^2. The numerical results are given in Table 1. Here, Δz was assumed to be 10 km; the energy of precipitating electrons ε was > 40 keV. The found magnitude of the electron flows during "stormy" experiments was $p \approx (0.6 - 8.8)\cdot 10^9$ m^{-2} s^{-1}. The calculated magnitudes of electron flows based on the experimental data from November 10th, 2004 after a powerful x-ray burst proved to be several times higher than that for other periods. The numerical results agree well with the known data on electron flows, both measured experimentally and estimated during disturbances of various nature [4–6,9]. The density of electron flows and their energy characteristics, according to theoretical calculations [4], are high enough to be responsible for the observed boost of electron concentration at the altitude of 78–87 km.

TABLE 1: Electron flow parameters

Date	10.11.04		12.11.04	13.11.04	17.11.04	31.05.03
z, km	81	87	84	78	84	84
$N_0 \cdot 10^{-8}$, m^{-3}	1.3	4.5	2.5	1.8	1.8	1.5
$N \cdot 10^{-8}$, m^{-3}	10.5	20	14	7.6	7.6	6.5
$q_0 \cdot 10^{-6}$, m^{-3}s^{-1}	0.17	2,0	0.6	0.3	0.3	0.23
$q \cdot 10^{-6}$, m^{-3}s^{-1}	11	40	19.6	5.6	5.6	4.23
$\Delta q \cdot 10^{-6}$, m^{-3}s^{-1}	10.8	38	19	5.3	5.3	4.0
$P_l \cdot 10^{5}$, J m^{-2}s^{-1}	3.7	12.9	6.5	1.8	1.8	1.4
$p \cdot 10^{-9}$, m^{-2}s^{-1}	1.7	8.8	2.9	0.8	0.8	0.6
ε, MeV	0.15	0.1	0.15	0.15	0.15	0.15
$P \cdot 10^{-9}$, W	3.7	12.9	6.5	1.8	1.8	1.4
$E \cdot 10^{12}$, J	13	46	23	4.3	8.6	5.0
$\Delta t \cdot 10^{-3}$, s	3.6	3.6	3.6	2.4	4.8	3.6

6. CONCLUSIONS

1. In course of experiments, we revealed a significant, as compared to undisturbed conditions, rise of electron concentration during 50–60 min in the middle-latitude D-region occurring 5–10 min after the sunrise terminator passage and after the powerful x-ray burst: the maximum growth of N was about 800–1500% at the altitude of 78 and 81 km and 450–550% at the altitude of 84 and 87 km.

2. It was revealed that during geomagnetic storms values of N are approximately 2–4 times higher than those under undisturbed conditions, on the background of variations $N(z,t)$ typical for the terminator passage (when increase of N lasts for tens of minutes).

3. In terms of the theory of electron precipitation from the magnetosphere during geomagnetic storms, we used experimental data to estimate energy characteristics of charged particle flows and prove the feasibility of such notion as terminator-enhanced precipitation of electrons. The electron flow magnitude in the experiments performed during geomagnetic storms was $p \approx (0.6-8.8)\cdot 10^{9}$ m^{-2} s^{-1}. The electron flow magnitude estimated on the basis of experimental data from November 10th, 2004 after a powerful x-ray burst turned to be several times higher than that in other periods. The obtained flow values are in a good agreement with theoretical estimations and known experimental data on electron flows under disturbances of the various nature.

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