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STUDYING OF THE IONOSPHERIC D-REGION RESPONSE TO GEOMAGNETIC STORM SUDDEN COMMENCEMENTS USING THE METHOD OF PARTIAL REFLECTION

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Possible response of the ionospheric D-region to the geomagnetic storm sudden commencements at origination of the impact solar front during the Sun flares is studied experimentally using the method of partial reflection. It is determined that after a few hours since the geomagnetic storm sudden commencements electron concentration in the D-region is increased by 50…150% within tens of minutes. The hypothesis on precipitation of high-power electrons from the radiation belt is used to explain the above phenomenon; calculations of parameters of the flow of precipitating electrons are performed.

KEY WORDS: *method of partial reflection, electron concentration variations, mid-latitude ionospheric D-region, electron precipitation, geomagnetic storm sudden commencements*

1. INTRODUCTION

The number of events occurring in the Sun and exerting a significant influence on the near-Earth plasma is rather great. Most part of them requires a more detail investigation as it has been done before and known by now. A part of geomagnetic storm sudden commencements (*ssc*) and sudden impulses (*si*) cause a number of effects in geomagnetic pulsations, i.e., the oscillations $Pc1$, $P_{SC}1,2\text{-}5$ are excited and the mode of the oscillations $Pc1\text{-}3$ varies [1,2]. It is known that occurrence of the impact solar front (which phenomenon is accompanied, as a rule, by geomagnetic storm sudden commencements (*ssc*)), results at the initial moment in an enhancement of precipitation of magnetospheric loaded particles, which are rapidly mixed with the magnetospheric plasma propelling from the interplanetary space after the *ssc*. This solar plasma cloud becomes after some time the reason for the second phase of the geomagnetic storm, during which propagation of anomalous events of the ionospheric ionization to middle latitudes is possible. During the said time an essential role of the ionization source in middle latitudes is played by the high-power protons along with the electrons, which are primarily causing the ionization anomalies at the altitudes of $z < 100$ km [3].

The objective of the present paper is to perform an experimental study of the effect of the *ssc* events on the parameters of the mid-latitude ionospheric D-region using the method of partial reflection (PR) [4].

2. EQUIPMENT, METHODS OF MEASUREMENTS AND DATA PROCESSING

Probing of the D-region was performed with the help of the partial reflection radar of V. Karazin Kharkiv National University [5], which is installed in the Kharkiv National University Radio Physical Observatory (geographical coordinates: $\varphi = 49.5^{\circ}$N, $\lambda = 36.3^{\circ}$E). Amplitudes of the mix of the PR signal and noise of standard and non-standard polarizations A_{mo}, A_{mx} (the indices *o, x*) were recorded to the magnetic disk after digitizing with the frequency of up to 10 Hz and the altitude step of 3 km. To separate amplitudes of the signal A_o, A_x at the noisy background two noise samplings of A_{no}, A_{no} were taken within the 50 kHz frequency bandwidth before emission of each of the probing pulses. Measurements of A_{mo}, A_{mx} and A_{no}, A_{no} were performed within the range of altitudes from 60 to 111 km for different seasons of the year in middle latitudes near Kharkiv, Ukraine in the years 1990 to 2001. Duration of continuous measurements was not less than 5 to 8 hours. Total number of observations was 7. Information about the experiments and *ssc* events is provided in Table 1 (the information about the *ssc* events is obtained at worldwide data centers via internet – http://www.sec.noaa.gov/). For the purpose of comparison there were performed similar measurements under the non-disturbed conditions using the PR method.

Estimates of average values of intensities of the PR signal $\left\langle A_{o,x}^2 \right\rangle$ and noise $\left\langle A_{no,nx}^2 \right\rangle$ were curried out upon 60 realizations during the time interval of 60 s. Statistical error of the above estimates did not exceed 10%.

TABLE 1: Information about the experiments and the *ssc* events

No.	Date	Commencement time for *ssc*, UT	Time of taking measurements, UT
1	23.03.1995	10:37:00	01:22:00(23)-09:46:00(24)
2	02.12.1996	10:41:00	08:03:00-14:21:00
3	13.01.1999	10:54:00 (osi)	08:00:00-14:48:00
4	17.01.2001	16:31:00	03:45:00-21:09:00
5	22.03.2001	13:42:00	01:22:00-17:48:00
6	11.04.2001	13:42:00	09:20:00-23:39:00
7	17.04.2002	11:07:00	20:05:00(16.04)-21:00:00(17.04)

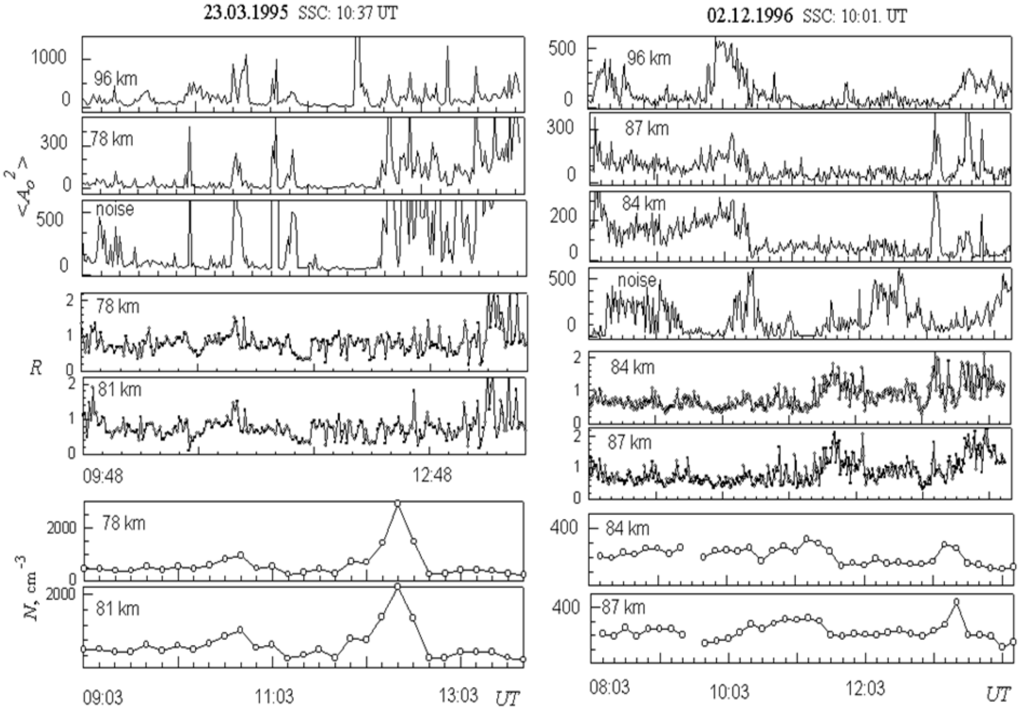
Based on the experimentally obtained data about $\left\langle A_{o,x}^2 \right\rangle$ at the fixed altitudes with the step of $\Delta z = 3$ km it was calculated the correlation $R(z,t) = \left\langle A_x^2 \right\rangle / \left\langle A_o^2 \right\rangle$, which was subsequently used for obtaining of the time and altitude electron density profiles $N(z,t)$ (z is the altitude over the surface of the Earth (in km), t is the time) under the methods of [6]. The profiles of $N(z)$ were calculated upon the averaging intervals of 10 minutes with the error, which was not exceeding 30%. Time and altitude variations of $\left\langle A_{o,x}^2 \right\rangle(z,t), \left\langle A_{no,nx}^2 \right\rangle(z,t)$, $R(z,t)$ and $N(z,t)$ were analyzed. For estimation of slow variations of $\left\langle A_{o,x}^2 \right\rangle$ or $N(z,t)$, it was used the fast Fourier transform algorithm for the time interval of 64 or 128 minutes.

3. EXPERIMENTAL RESULTS

As the typical examples we consider the response to the *ssc* events, which occurred on 23.03.1995 at 10:37 UT, 02.12.1996 at 10:01 UT, 17.01.2001 at 16:31 UT and 22.03.2001 at 13:42 UT.

Figures 1 and 2 provide the examples of time and altitude variations of $\left\langle A_o^2 \right\rangle(z,t)$, $R(z,t)$ and $N(z,t)$ obtained as the result of the experiments performed during the *ssc* events. We note some basic particularities of the D-region response to the above events. In the experiment held on 02.12.1996, an abrupt increase of radio wave absorption by several times with the duration of several hours was noted in the entire D-region approximately after 30…40 minutes since the *ssc* event. Average intensities of the PR signals $\left\langle A_{o,x}^2 \right\rangle(z,t)$ decreased by several times. Approximately after 3 hours almost in the entire D-region there are noted the quasi-periodic variations in $\left\langle A_{o,x}^2 \right\rangle(z,t)$ with the approximate period of T~20 minutes, at that $\left\langle A_{o,x}^2 \right\rangle(z,t)$ is increased by the values from several to tens of times. The radio noise intensities on both of the magnetic ion components of $\left\langle A_{no,x}^2 \right\rangle(z,t)$ started increasing by the values from several to tens of times almost immediately after the *ssc* event during about 30 minutes with subsequent decreasing to the previous values during about 20 minutes; after that there were observed quasi-periodic variations of $\left\langle A_{no,x}^2 \right\rangle(z,t)$ with the period of T~120 minutes.

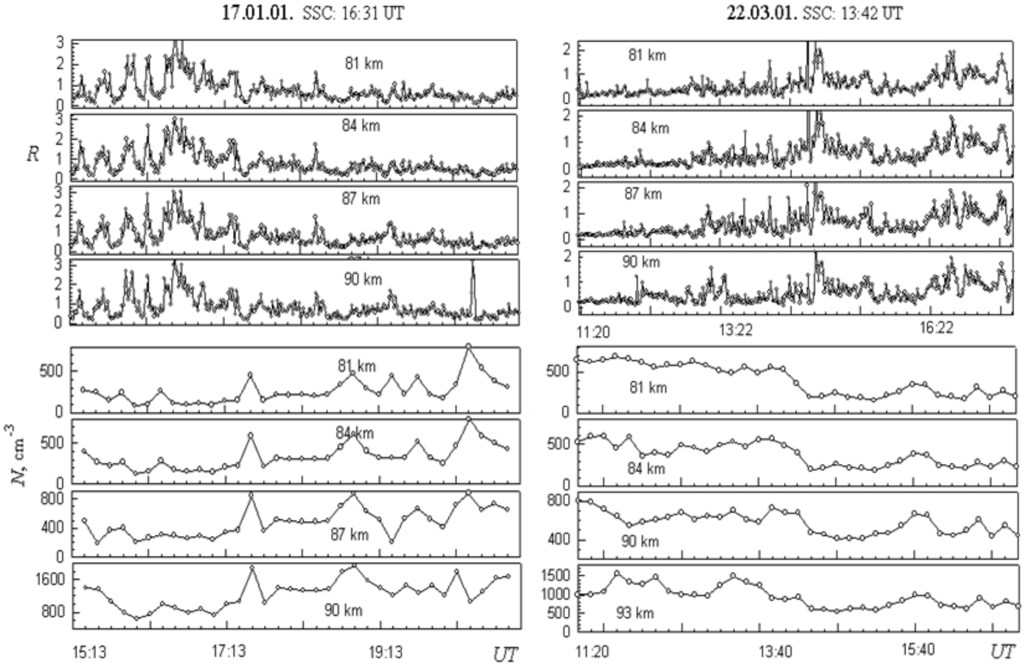
In the time and altitude course of $R(z,t)$ we admit increasing of the values of R by 50…70% within the period of time from 11:23 to 12:13 UT and a short-term (~15 minutes) decreasing of $R(z,t)$ by approximately 1.5…2 times after 180 minutes since the *ssc* event. In the time and altitude course of $N(z,t)$ after about 50…60 minutes it is observed an increase of $N(z)$ by ~50% during 15…25 minutes. After 180 minutes since the *ssc* event the $N(z,t)$ increased by ~100% during 20…25 minutes.



a) b)

FIG. 1: Time and altitude dependences of the radio noise, $\langle A_o^2 \rangle(t)$, and the intensity of PR signals, $\langle A_o^2 \rangle(z,t)$, their correlation $R(z,t) = \langle A_x^2 \rangle / \langle A_o^2 \rangle$ and the electron density, $N(z,t)$, during the *ssc* events of 23.03.1995 (the time of the *ssc* events was 10:37 UT) (a) and of 02.12.1996 (10:01 UT) (b)

In the experiment held on 23.03.1995 there occurred a short-term (of about 2 minutes) the electron precipitation after 6…7 minutes since the *ssc* event, which was revealed explicitly in the time and altitude behavior of $\langle A_{o,x}^2 \rangle(z,t)$ and $N(z,t)$. At that, at the altitudes of 78…93 km the electron density increased by up to 100% during 5 to 10 minutes. In the time and altitude course of $\langle A_{o,x}^2 \rangle(z,t)$ the quasi-periodic changes were observed during 60…70 minutes (the values of $\langle A_{o,x}^2 \rangle(z,t)$ varied by the values from several to tens of times), which correlated, primarily, with the radio noise. After about 100 minutes since the *ssc* event, the intensities of PR signals and radio noise increased by the values from several to tens of times, at that, the quasi-periodic changes were absent. In the time and altitude course of $R(z,t)$ there occurred a short-term (7 to 8 minutes) decreasing of the values of R by 80…100% after several minutes (6 to 7 minutes) and decreasing of $R(z,t)$ (~15 minutes) by 1.5…2 times after approximately 60 minutes since the *ssc* event (quasi-periodic variations of $\langle A_{o,x}^2 \rangle (z,t)$ were not observed after that). In the time and altitude course of $N(z,t)$ an increase of $N(z)$ by more than 100% was observed during the period of 30…40 minutes after 60…65 minutes since the *ssc* event.



a) b)

FIG. 2: Time and altitude correlations of $R(z,t) = \langle A_x^2 \rangle / \langle A_o^2 \rangle$ and electron densities, $N(z,t)$, during the *ssc* events of 23.03.1995 (the time of the *ssc* events was 10:37 UT) (a) and of 02.12.1996 (10:01 UT) (b)

During the experiment of 17.01.2001 it appeared to be typical a short-term (~10 minutes long) increasing of the electron density by approximately 1.5…2 times at the altitudes of 81 to 90 km after 60 minutes since the *ssc* event. After 130 minutes during about two hours there were observed quasi-periodic increases of $N(z,t)$ by more than 50…100% with the duration of 10 to 30 minutes. In the time and altitude course of $R(z,t)$ after the event we admit a gradual decreasing of the values by approximately 1.5…2 times, a short-term (10 to 12 minutes) decreasing of the values of R by 80…100% after 60 minutes and decreasing of $R(z,t)$ with the duration of ~20 minutes by 1.5 times after about 120 minutes since the *ssc* event (insignificant quasi-periodic variations of $\langle A_{o,x}^2 \rangle (z,t)$ were observed after that).

For the experiment curried out on 22.03.2001, in the time and altitude behavior of $R(z,t)$ it appeared to be typical decreasing of the values of R by 30…50% with the duration of 35 to 40 minutes after approximately 110 minutes since the *ssc* event with subsequent increasing by 1.5…2 times and quasi-harmonic variations. At the same time, in the time and altitude course of $N(z,t)$ there occurred an increase of the values of N by 50…60% within the period of 30 to 40 minutes. Decreasing of $N(z,t)$ after 13:40 to 14:00 UT, is stipulated, apparently, by the daily course and not related to *ssc.*

In the experiment of 17 April 2002 (Item No. 7 in Table 1) strong signals are periodically observed after 12:55 UT within the range of altitudes z = 72–78 km during 10 to 25 minutes (the signal-to-noise ratio is over 3). It should be noted that at the absence of disturbances, the partially reflected signals from the above altitude interval are not observed. Signals of that type are not detected with the help of our equipment or their levels are substantially lower than the noise levels. It is stipulated by the particular features of the lower mid-latitude ionosphere and, primarily, by small values of electron concentrations at such altitudes. It is important to note that during the above periods of disturbance the electron density in the ionospheric D-region increased by more than 100% (see dependence of $N(t)$ for several $z = constant$ in Fig. 3). At the same time, after about 12:00 UT, the satellite measurements by GOES-8 (W75) (http://solar.sec.noaa.gov/weekly/index.html) show a substantial increase of the proton flows having the powers of more than 1, 10, 30 and 100 MeV.

It should be noted that within the altitude range of $z = 81…90$ km variations of the electron density are revealed less explicitly because at such altitudes ionization occurs under the influence from the solar UV and X-ray radiation and it does not depend upon the protons. At that, the flows of electrons with the energies of more than 2 MeV, which were measured with the help of the GOES-8 (W75) satellite, precipitated from the Van Allen radiation belt after about 11:00 UT and resulted in the ionization peak at lower altitudes.

Expressly revealed typical particularities inherent to the above experiments were not revealed in any other of the remaining experiments considered by us.

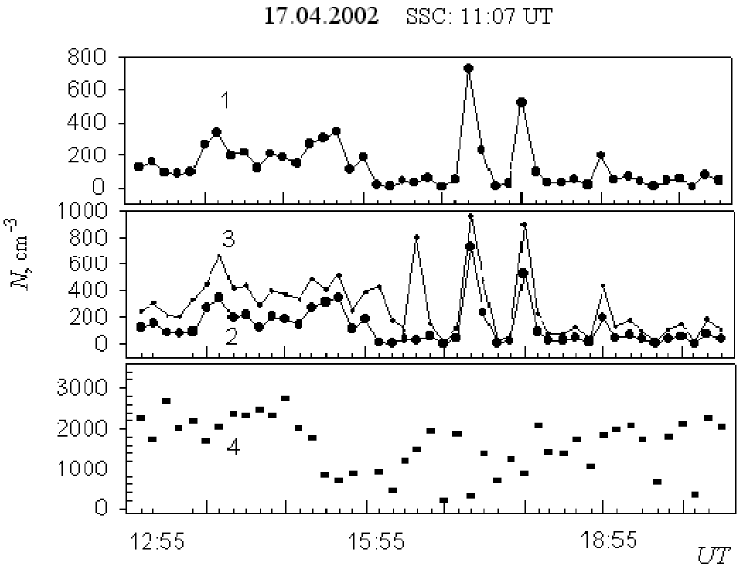


FIG. 3: Time variations of the electron density at various altitudes during the experiment held on 17.04.2002 (the curves correspond to: 1 – z = 72 km, 2 – z = 75 km, 3 – z = 78 km, 4 – z = 84 km)

4. CALCULATION RESULTS. DISCUSSION

Variations of average noise intensities and the intensity dispersion can be explained as follows. The noise in the frequency bandwidth of the order of 2…3 MHz represents by itself overlapping of the signals from the radio devices operating within the bandwidth concerned. As it is shown by the experimental results (calculations of $N(z,t)$) the *ssc* event is accompanied by the increase of the electron concentration and absorption of radio signals in the ionosphere upon substantial areas with the typical dimension L of several thousand kilometers. Increased absorption results in weakening of the interference received by both main lobe and the side lobes of the PR radar antenna system pattern consisting of orthogonal vertical rhombs. An adverse effect is revealed with decreasing of the values of $N(z,t)$.

To explain variations of average values of the PR signal intensity and the intensity dispersion we take into consideration the fact that (see, for example, [7]) $\left\langle A_{x,o}^2 \right\rangle \propto \dfrac{\overline{\Delta N^2}}{\Omega_\pm^2 + \nu^2} \exp\left\{-4K_{x,o}\right\}$, where $\overline{\Delta N^2}$ is the fluctuation intensity of N, $\Omega_\pm = \omega \pm \omega_L$, $\omega_L = 2\pi f_L, f_L = f_B \cos\alpha \approx 1.3\,\text{MHz}$, f_B is the gyro frequency of the electrons, α is the angle between the vertical and the vector of the geomagnetic field induction, ν is the frequency of impacts between the electrons and the neutrals, $K_{x,o}$ is the integral coefficient of absorption of the PR-signal with *x*- and *o*-polarizations.

The following processes occur after the *ssc* event: 1) variations (increasing and decreasing) of *N*, and, thus, of $K_{x,o}$ as well; 2) essential variations of $\overline{\Delta N^2}$ (it is possible at a high turbulence of the medium that may be resulted by, for instance, flows of precipitating loaded particles). Increasing and decreasing of $\left\langle A_{x,o}^2 \right\rangle$ can be completely explained by the above factors. Whereas the increase of dispersion of the signal intensities demonstrates the non-stationarity of the processes along with an incomplete 'deduction' of the noise.

Experimentally obtained variations of the ratio between the intensities *R* and their dispersion σ_R after the *ssc* event can be explained as follows. Considering that $R = \dfrac{\left\langle A_x^2 \right\rangle}{\left\langle A_o^2 \right\rangle} = \dfrac{\Omega_+^2 + \nu^2}{\Omega_-^2 + \nu^2} \exp\left\{-4\left(K_x - K_o\right)\right\}$ and $\Omega_+^2 >> \nu^2$, $\Omega_-^2 >> \nu^2$ in a substantial portion of the ionospheric D-region ($z \approx 75 \ldots 90$ km), then we can put down that $R \approx \dfrac{\Omega_+^2}{\Omega_-^2} \exp\left\{-4\left(K_x - K_0\right)\right\}$. In this condition $K_{x,o}$ increases with the increase of *N* that results in decreasing of R and, vice versa, with decreasing (recovering to the background values) of *N*, $K_{x,o}$ is decreasing and, thus, the value of R increases. The growth of σ_R is related to enhancement of the medium non-stationarity.

The extending of *N* observed after the above-mentioned time periods since the *ssc* event might be caused by ionization of the ionospheric plasma in the D-region with the flows of high-power electrons precipitating from the magnetosphere. Previously, the same technique was used to explain the results of experimental research described in the papers [3,8–12].

The probability of precipitation of the particles in middle latitudes has been discussed more than once (see, for example, [3,8–12]). The role of corpuscle ionization of the mid-latitude ionospheric D-region is confirmed experimentally (see, for example, [3,8–12]). The electrons and protons can play an essential role in ionization of the lower ionosphere at the altitudes of 50…100 km at night and during the periods of excitations of different nature – both of natural (solar flares, magnetic storms, thunderstorms, solar terminator, powerful earthquakes etc.) and man-made type (high-power explosions, rocket launches, operation of powerful heating stands within the radio frequency band, radiation by the high-voltage electric power transmission lines etc.).

Precipitation might occur resulting from redistribution of the trapped particles to the pitch corners, that might result either from deflection of the field power lines configuration (the geomagnetic traps), or from decreasing of the 'transversal' energy $\varepsilon_\perp$ of the loaded particles. Moreover, in the process of establishment and relaxation of excitations of the ionospheric plasma conductivity tensor, the polarization field E_p possesses also the vortex component E_r. During the passage of the terminator there might occur substantial variations of the ionospheric plasma conductivity tensor and variations of the electric field components E_p and E_r, and, therefore, of the components $\varepsilon_\perp$.

For the considered experimental data, let us estimate the flow parameters based on the mechanism of high-power electron precipitation from the radiation belt as it is done for the ionospheric sources of excitation of other kinds – rocket launches, magnetic storms, and heating of the ionosphere with the help of the powerful radio frequency radiation [3,8–13]. Upon the experimental values of $N(z,t)$ under the non-disturbed N_o and disturbed N conditions we estimate the rate of ionization $q_o = \alpha_o N_0^2$ and $q = \alpha N^2$ (the index *"0"* corresponds to the non-disturbed conditions). At the altitudes of $z > 75$ km in the ionospheric D-region, if the recombination of electrons with the ions of NO^+ and O_2^+ is considered as the basic one, α varies approximately from 10^{-11} to 2 10^{-13}m^{3}s^{-1} (further we shall assume that $\alpha \approx \alpha_o$, i.e., we neglect heating of the atmosphere at the electron precipitation). The flow density P_l of the power P of the particles with the energy ε we determine as (see, for example, [9]) $P_l \approx 2\varepsilon_i \Delta z \Delta q = \varepsilon p$, where $\Delta q = q - q_o$, $\varepsilon_i \approx 35$ eV is the energy of one ionization session, Δz is the altitude range of the efficient absorption of the flow p of electrons with the given energy ε (this expression is true if we neglect the distribution of precipitating electrons upon their energies). The power P and the energy E of the electrons precipitating over the area S at the precipitation duration Δt, can be estimated based on the correlations $P = P_1 S$ and $E = P\Delta t$. During the calculations based on the analysis of PR signals and $N(z,t)$ we assumed that $\Delta t = 1.2$ 10^3s and $S = 10^{14}$ m^2.

The results of calculations for the discussed experiments are provided in Table 2. For the convenience of calculation we accepted that $\Delta z = 10$ km; we also assumed that the energy of the precipitating electrons $\varepsilon > 40$ keV, that had been well substantiated (see, for example, [7,11,13]). The provided calculation results form a good match with the known data about the electron flows, which were experimentally obtained (or estimated) for excitations of different nature. The density of electron flows and their energy characteristics are matched well with the theoretical calculations from [7,9,14]; they can provide, to the full extent, for the observed increasing of the electronic density of N at 81…90 km.

Over a period of the experiment of 17.04.2002 (please, see earlier notes), it was recorded a sharp increase of the proton flows with the energies of more than 1, 10, 30 and 100 MeV. The said effects are revealed with the time delay of more than 30 minutes with regards to commencement of the solar protons precipitation event. If the solar corpuscles are propagated from the Sun to the Earth along a straight line, then their velocity would be equal to (5…6)·10^7 mps and their energies – to 20 MeV. The fact of increasing of N at the altitude of 72…75 km with the factor of 7 during the period from 13:45 till 14:15 and after 16:25 UT shows that the electron power is ~10–20 MeV, and the flow density is $p \approx 10^7$ m^{-2} s^{-1} (Table 2).

TABLE 2: Parameters of the precipitating particles flows

Date	**17.01.2001**	**22.03.2001**	**23.03.1995**	**02.12.1996**	**17.04.2002**
z, km	81	84	81	87	75
N_o, m^{-3}	$3.0\ 10^{8}$	$2.3\ 10^{8}$	$6.0\ 10^{8}$	$2.0\ 10^{8}$	$1.1\ 10^{8}$
N, m^{-3}	$6.0\ 10^{8}$	$4.2\ 10^{8}$	$2.0\ 10^{9}$	$4.1\ 10^{8}$	$3.0\ 10^{8}$
q_o, $m^{-3}s^{-1}$	$5.4\ 10^{4}$	$4.2\ 10^{4}$	$3.8\ 10^{6}$	$1.8\ 10^{5}$	$1.2\ 10^{5}$
q, $m^{-3}s^{-1}$	$2.2\ 10^{5}$	$1.4\ 10^{5}$	$4.2\ 10^{7}$	$7.63\ 10^{5}$	$9.0\ 10^{5}$
P_1, J $m^{-2}s^{-1}$	$5.7\ 10^{-7}$	$3.4\ 10^{-7}$	$1.5\ 10^{-6}$	$2.3\ 10^{-8}$	$2.6\ 10^{-6}$
p, $m^{-2}s^{-1}$	4.8 107	$2.8\ 10^{7}$	$6.7\ 10^{7}$	$4.0\ 10^{6}$	$0.9\ 10^{6}$
ε, MeV	0.08	0.08	0.15	0.04	20
P, W	$5.7\ 10^{7}$	$3.4\ 10^{7}$	$1.5\ 10^{8}$	$2.3\ 10^{6}$	$2.6\ 10^{8}$
E, J	$2.3\ 10^{12}$	$1.7\ 10^{12}$	$1.8\ 10^{11}$	$2.8\ 10^{9}$	$1.0\ 10^{13}$
Energetic species	Electrons	Electrons	Electrons	Electrons	Protons

5. CONCLUSIONS

1. It is experimentally discovered an increasing of the electron density by ~ 50…150% during the period of 10 to 40 minutes in the mid-latitude ionospheric D-region after 2…2.5 hours since the geomagnetic storm sudden commencements.
2. Within the framework of the hypothesis on the electrons precipitating from the magnetosphere there were performed the calculations and it was shown the possibility of the electron precipitation from the magnetosphere as the result of the geomagnetic storm sudden commencements.
3. The obtained estimates for the densities of the electron flows with the energy of 40 to 80 keV provided for their values of $10^{7}…10^{8}m^{-2}s^{-1}$.
4. It is experimentally detected increasing of the electron density in the lower mid-latitude ionospheric D-region (72–78 km) by 5…7 times during 10 to 15 minutes in the process of the proton precipitation after the *ssc* event. The densities of the proton flows with the energy of 20 MeV are estimated; their values amounted to $p \approx 10^{7}m^{-2}s^{-1}$.

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