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APPLIED RADIO PHYSICS: SPACE, ATMOSPHERE AND EARTH SURFACE RESEARCH

VARIATIONS OF ELECTRON DENSITY IN THE MIDLATITUDE IONOSPHERE D-REGION DURING THE GEOMAGNETIC STORM IN DECEMBER 2006

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Variations of the electron density in the midlatitude ionosphere D-region were studied experimentally with the help of the partial reflection method during the geomagnetic storm in December 2006. Their comparison with the results obtained before and after the geomagnetic storm is performed under the non-excited conditions. The quasi-periodic growth of the electron density in the D-region is detected during tens of minutes by more than 50…100% with the periods of 30…60 minutes.

KEY WORDS: *electron density, geomagnetic storm, midlatitude ionosphere D-region, flux of charged particles.*

1. INTRODUCTION

It is known that geomagnetic storms (GMS), which are resulted from the non-stationary processes in the Sun, exert a serious influence on the state of space weather and dynamics of the subsurface ionospheric plasma. Parameters of each GMS are strongly dependent on the energy of non-stationary processes in the Sun and from the preceding to it state within the "Earth – Space" system in general. For that reason each GMS is a unique one and it is accompanied by a complex of events in the surface plasma. In addition to the common features, such events possess certain particularities that cause correspondent typical variations of the ionospheric parameters. Investigations of the GMS influence upon the surface plasma are actual due to their large scientific and applicable values. The commencement of GMS that occurs in a certain time after the solar flares is accompanied by the flares of the X-ray (XRA) and optical (FLA) ranges, as well as by precipitations of protons (SPE) and electrons into the Earth ionosphere. The above events last during the time periods from several tens of hours to 10 days and more depending upon the size of the GMS. The electrons precipitating from the radiation belts are an essential source of additional ionization of the midlatitude D-region up to the latitudes of $\sim 45\ldots60^{\circ}$ at the altitudes of $z \sim 80...100$ km. Moreover, during the period of solar flares and GMS the proton fluxes penetrate to the region of the altitudes of $z \sim 55–75$ km and may result in a substantial variation of ionization therein. The midlatitude D-region response to GMS is of a complex and ambiguous manner, and it is not studied well enough. It is stipulated by complex physical and chemical processes as well as by episodic nature of direct measurements with the help of the sounding rockets techniques and complications while applying the indirect remote techniques. Therefore, there exists a necessity in continuation of the experimental studies and accumulation of the information necessary for studying this issue. The present paper, which is a part of investigations (see, for example, [1–4]) performed in V. Karazin Kharkiv National University, provides the results of experimental research of variations of electron densities $N(z)$ in the midlatitude D-region using the method of partial reflections (PR) during a strong GMS in December 2006 and their comparison with the results obtained under the non-excited conditions before and after the GMS.

2. INFORMATION ABOUT THE EXPERIMENTS

Experimental researches were held at the V. Karazin Kharkiv National University Radio Physical Observatory near the city of Kharkiv with the help of a set of equipment [5] using the method of PR. Measurements of the PR signal amplitudes and radio noises were performed during the GMS in December 2006. The observations were carried out from 16.30 LT 05.12.2006 till 21.00 LT 22.12.2006 in the 24-hour cycles before, during and after GMS. It is an important particularity because the known in the references experimental studies are episodic. During the experiment there were recorded time and altitude dependences of the amplitudes of the mix of PR signal and radio noise $A_{so,x}(z,t)$ (t is the time, the indices “o” and “x” correspond to the standard and non-standard polarizations) from 22 altitude levels starting from 60 km after each $\Delta z = 3$ km. The measurements of $A_{so,x}(z,t)$ and $A_{no,x}(t)$ were performed in continuous sessions with the duration from single hours to tens of hours. To separate the PR signal amplitudes $A_{o,x}(z,t)$ there were also recorded the amplitudes of radio noise $A_{no,x}(t)$. Estimations of the average intensity values of the PR signal $<A^2_{x,o}>$ and noises $<A^2_{nx,no}>$ were executed upon 60 realizations for 60 s. The time and altitude dependences of $<A^2_{x,o}>(z,t)$ and $<A^2_{nx,no}>(t)$ were calculated. On the basis of the obtained

$<A^2_{x,o}>(z)$ their ratio R (the $R(z)$ profiles) used for obtaining the electron density $N(z)$ profiles was calculated under the technique [6] at the fixed altitudes with the step of $\triangle z = 3$ km upon the averaging intervals $\triangle t = 5$ and 10 minutes. The calculation error for the profiles $N(z)$ upon the averaging intervals of 10 or 5 minutes was not exceeding 30% and 50% correspondingly. Time and altitude dependences of variation of the obtained dependences of $<A^2_{x,o}>(z,t)$, $<A^2_{nx,no}>(t)$, and $N(z,t)$ were analyzed.

3. INFORMATION ABOUT THE SPACE WEATHER

The information about the space weather is provided in Fig. 1. The period concerned can be conditionally subdivided in three periods: 1) 05–12.12.2006; 2) 13–15.12.2006; 3) after 15.12.2006. We briefly characterize them on the basis of the geophysical data obtained at the global climatic data centers [http://www.sec.noaa.gov/, http://swdcwww.kugi.kyoto-u.ac.jp/dstdir/ index. html].

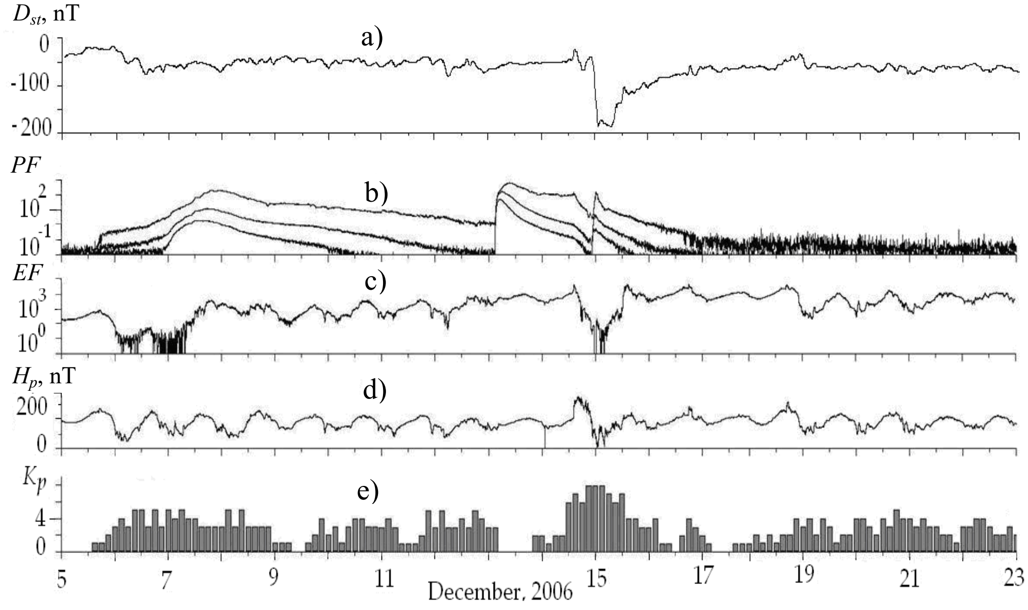

FIG. 1: Time-related data characterizing the space weather during the GMS in December 2006: (a) – variations of the index D_{st}; (b) – averaged for 5 minutes proton fluxes of 10, 50 and 100 MeV (proton/cm^2·s·average) measured from the GOES– satellite; (c) – electron fluxes with the energy > 2 MeV measured from the GOES–12 satellite; (d) – averaged for 5 minutes values of H– the geomagnetic field component upon the measurements at the GOES–12 satellite; (e) – values of the geomagnetic activity planetary index K_p

The following is typical for the first period: 1) the solar activity varied from very low at the beginning of the month and till December 5 the last date included, to high on December 6 as the result of three large solar flares (SF), which were realized in the visible part of the Sun in the region 930 (Table 1).

TABLE 1: Information about strong solar flares

Date	Time, LT	Type	Integral flux, Joule/m^2	Maximum radio emission flux, 245 MHz	Maximum radio emission flux, 2695 MHz
05.12.2006	12.28–12.38(max)–13.00	X9.0/2n	0.710	210000	12000
06.12.2006	10.02–10.23(max)–11.18	M6.0/sf	0.140	350	340
06.12.2006	20.29–20.47(max)–23.35	X6.5/3b	0.480	30000	5800
07.12.2006	20.41–21.03(max)–22.59	M2.0/1n	0.370	85	2600
13.12.2006	04.20–04.34(max)–08.18	X3.4/4b	0.510	100000	44000
14.12.2006	23.07–00.15(max)–00.21	X1.5/sf	0.120	99	620

On December 7 the solar activity decreased to the moderate after the flare M2.0/1n and then it remained very low till December 12, the latest date included; 2) the geomagnetic field varied from quiet on December 5 to slightly excited on December 6 (approximately from 06.00 UT on December 6 and till 11.00 UT on December 8). A small CMS was realized after the flare X9/2n. It is typical that during this weak GMS (Fig. 1(c)) the electron fluxes decreased by more than 2 orders, and thereafter the geomagnetic field remained quiet with some excited periods up to December 14; 3) the increase of the proton fluxes with the energies of ≥ 10 and 100 MeV was stipulated by the proton flare X9.0/2n on December 5. Electron fluxes with the energies of ≥ 2 MeV during 7–10 December were increased as compared with the non-excited ones. On December 6 and at the beginning of December 7 the fluxes of precipitating electrons were strongly fluctuating (Fig. 1(c)).

The following is typical for the second period: 1) on 13–15 December the solar activity increased to a high one due to the strong SF X3/4b in the visible region 930 of the Sun, which flare generated complex coronal mass ejections (CME) of the circumscribed halo type. On December 15 at 00.15 LT another strong proton flare X1.5 was realized in the region 930 of the Sun. It generated complex CME of the asymmetrical circumscribed halo type. Both flares were geo-effective; 2) variation of the geomagnetic field was essential during the period concerned: the values of the D_{st}-index decreased from -40 – -50 nT to -185 – -187 nT during several hours with subsequent gradual increase of the values to D_{st} = -95 – -105 nT. Variations of the H_p-component of the geomagnetic field were essential and exceeded 100 nT on 14–15 December; 3) a substantial increase of the proton fluxes with the energies of ≥ 10 MeV and ≥ 100 MeV (Fig. 1(b)) on December 13 was stipulated by the flare X3/4b. The flare SF X1.5 resulted in an additional burst of the proton fluxes on December 15 (Fig. 1(b)), after that, the fluxes decreased to the background ones on the above day. The electron fluxes with the energies of ≥ 2 MeV were increased during that period (Fig. 1(c)) and fluctuated strongly. The third period is a typically non-excited one. The following is typical for it: on 15–17 December the solar activity decreased to the low one and then – to the very low remaining very low up to the end of observations. There were no geo-effective events. The geomagnetic field varied in essentially. The proton fluxes at the orbits of the satellites were recorded at the level of the non-excited background values. The electron fluxes of different energies remained high (that is apparently typical for the after-storm period [7]) and increased as compared to the fluxes with the non-excited conditions. It is known that the index D_{st} determines the degree of the geomagnetic field excitation and, thus, the GMS intensity. During the period of GMS of 14–15 December the geomagnetic activity indices A_{pmax} and K_{pmax} amounted to 107 and 8 correspondingly. This GMS is referred to strong or very strong ones. The energy E_m and the power P_m of such GMS are equal to ~ 6.5 10^{15} Joule and ~ 7.5 10^{11} W correspondingly. The energy of the geomagnetic storm estimated under the techniques of [8], amounted at $D^{*}_{st\min} \approx 187$ nTl to the value of $\approx 5.7\ 10^{15}$ Joule, the maximum value of the power (on December 15) was $\approx 5.5\ 10^{11}$ W ($\Delta t = 3$ hr).

4. EXPERIMENTAL RESULTS AND DISCUSSION

We consider basic peculiarities of variations of $N(z,t)$ observed during the experiments under the non-excited conditions and during the GMS in December 2006. It is important that the experiments were also performed during the periods of passages of the sunrise and sunset solar terminators (the sunrise ST and the sunset ST). During the experiment of December 5 (the non-excited day: K_p= 0…2) there were determined no expressed particular features in the time and altitude variations of PR signals from the altitudes of z = 78…87 km and of the noises. They reflected a typical course of such characteristics for the non-excited conditions for that season of the year. The PR signal-to-noise ratio amounted to $s(z,t) = < A^2_{xo} > (z,t) / < A^2_{nx,no} > (t) \approx 1$. Variations of $N(z,t)$ corresponded to the typical values for the non-excited winter conditions (Fig. 2). On December 6 and 7 the index K_p increased up to 4…5. On December 6 a small GMS was realized. On that day the ratio s = 10–1000 within the altitude range of 72…90 km during the entire daytime period. It is typical that during the night time it is often s = 10–100 (Fig. 3).

On that day, the values of $N(z,t)$ in the D-region were increased as compared to the typical non-excited conditions. The daily course of $N(z,t)$ (dependence of $N(z,\chi)$ upon the zenith angle of the Sun χ) was observed explicitly.

It is also typical that during the night time (Fig. 2) there were marked substantial variations of $N(z,t)$, which had been absent during the preceding day. This behavior of the PR signals and $N(z,t)$ is related, the most probably, to the GMS. During the daytime on December 7 s = 10…100 within the range of 60…90 km (Fig. 3).

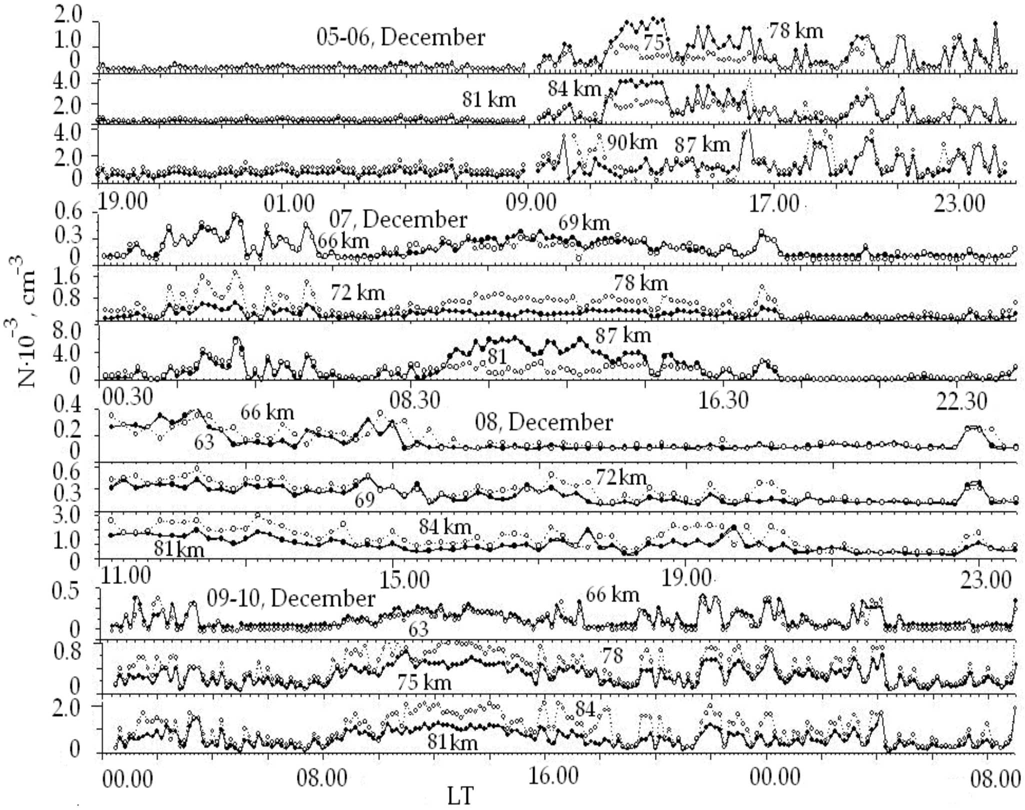

FIG. 2: Variations of the electron densities at fixed altitudes in the midlatitude ionosphere D-region from December 5 till December 10, 2006

It is typical that the intensive PR signals ($s = 10\ldots70$) were observed in the region of $z < 70$ km. Under the non-excited conditions PR signals with $s > 1$ are seldom recorded from $z < 70$ km in this point of observation that is stipulated by small values of N in this region. The PR signals with $s > 1\ldots10$ were recorded episodically almost within the entire D-region during the night time. The above facts witnessed that during that day ionization in the D-region was, apparently, partially controlled by the fluxes of precipitating protons (at least, at the altitudes lower than 80 km that was not a contradiction to the known provisions [9] from the physics and chemistry of the ionosphere), which, as it was noted above, were stipulated by the flare X9/2n and attained their maximum values on that day. Variations of $N(z,t)$ on December 7 are shown in Fig. 2. It is clearly seen that the values of $N(z,t)$ on that day (till approximately 18 hours LT) within the range of 63…84 km were increased as compared to the non-excited ones (during the night time of the first half of the day there occurred both an essential increase of $N(z,t)$, and quasi-periodic variations of $N(z,t)$ within the entire D-region. It is important that approximately the same variations of $N(z,t)$ occurred within the earlier hours during the night time of the previous day). In the D-region ionization was, apparently, partially controlled by the fluxes of precipitating protons. It is also noteworthy that during the night time in the second half of the day the values of $N(z,t)$ were at the level of the non-excited background values typical for that season of the year.

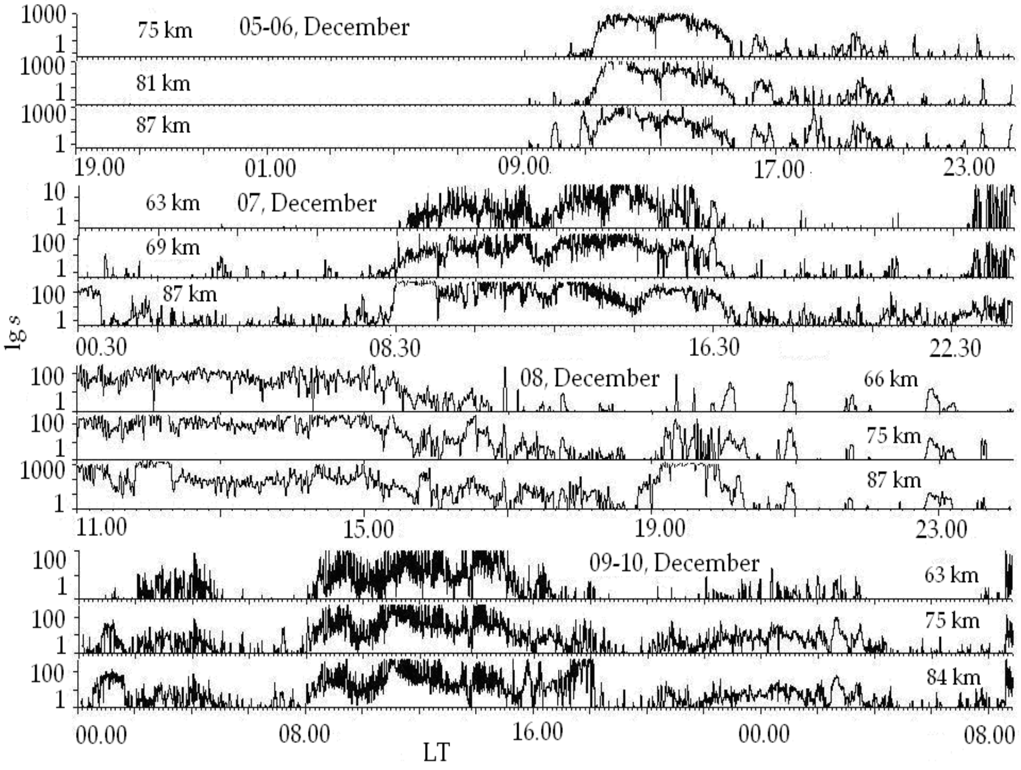

FIG. 3: Variations of the PR signal-to-noise ratio $s(z,t) = \langle A^2_{x,o} \rangle (z,t) / \langle A^2_{nx,no} \rangle (t)$ during the experiments performed on 5–10 December 2006

During the experiment of December 8 it was typical that after 20…120 minutes (for the altitude levels of 87…69 km) after the passage of the sunset ST intensive PR signals were recorded within 60…100 minutes and the values of s increased to $s = 10\ldots300$. We note that this behavior of s sometimes turns out to be typical for the midlatitude D-region ([4]). As it is evident in Fig. 2, during the above period of time the electron density increased at the altitudes of 81…87 km by 50…100%. Besides, at the night time $s = 10\ldots80$ episodically during 15 to 50 minutes. The dependence of $N(z,\chi)$ was traced clearly on that day. In general, during the night time in the second half of the day the values of $N(z,t)$ were at the level of the non-excited values typical for that season of the year. A short-term increase of the values of $N(z,t)$ at 22.35–23.00 LT (during that period of time $s = 10\ldots80$), is related apparently to a short-term precipitation of charged particles (the proton fluxes were still high). On 9–10 December $s = 10\ldots500$ at the altitudes of 63…87 km. During the night time before the sunrise and after the sunset $s = 1\ldots50$ within several hours (Fig. 3). During the above periods there occurred quasiperiodic variations of $N(z,t)$ with the amplitude of more than 100%, the period of $T \approx 40\ldots50$ minutes and the duration of 1…3 periods. It is typical that in the morning it would be $s < 1$ (i.e., the case when the PR signals were almost absent) in approximately 60…10 minutes before the moment of passage of the sunrise ST. In 120…40 minutes (63…87 km) after the passage of the sunrise ST $s >> 1$. During the period of the passage of the sunset ST and within tens of minutes after it the values of $s(z,t)$, same as during the previous day, decreased comparatively gradually to = 0.5…2. It is important that during the night time in tens or hundreds of minutes for the altitude levels of 87…63 km after the passage of the sunset ST, intensive PR signals (the values of s increased up to $s = 10\ldots50$) were recorded within 3…8 hours (approximately till 04.30 LT of December 10). This behavior of $s(z,t)$ is not typical for the observations in the midlatitude D-region, because, as a rule, during the night hours and under the non-excited conditions the electron density is much less than at the daytime and, therefore, the level of the PR signals is small as compared to the level of radio noise, which, as it is known, increase essentially during the night time. The most probable reason for such behavior of the PR signals on that day were, apparently, precipitations of highly energetic particles after the above-mentioned GMS, which could be initiated by the passage of the sunset ST (i.e., being the result of occurrence of the repeated interaction of the ionosphere-magnetosphere system in the middle latitudes). The fluxes of protons and electrons were still high on that day. During that period the electron density at 66…84 km increased by more than 50…150% (Fig. 2). Similar results were obtained in [3,4] and in other experiments. It was expressed an assumption [4] that such a substantial increase of N was the result of the particles precipitation from the magnetosphere during the passage of the terminator. According to the calculations [4,10], the electron fluxes with the densities of $p \sim 10^7\ldots10^8\ \mathrm{m^{-2}s^{-1}}$ are required to provide for the observed increase of N. Such values of p are not considered to be large. We note that same as in the previous experiments the dependence of $N(z,\chi)$ was observed clearly on that day.

In the experiment of December 14 intensive PR signals were recorded from $z = 69\ldots87$ km ($s = 1\ldots1000$) during the daytime. It is typical that PR signals disappeared (or were lower than the level of noises) in tens of minutes before or immediately after the passage of the sunset ST (Fig. 4). During the night time $s = 0.1\ldots1$, episodically $s = 1\ldots70$. Same as in the previous experiments, the dependence of $N(z,\chi)$ (for example, variation of $N(z,t)$ in Fig. 5) was observed clearly during the daytime. Burst increases of $N(z,t)$ with the duration of 10…30 minutes with the period of $T \approx 60$ minutes were recorded episodically during the night hours. The GMS development phase continued during those hours; all the geophysical parameters characterizing the state of the space weather were subject to substantial variations (Fig. 1). Probable reasons of such variations of $N(z,t)$ could be represented by precipitations of energetic protons and electrons. It cannot be excluded that those variations could be stipulated by the acoustic gravity waves (AGW), one of the reasons for development of which could be represented by substantial variations of the geomagnetic field.

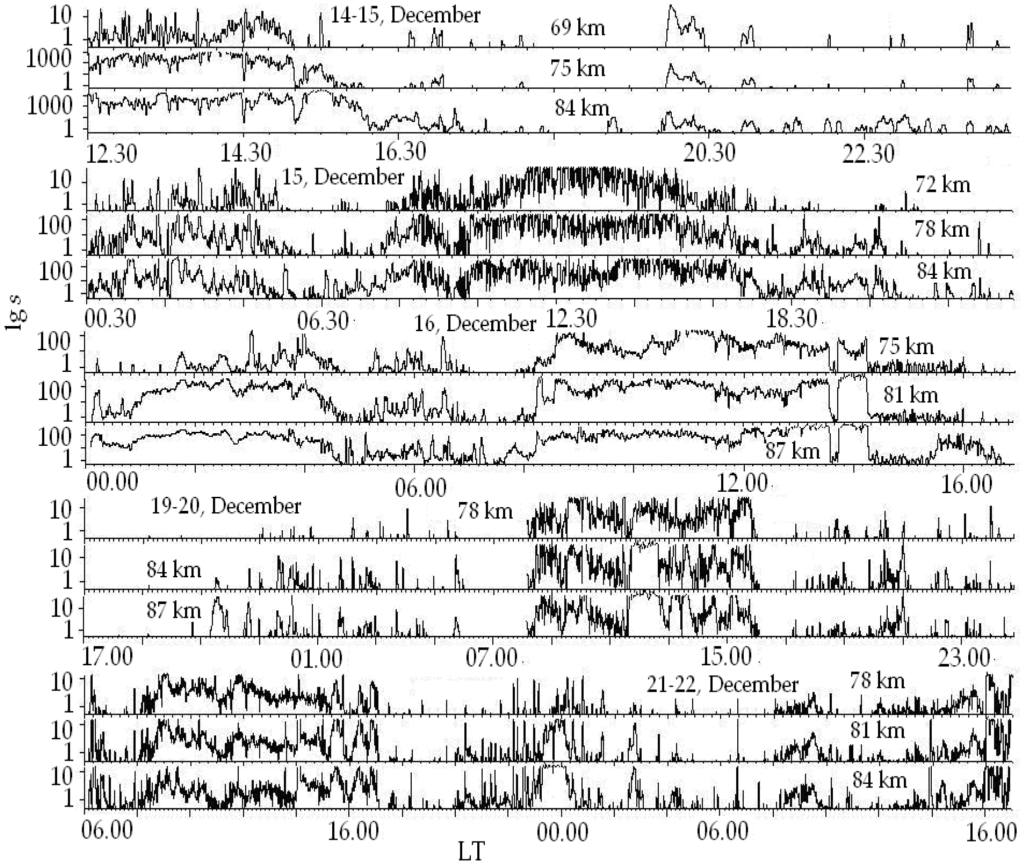

FIG. 4: Same as in Fig. 3 for 14–16 and 19–22 December 2006

The value of the quasiperiod, which is typical for the excitations provoked by the AGW, also speaks in favor of the above. At 23.00 LT launching of the Delta-2 space vehicle (SV) was performed from the Vandenberg launching site (in Florida, the distance to the place of observation was 9 330 km). SV of this type is referred to the medium-class SV (total weight – 230 tons; initial thrust – 360000 kgs; operation time of 1(0), 2(1), 3(2) and 4(3) stages – 64(0), 256(1), 444(2), 88(3) s; power of the engines – ~ 10^9–10^{10} W; energy release – ≥ 10^{12} Joule). After the launch of SV in

$\Delta t \sim 10$ (at the altitudes of 84…90 km) and 50 minutes (at 69…87 km) there were observed short-term burst increases of $N(z,t)$ by 50…150% with the duration of about 20…25 minutes. According to [6] the experimentally determined excitations of $N(z,t)$ in the midlatitude D-region in 10…15 minutes after the launch of SV can be related, based on the response delay time, to generation of the magneto hydro dynamic (MHD) excitations in the ionospheric plasma, which might result in pulsating precipitations of high-energy electrons by influencing upon the Earth radiation belts under certain conditions. The latter may cause, in their turn, the experimentally observed variations of $N(z,t)$ at large distances from the SV launching site. A similar mechanism was suggested previously for explaining the experimental results obtained during powerful remote earthquakes and strong thunderstorms (see, for example, [4]).

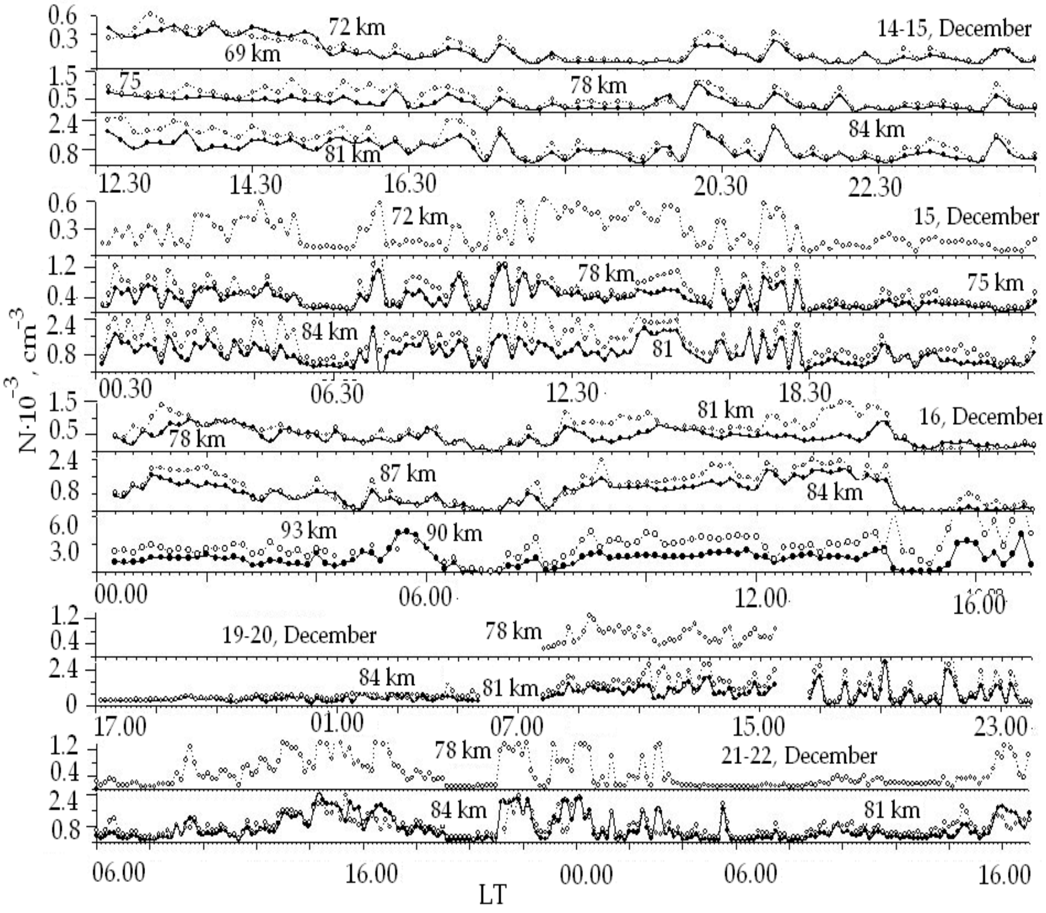

FIG. 5: Same as in Fig. 2 for 14–16 and 19–22 December 2006

The excitations of $N(z,t)$ in 45…50 minutes after the launch of SV, are apparently related to switching on of the correcting rocket engines. It is little probable that such significant excitations are related to propagation of the waves (AGW, in particular) in the lower ionosphere. It is more probable that those excitations of $N(z,t)$ are resulted from the pulsating fluxes of particles from the magnetosphere. These precipitation processes can be stipulated by switching on of the correcting rocket engines [4,10]. Estimations of the electron flux densities for the considered experiment for the altitude of 84 km provide for $p \approx 10^8$ m^{-2}s^{-1} that is not in contradiction to the calculations in [10] and to the results of the paper [4].

On December 15 during the night time before the sunrise, approximately before 05.20 LT (in the GMS maximum phase) intensive PR signals ($s = 1$–200, see Fig. 5) were recorded within the altitude interval of 72…87 km. During that period of time the electron density exceeded the non-excited background values by 2…4 times. It is typical, same as in the experiment of December 9, that in the morning within the altitude range of 72…81 km it is $s < 1$ (i.e., the case when the PR signals are almost absent) in approximately 40…20 minutes before the moment of the passage of the sunrise ST. At the altitudes of 84…87 km $s > 1$ in approximately 20 minutes before the passage of the sunrise ST and consequently $s >> 1$ after 08.10 LT during the entire daytime. During the daytime till approximately 12 hours, same as in the experiment of December 6, there were observed quasiperiodic variations of $N(z,t)$ with the period of $T \approx 60$ minutes and the amplitude of $> 100\%$. Probable reason for the above variations can be represented by precipitations of charged particles, however, the stimulation mechanism of the precipitations remains unclear. During approximately 4.5 hours after the passage of the sunset ST within the altitude interval of 75…87 km $s \approx 1 \ldots 50$ and the electron density is increased as compared with the non-excited conditions for that season of the year (variations of $N(z,t)$ possess, as it is shown in Fig. 5, the quasi-periodical mode with the period of $T \approx 40 \ldots 45$ minutes) that is not typical for observations in the middle latitudes [4,5,10]. It is most probable that such behavior of $s(z,t)$ and $N(z,t)$ on that day is stipulated by precipitations of charged particles from the magnetosphere after the GMS. Precipitations of electrons could be stimulated by the passage of the solar terminator. The electron fluxes, as it is evident from the data provided in Fig. 1, increased substantially and fluctuated; while the proton fluxes still remained rather high. It is important that the quasiperiodic variations of $N(z,t)$, as it is evident from Fig. 4, commenced in 60…70 minutes before the moment of the passage of the sunset ST. It is noteworthy that in the considered experiments typical variations of $s(z,t)$ and $N(z,t)$ during the passage of the sunset ST, commenced in tens of minutes before the moment of the sunset ST and continued during tens to hundreds of minutes after it. It is important that similar variations of $s(z,t)$ and $N(z,t)$ were observed previously both under the non-excited (lower value) and under the excited conditions [3,4]. As it is evident from Fig. 4, till the end of the day of December 15 $s(z,t) < 1$. During the experiment of December 16 at the night and morning hours $s(z,t)>>1$ almost up to the time of the passage of the sunrise ST. During that period the electron density was substantially increased as compared with the non-excited values typical for that season of the year. In approximately 20 minutes before the time of the passage of the sunrise ST and until 07.20. LT the electron density was at the level of the non-excited background values. After that it is commenced a typical daytime increase of the values of $N(z,t)$ with the clearly expressed dependence of $N(z,\chi)$. We also note the fact that typical decreasing of $s(z,t)$ and $N(z,t)$ commenced on that day in tens to hundreds of minutes before the time of the passage of the sunset ST, that is typical for this season of the year under the non-excited conditions [4].

The experiments of 19–22 December were held under the typical non-excited conditions. As it is evident from Fig. 1, the proton fluxes were almost absent during that time, and the electron fluxes still remained high. In the above experiments during the daytime it was $s = 1 \ldots 50$, the variations of $N(z,t)$ corresponded to the non-excited conditions typical for that season of the year. The dependence of $N(z,\chi)$ upon the zenith angle of the Sun (Fig. 5) was traced clearly. During the night time $s(z,t)<1$, $s = 1 \ldots 15$ episodically with the duration of 10…20 minutes (during those periods there were recorded the burst increases of $N(z,t)$ by 50…100%). On 21–22 December during the time interval of about 22.00 – 01.10 LT s = 1…50 and the values of N exceeded typical background values by approximately 1.5…3 times. Such variations of $N(z,t)$ were stipulated, apparently, by episodic precipitations of the electrons after GMS, the fluxes of which remained high as it was mentioned above. It was mentioned previously that the above phenomena are rather well known (see, for example, [4,10]). According to the techniques [10] and based on the experimental data about the variations of $N(z,t)$ we estimate the energy characteristics of the electron fluxes. The results of the calculations are provided in Table 2.

TABLE 2: Parameters of electron and proton fluxes

Date	*z*, km	Δ*T*, LT	*p*, $m^{-2}s^{-1}$	Assumed type of particles
06.12.2006	87	18.10. – 18.50.	2.5×10^8	electrons
07.12.2006	78	02.30. – 04.00.	0.5×10^8	protons
09.12.2006	81 84	03.00. – 03.40. 19.20. –19.50.	0.7×10^8 1.7×10^8	protons electrons
10.12.2006	81	03.40. – 04.20.	1.5×10^8	protons
14.12.2006	72	20.00. – 20.30.	0.9×10^8	protons
15.12.2006	78	17.10. – 17.50.	4.5×10^8	electrons
21.12.2006	84	21.00. – 22.20.	4.1×10^8	electrons

The results show that the observed variations of N in the lower ionosphere could be caused by the electron and proton fluxes with $p \sim 10^7$–10^9 $m^{-2}s^{-1}$. Such values of the fluxes are similar in their values with the values during the excitations having other nature, and they are not represented as large in the midlatitude ionosphere.

5. CONCLUSION

The following particularities are determined for variations of $N(z,t)$ during the considered observations under the non-excited conditions and during GMS:

1. On the non-excited days, time and altitude variations of the electron density corresponded to the typical non-excited conditions with the clearly expressed dependence of $N(z,\chi)$ on the zenith angle of the Sun.
2. On the days during GMS the dependence of $N(z,\chi)$ was traced clearly. At that, the values of $N(z)$ exceeded the correspondent values of $N(z)$ on the non-excited days. The increase of N observed in the period of GMS can be caused by ionization of the ionospheric plasma in the midlatitude D-region with the fluxes of charged particles precipitating from the magnetosphere.
3. The previously determined particularities [3,4] were reliably confirmed: the passages of the sunrise ST and the sunset ST during the periods of GMS were accompanied by quasiperiodic variations of $N(z,t)$ in almost all the experiments. Typical substantial variations of $s(z,t)$ and $N(z,t)$ in the period of the sunset ST commenced in tens of minutes before the moment of the sunset ST and continued during tens to hundreds of minutes thereafter; the periods of such variations were $T \approx 30\ldots40$ minutes; the value of excitations of $N(z,t)$ amounted to hundreds of percent. During the periods of GMS such variations were more expressed than on the non-excited days. On the excited days after the passage of the sunrise ST the typical increase of the values of $N(z,t)$ commenced in 10…50 minutes earlier than on the non-excited days.
4. During the night time in the period of GMS and during several days afterwards the increase of $N(z,t)$ by 50…150% and more with the duration from tens to hundreds of minutes was observed episodically. During the daytime on the excited days it was determined the availability of quasiperiodic variations of $N(z,t)$ with the period of $T \approx 60$ minutes and the amplitude of more than 100%.
5. The typical particularity consisting of the fact that during the period of GMS intensive PR signals ($s = 10\ldots70$) are observed within the altitude domain of $z < 72$ km, is determined and confirmed. Under the normal, non-excited conditions the PR signals with $s > 1$ are recorded quite seldom in the middle latitudes from the altitudes of <72 km that is stipulated by small values of N in the given domain of the altitudes. During that period of time the ionization was apparently controlled to a significant extent by the fluxes of precipitating

protons having rather high values. Estimations of the fluxes performed on the basis of the experimental data showed that the density of the fluxes of precipitating particles was sufficiently high and amounted to $p \sim 10^7 \ldots 10^8$ m^{-2} s^{-1}.

6. During the periods of GMS and in the experiments after the GMS, the PR signals with $s > 1 \ldots 10$ were recorded episodically almost within the entire D-region during the night time; and episodic and quasiperiodic variations of $N(z,t)$ up to the order of the value within tens to hundreds of minutes with $T \approx 40 \ldots 50$ minutes were observed. Apparently, such excitations of $N(z,t)$ are caused by the fluxes of precipitating charged particles. The estimates showed that the density of the fluxes of precipitating particles was $p \sim 10^8$ m^{-2} s^{-1}. The hypothesis of precipitation of charged particles into the midlatitude ionosphere is also supported by the fact that previously (see, for example, [4]) we repeatedly observed visually the typical – of the "polar lights" type – glow of the atmosphere with the duration of 20…60 minutes in the night hours during GMS (for example, in March and April 2001, in October 2003, in April, June and November 2004, in January and August 2005). The role of corpuscular ionization of the midlatitude D-region is confirmed experimentally (see, for example, [4] and the references therein): the electrons and protons may play an important role in ionization of the lower ionosphere at the altitudes of 50…100 km at night and during the periods of excitation having different nature of both natural and artificial kinds.

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