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EXPERIMENTAL INVESTIGATIONS OF THE MIDDLE LATITUDE IONOSPHERIC D-REGION REACTION TO GEOMAGNETIC SUDDEN STORM COMMENCEMENTS

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Abstract. Using a partial reflection technique there was experimentally investigated possible reactions of the middle latitude ionospheric D-region to geomagnetic sudden storm commencements under The appearance of a solar shock front during flares on the Sun. The ionospheric D-region electron density was found to increase, for several hours after the geomagnetic sudden storm commencements, by 50-150% over several tens of minutes. In order to explain such a phenomenon, we have used a hypothesis of high-energy electrons precipitating from the radiation belts and have performed parameter calculations of the precipitating electron flow.

Key words: ionosphere, D-region, partial reflections, geomagnetic sudden storm commencements, high energy electron precipitation, proton.

1. Introduction

A number of phenomena arising from the Sun and having considerable effects on the near-Earth plasma are rather large. Most of them require such studies which should be more detailed than those known at present.

Some of the geomagnetic sudden storm commencements (*ssc*) and sudden impulse (*si*) cause a number of effects in the geomagnetic pulsations: oscillations $Pc1$ and $P_{SC}1$,2-5 being excited (Troitskaya et al. (1979)), a mode of oscillations $Pc1$-3 being charged (Gul'yel'mi and Troitskaya (1973)).

As is known, the solar front arising (which, as a rule, is accompained by the *ssc*) causes at the first moment the increase in precipitating magnetospheric charged particles which, after the *ssc*, are quickly mixed up with the magnetospheric plasma coming from the interplanetary space. This solar plasma cloud is after some time a cause of the second phase of the geomagnetic storm during which spreading of anomalous phenomena of the ionospheric ionization is possible down to the middle latitudes. Over this period, an important role as an ionization source in the middle latitudes is played by the high-energy protons together with the high-energy electrons which mainly cause ionization anomalies at $z < 100$ km (Knut and Vurzburger(1976)).

The purpose of this paper is the experimental investigation – by means of the technique of partial reflections (PR) (Belrose and Burke (1964), Belrose (1970)) - *ssc* effects on the parameters of middle latitude D-region of the ionosphere.

2. Equipment, methods of data measuring and processing

In order to sound the ionospheric D-region during the *ssc*-events, there was used a partial reflection (PR) radar (Tyrnov et al. 1994). The main parameters of the facility are as follows: the operating frequencies being $f = 2$-4 MHz, the duration of sounding pulses being $\tau = 25$ mcs with the repetition frequency $F = 1$-5 Hz, the radiated pulse power being $P_i = 150$ kw, the antenna gain coefficient being $G = 40$-150. Amplitudes of mixing PR signals and noise of the ordinary and extraordinary polarizations, A_{mo} , A_{mx} (indices o,x), were recorded on a magnetic carrier after digitizing with the frequency of 1 Hz. In order to separate signal amplitudes A_o , A_x , on the noise background before radiating each sounding pulse, there were carried out 2-6 noise samples of A_{no} A_{nx} .

The measurements of A_{mo} , A_{mx} and A_{no} A_{nx} noise were carried out within a height range of 60-111 km for different seasons in the middle latitude near Kharkiv City (Table 1) over 1990-2001. The duration of continuous measurements was 7-24 hours. The total number of observations is 7. The data on the experiments and *ssc*-events are given in Table 2.

Table 1. Coordinates of Kharkiv V. Karazin National University Radiophysical Observatory

	Geographic		Geomagnetic				
Elevation (m)	Latitude (N)	Longitude (E)	Latitude (N)	Longitude (E)	Inclination	Declination (W)	L
156	49° 38'	36° 20'	45.37°	118.7°	66° 36.8'	6° 19.6'	~2.0

Table 2. Data on experiments and *ssc*-events

N	Date	*ssc*-time, UT	PR measurement time, UT
1	23.03.1995	10:37:00	01:22:00(23.03)-09:46:00(24.03)
2	02.12.1996	10:41:00	08:03:00-14:21:00
3	13.01.1999	10:54:00	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	20:05:10(16.04)-21:00:00(17.04)

The data on the *ssc*-events have been obtained by using the Internet – ftp.ngdc.noaa.gov/STP/.

Estimating the average intensities of the PR signal $<A^2_{o,x}>$ and noise $<A^2_{no,nx}>$ was made using 60 realizations over the 60 sec period. The statistical error of estimations obtained did not exceed 10%. Using data on $<A^2_{o,x}>$ values, we have calculated their ratio, $R = <A^2_x> / <A^2_o>$, used further to obtain height-time electron density profiles, $N(z,t)$ (z is the height in km over the Earth surface, t is the time), in accordance with the differential absorption technique (Belrose 1964, 1970) using the methods of Gokov et al. (1990). When obtaining the $N(z)$ profiles, we use the model profile of the electron-molecule collision frequency, $\nu(z$, of Gurevich (1978) which was made more precise by according to Misyura et al. (1991) for different seasons.

The $N(z)$ profiles were calculated for the average intervals of 10 min over the whole observation period with an error not more than 30%.

For estimating slow variations of $<A^2_{o,x}>$ or $N(z,t)$, there was used an algorithm of the rapid Fourier transformation over the time interval of 64 or 128 min.

3. Experimental results

As characteristic examples, we shall consider the reaction to the *ssc*-events occurred on 23.03.1995 at 10:37 UT (No.1 in Table 2), 02.12.1996 at 10:01 UT (No.2), 17.01.2001 at 16:31 UT (No.4) and 22.03.2001 at 13:42 UT (No.5).

Figs. 1-2 show the height-time variations of $<A^2_o>(z,t), R(z,t)$ and $N(z,t)$, obtained in the experiments conducted during the *ssc*-events.

Note the main special features on the D-region response to the events. In the experiment conducted on 02.12.1996 (Fig. 1(b)), approximately 30-40 min after the *ssc*-event, we have observed a sharp increase by several times in the absorption of radio waves, lasting for several hours. The average PR signal intensities, $<A^2_{o,x}>(z,t)$, become smaller by several times. About 3 hours later, practically over the whole D-region, there are observed quasi-periodic changes in $<A^2_{o,x}>(z,t)$ with their approximate period of $T \sim 20$ min, $<A^2_{o,x}>(z,t)$ becoming units-tens larger. Almost immediately after the *ssc*-event, the radio noise intensities on both magnetoionic components of $<A^2_{n\,o,x}>(t)$ started becoming units-tens larger over the 30 min period with the following decrease down to nearly the previous values within 20 min; after that there were observed quasi-periodic changes in $<A^2_{n\,o,x}>(t)$ with the approximate period of $T \approx 120$ min.

In the height-time *R(z,t)* variation, one notes an increase in the *R* values by 50-80% within 11:23-12:13 UT and short-time (~15 min) oscillation of *R(z,t)* 1.5-2 smaller 180 min after the *ssc*.

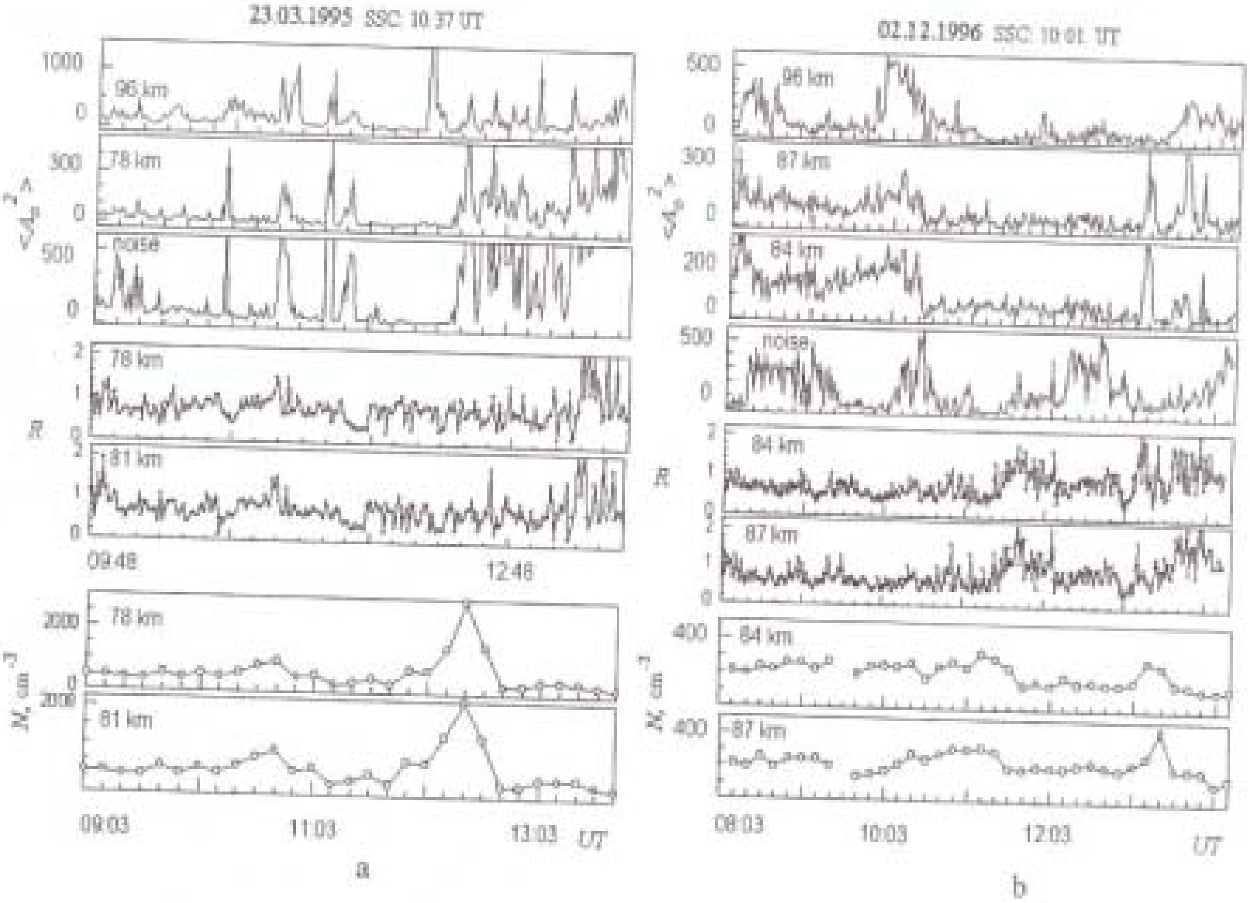

Fig. 1. Height-temporal dependences of radio noise, $\langle A_o^2 \rangle(t)$, and partial reflection signal intensities, $\langle A_o^2 \rangle(z,t)$, their ratio $R(z,t) = \langle A_x^2 \rangle / \langle A_o^2 \rangle$ and electron density, *N(z,t)*, during the *ssc*-events 23.03.1995 (the *ssc*-event time is 10:37 UT) (a) and 02.12.1996 (10:01 UT) (b).

In the height-time *N(z,t)* variation, 50-60 min later one observes an increase in *N(z)* by ~50% within 15-25 min. 180 min after the *ssc*, the *N(z,t)* value increased by ~100% within 20-25 min.

In the experiment of 23.03.1995 (Fig.1(a)), 6-7 min after the *ssc*, there occurred a short-time (about 2 min) electron participation, which clearly manifested itself in the height-time dependences of $\langle A_{o,x}^2 \rangle(z,t)$ and *N(z,t)*. At the same time, the electron density increased by 50-100% within 5-10 min.

In the height-time $\langle A_{o,x}^2 \rangle(z,t)$ variation, within about 60-70 min there were observed quasi-periodic changes (the $\langle A_{o,x}^2 \rangle(z,t)$ values changed from units to tens of the magnitude) which mainly correlate to the radio noise. About 100 min after the *ssc*, the PR signals and radio noise intensities became units-tens larger, and quasi-periodic changes were not observed.

In the height-time *R(z,t)* variation, note a short-time (7-8 min) decrease in the *R* values by 80-100% within several minutes (6-7 min) and *R(z,t)* becoming (~15 min) 1.5-2 times smaller about 60 min after the *ssc* (after that, quasi-periodic changes in $\langle A_{o,x}^2 \rangle(z,t)$ were not observed).

In the height-time *N(z,t)* variation, about 60-65 min after the *ssc* we observed *N(z)* increase by more than 100% during 30-40 min.

In the experiment of 17.01.2001 (Fig.2(a)), there was observed a characteristic short-time (about 10 min) increasing (1.5-2 times) in the electron density values at 81-90 km, 60 min after the *ssc*.

Then, 130 min later, over about 2 hours we observed quasi-periodic $N(z)$ increasings, with their duration of 10-30 min, by more than 50-100%. In the height-time $R(z,t)$ variation, after the event we note a smooth increase 1.5-2 times in the value, a short-time (10-12 min) decrease in the R values by 80-100%, 60 min after, whith the $R(z,t)$ value becoming (over about 20 min) 1.5 times smaller about 120 min after the *ssc* (after that moment, there were observed small quasi-periodic changes in $<A^2_{o,s}>(z,t)$).

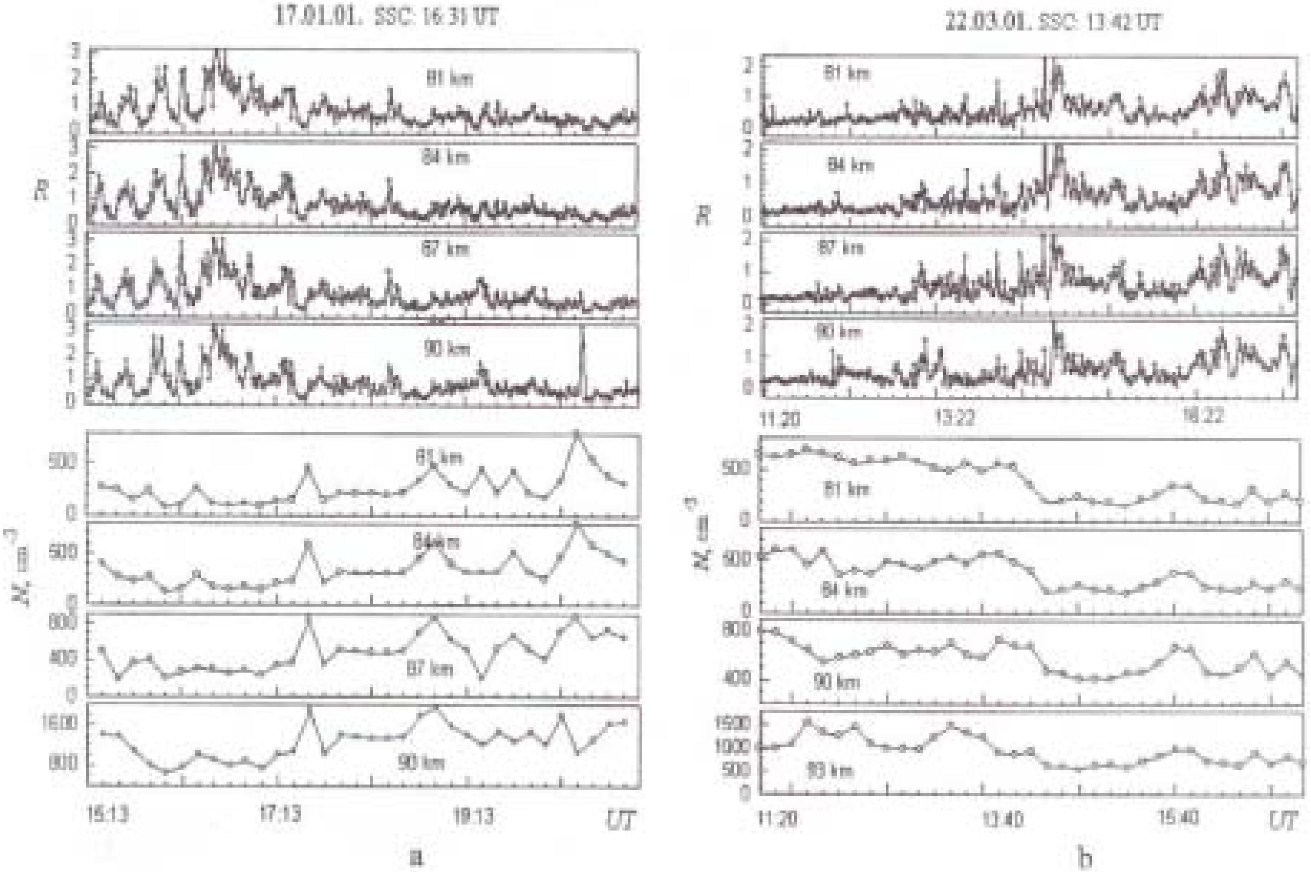

Fig. 2. Height-temporal dependences of radio noise and partial reflection signal intensities, ratio $R(z,t) = <A^2_s>/<A^2_o>$ and electron density, $N(z,t)$, during the *ssc*-events 17.01.2001 (the *ssc*-event time is 16:31 UT) (a) and 22.03.2001 (13:42 UT)(b).

In the experiment of 22.01.2001 in the height-time $R(z,t)$ variation, there was observed a characteristic decrease in the R values by 30-50% with its duration of about 35-40 min approximately 110 min after the *ssc*, with a subsequent increasing (1.5-2 times) and qusi-harmonic changes. At the same time, an increase in the electron density in the height-time $N(z,t)$ variation by 50-60% with its duration of 30-40 min took place. An $N(z,t)$ decreasing after 13:40-14:00 UT seems to have been caused by the diurnal variation, being not connected with the *ssc*.

In the April 17, 2002 (No.7 in Table 2), experiment, after 12:55 UT the strong signals were intermittently observed in the $z = 72 - 78$ km altitude range over 10 – 25 min intervals (signal-to-noise ratio of more than 3). It should be emphasized that in the absence of disturbances, signals from this altitude interval are usually absent or their levels are significantly lower than the noise levels. In regard to the electron density during these disturbed intervals, it increased by more than 100% (see $N(t)$ at a few z = *constant* in Figure 3). At this time approximately after 12:00 UT, the GOES-8 (W75) satellite measurements (http://solar.sec.noaa.gov/weekly/index.html) exhibit a significant increase in the fluxes of protons with energy more than 1, 10, 30, and 100-MeV.

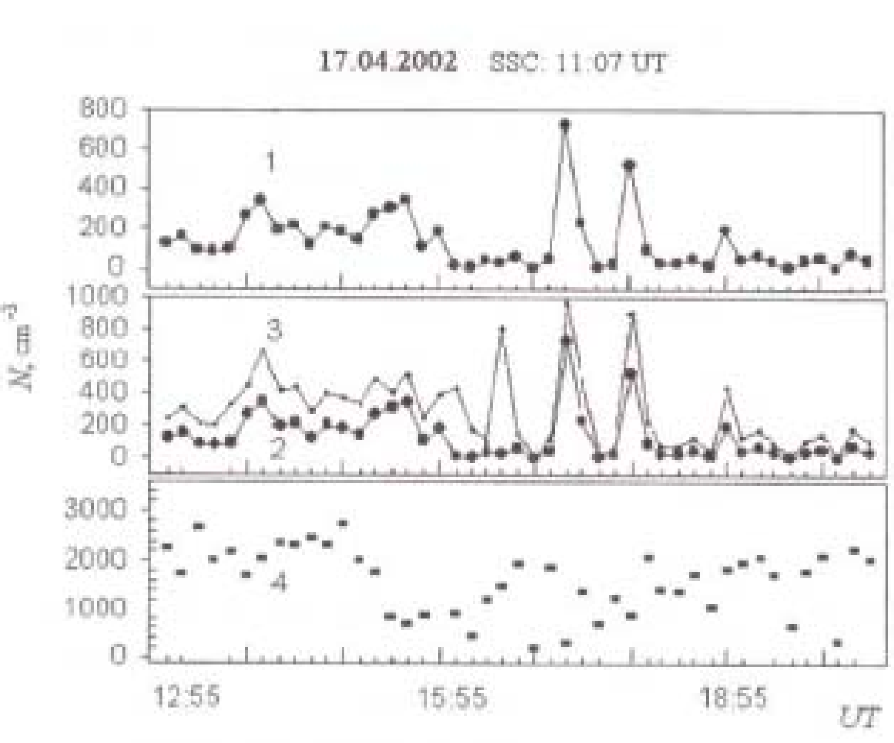

Fig. 3 Electron density, *N(z,t)*, against time for selected altitudes during April 17, 2002 (curve 1 for 72 km, 2 for 75 km, 3 for 78 km, 4 for 84 km).

It should be noted that in the z = 81 km – 90 km altitude range the electron density variations are less pronounced because the ionization at these altitudes is produced by the solar UV and X-ray radiations and is not affected by the protons. The electrons with energy more than 2 MeV measured by the GOES-8 (W75) satellite to precipitate from the Van Allen radiation belts approximately after 11:00 UT produce a peak in ionization at even lower altitudes.

In the rest of our experiment considered, distinct characteristic special features inherent in the mentioned ones were not found.

4. Calculation results and discussion.

Let us try and discuss the above-described typical special features of the height-time behaviour of the characteristics of the radio noise, PR signals and the D-region electron density.

The changes in the average values of the noise intensity and its dispersion may be explained as follows. The noise within 2-3 MHz is the supperposition of the signals from the radio equipment operating in this range. The *ssc*-event, as is shown from the experimental result (the *N(z,t)* calculations), is accompanied by increasing both the electron density and radio signal absorption in the ionosphere over considerable areas having their characteristic *L*-size of several thousands of kilometers. The absorption enhancement leads to weakening interference received by both the main- and the side-lobes of the directive pattern of the PR radar antenna system consisting of orthogonal vertical rhombes. An opposite effect occurs under the decrease in *N(z,t)* values.

When explaining the average values of the PR signal intensity and its dispersion, we take into account that (e.g. see Chernogor (1985))

$$< A^2_{x,o} > \propto \frac{\overline{\Delta N^2}}{\Omega^2_L + \nu^2} \exp\{-4K_{x,o}\},$$

where $\overline{\Delta N^2}$ is the intensity of N - fluctuations, $\Omega_L = \omega \pm \omega_L$, $\omega_L = 2\pi f_L$, $f_L = f_B \cos\alpha \approx 1.3$ MGz, f_B is the electron gyrofrequency, α is the angle between the vertical and the vector of the geomagnetic field induction, ν is the electron/neutral collision frequency, and $K_{x,o}$ is the integral PR signal absorption coefficient of x- and o- polarizations.

After the commencement of the *ssc*-event, the following processes take place:

1) variations (both increasing and decreasing) of N, and, hence, $K_{x,o}$;

2) considerable $\overline{\Delta N^2}$-variations (they are possible under strong turbulization of the medium, which might be caused, for instance, by the flows of precipitating charged particles).

These factors may completely explain both the increase and decrease in $< A^2_{x,o} >$. As for the signal intensity dispersion increase, it indicates the rate changing of the processes, with incomplete "subtraction" of the noise being indicated as well.

The experimental variations of the ratio of R intensities and the R dispersion, σ_R, after the *ssc*-event, may be explained as follows. As

$$R = \frac{< A_x^2 >}{< A_o^2 >} = \frac{\Omega_+^2 + \nu^2}{\Omega_-^2 + \nu^2} \exp\{-4(K_x - K_o)\}$$

(where $(K_x - K_o)$ is differential absorption) and $\Omega_+^2 >> \nu^2$, $\Omega_-^2 >> \nu^2$ in considerable part of the ionospheric D-region ($z \approx 75 - 90$ km), then we may write down:

$$R \approx \frac{\Omega_+^2}{\Omega_-^2} \exp\{-4(K_x - K_o)\}.$$

Under N increasing, $(K_x - K_o)$ increases as well leading to R decreasing; and vice versa, under N decreasing (coming back to the background values), $(K_x - K_o)$ decreases as well leading to R increasing. The σ_R increase is connected with rate changing of the medium.

The N increasing observed over the above-mentioned time periods after the *ssc*-event may be caused by the D-region ionospheric plasma ionization produced by the flows of energetic electrons and protons precipitating from the magnetosphere. Formerly, such a mechanism was used to explain some experimental investigations (Knut and Vurzburger (1976)).

Importance of the middle latitude particle precipitation was discussed (see, for instance, Lastovicka and Fedorova (1976); Knut and Vurzburger (1976); Knut and Fedorova (1977); Lyatsky and Maltsev (1983); Hargreaves (1979, 1992); Gokov and Gritchin (1996); Chernogor (1997); Chernogor et al. (1998); Garmash et al. (1999); Gokov and Chernogor (2000); Gokov and Tyrnov (2000)). The precipitation may arise as a result of pitch angle redistribution of the radiation belt particles; this may be caused either by configuration distortion of the field lines (geomagnetic traps) or by decreasing in the "transverse" energy, $\varepsilon_\perp$, of moving charged particles.

On the basis of the mechanism of high energy electrons (and protons, - see data of the experiment at 17.04.2002) precipitating from the radiation belt, we shall estimate the flow parameters as it is done in Chernogor (1997); Chernogor et al. (1998); Garmash et al. (1999); Gokov and Gritchin (1996); Gokov and Tyrnov (2000) for ionospheric disturbance sources of another nature: rocket launches, magnetic storms, heating of the ionosphere by means of powerful radio-frequency radiation. From the experimental electron density values under the undisturbed N_o and disturbed N conditions, we shall estimate the ionization rate, $q_o = \alpha_o N_o^2$ and $q = \alpha N^2$ ("o" corresponding to the undisturbed conditions). At $z > 75$ km in the D-region, the recombination of electrons with ions NO^+ and O_2^+ (which is proved to be correct by Danilov (1989)) is considered main, and α changes approximately from 10^{-11} to $2\ 10^{-13}$ m^{3}sec^{-1} (further, we take $\alpha \approx \alpha_o$, i.e. neglecting the atmosphere heating under precipitating electrons). The flow density, P_1, of the power, P, of a particle having the ε energy will be taken as (see, for instance, Chernogor et al. (1998)) $P_l \approx 2\varepsilon_i \Delta z \Delta q = \varepsilon p$, where $\Delta q = q - q_o$, $\varepsilon_i \approx 35$ eV is the energy of one ionization act, Δz is the height range of effective absorption of the p flow of electrons with the given ε energy (this expression is valid if one neglects the energy distribution of precipitating electrons). The P power and the E energy of electrons precipitating upon the S area for the precipitating duration, Δt, may be estimated for the relationships of $P = P_l S$ and $E = P \Delta t$. In the calculations on the basis of analyzing PR signals and $N(z,t)$, we have used $\Delta t = 1.2\ 10^3$ sec and $S = 10^{14}$ m^2.

Calculation results of the given values for the experiments discussed are presented in Table 3.

For convenience of the calculations, we took Δz =10 km, and it was also assumed that the energy of precipitating electrons was ε >40 keV, which was rather correct (see, for instance, the data for solar flares and magnetic storms and other sources in Chernogor (1997); Chernogor et al. (1998); Garmash et al. (1988)). The calculation results presented agree with the known data on electron flows, experimentally obtained (or estimated) for disturbances of different natures. The densities of the electron flows and their energy characteristics agree with the theoretical calculations from Chernogor (1997); Chernogor et al. (1998); they may fully provide an increase in the electron density, N, observed at 81-90 km.

Table 3. The electron (proton) flow parameters.

Date	17.01.2001	22.03.2001	23.03.1995	02.12.1996	17.04.2002
z, km	81	84	81	87	75
N_0, 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_0, 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

In the experiment of 17.04.2002 (see earlier remarks), it was registered a strong increase of flows of protons with energies greater than 1, 10, 30 and 100 MeV. The effects appear with time delays of more than 30 min with respect to the start of solar proton event. If solar corpuscles propagate along the straight line from the sun to the earth, then their velocity would be equal to (5-6)·10^7 m/s and their energy - 20 MeV. The fact of the increase in N at the 72-75 km altitude by a factor of 7 in periods 13:45-14:15 and after 16:25 UT indicate that the electron energy is ~10–20 MeV, and the flux is $p \approx 10^7$ m^{-2} s^{-1} (Table 3).

5. Conclusion

1. An increase in the electron density by ~50-150% with its duration of 10-40 min in the middle latitude ionospheric D-region about 2-2.5 hours after geomagnetic sudden storm commencements was experimentally found.

2. Within the hypothesis of electrons precipitating from the magnetosphere, calculations were carried out, and the possibility of electron precipitation caused by geomagnetic sudden storm commencements was shown.

3. There were estimated densities of the electron flows with energies of 40-80 keV, the values of which were 10^7-10^8m^{-2}sec^{-1}.

4. An increase in the electron density at the bottom of D-region of the midlatitude ionosphere (72-78 km) by 5-7 times within 10-15 minutes during the precipitations of protons after the *ssc* was experimentally found. There were estimated densities of the proton flows ($p \approx 10^7$m^{-2}sec^{-1}) with energies of 20 MeV.

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