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Experimental Investigation of Middle Latitude D-region Ionosphere Responding to Events Related to Proton Precipitations

A.M. Gokov and O.F. Tyrnov

V. Karazin National University of Kharkov, 4, Svoboda Sq., Kharkov, 61077, Ukraine

Using a partial reflection technique, there were experimentally investigated changes in the electron density, N, in the ionospheric D-region at the time of solar proton events, *spe*. Increasing by more than 50-100% in the electron density in the lower D-region of the ionosphere (~70-80 km) was observed during several tens of minutes. Estimations of changes in the ionization rate were made. On the basis of the experimental data on electron density changes over the proton precipitation periods, corresponding flows were estimated, being $\sim 10^6$-$10^7 \mathrm{m}^{-2}\mathrm{sec}^{-1}$.

1. Introduction

At present, a part played by the corpuscular ionization in the middle latitude ionospheric D-region was confirmed in an experimental way (see, e.g., [1-20]). The charged particles (electrons and protons) may play a significant role in the lower ionosphere ionization at $z < 90$-100 km (z is the height above the Earth) at night and over the periods of disturbances having different natures both of a natural (solar flares, magnetic storms, thunderstorms, solar terminator, strong earthquakes, etc.) [4-9, 11-20] and an artificial character (industrial explosions, space rocket launches, powerful heating stands operating in the radio-frequency range, radiating high-voltage transmission lines, etc.) [10, 21-26]. Nowadays, there is already no doubt that during the magnetic storms and 5-14 days after them, electrons with $\varepsilon \geq 40$ keV precipitating from the radiation belt are an essential source generating additional ionization of the ionospheric D-region (up to latitudes of ~45-60°) at $z \simeq$ 80-100 km [4-8, 10]. Moreover, at a periods of solar flares and magnetic storms, the increased (often several orders higher) proton flow values are recorded in the satellite measurements. These flows penetrate down to the lower ionospheric D-region heights ($z = 55$-75 km) and may cause considerable changes in the ionization in this part of the ionosphere [3, 10, 27, 28]. However, there are considerable difficulties in measuring the flows of precipitating charged particles at the middle latitudes and in obtaining the correct estimations of their energy contribution at $z < 90$-100 km, using the satellite measurements made at the considerably larger heights ($z > 200$ km).

The role of the proton flows precipitating in the high D-region of the ionosphere has been studied rather well [27]. Possible effects of these flows on the middle latitude D-region of the ionosphere have been studied insufficiently: there are only episodical experimental investigations (see, for instance, [5, 10]); therefore there is necessity to perform experimental investigations and to acumulate information in order to study this problem which is important both from a theoretical point of view and from that of solving a whole number of practical problem of radio communication, radio-navigation, etc.

This paper deals with experimental results obtained by the partial reflection (PR) technique at a middle latitude for the several solar proton events (*spe*) over the periods of solar flares and magnetic storms.

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2. Equipment, experimental procedure and data processing

The experimental investigations were carried out by means of the complex equipment [29] using the PR technique at the V. Karazin Kharkiv National University Radiophysical Observatory situated near the city of Kharkiv (see the Table 1).

Table 1.

Coordinates of V. Karazin Kharkiv 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

To analyze the records of PR signal obtained during the several events of proton precipitating into the Earth ionosphere was selected from the observatory experimental data bank.

The main parameters of the PR technique complex when carrying out the investigations were as follows: operating frequencies $f = 2.1$ and 2.31 MHz, the sounding pulse length $\tau = 25$ mcsec, the repetition rate $F = 1$ Hz, the peak pulse power $P = 100$ kW, the antenna gain coefficient $G = 40$.

During the experiment there were recorded height-time dependences of the mixture amplitudes of the partially reflected signal and radio noise, $A_{so,x}(z,t)$, (where t is the time, "o" and "x" correspond to the ordinary and extraordinary polarizations, respectively) from 14 or 22 height levels, beginning from 45 or 60 km with a step of $\Delta z = 3$ km. In order to select the amplitudes of partially reflected signals, $A_{o,x}(z,t)$, there were also recorded those of only radio noise, $A_{no,x}(z,t)$, (2-6 samples at the 50 kHz frequency band) at the moments preceding a sounding pulse radiation.

Estimating of the mean values of PR signal intensities, $< A^2_{o,x} >$, and of the noise, $< A^2_{no,x} >$, was made by means of 60 realizations over a time interval of 60 sec. A statistical error of this estimating was not more than 10%. Height-time dependences of $< A^2_{o,x} > (z,t)$ and $< A^2_{no,x} > (t)$ were calculated.

Table 2.

Information on the experiments and *spe* events

No	Date	Time of the *spe* event, UT	Proton Flow, pfu	Time of the Measurements, UT
1	24.01.2003	During the day	13	06:10:00-21:00:00
2	17.04. 2002	12:00-15:40(max)-18:00	24	12:55:00-21:00:00
3	24.04.2002	05:50-06:50(max)-	16	01:30:10-18:30:00
4	17.03.2002	08:20-08:50(max)-	13	07:20:00-11:00:00
5	20.03.2002	15:10-15:25(max)-	19	02:00:00-19:32:00
6	20.02.2002	07:30-07:55(max)-	13	03:05:00-19:57:00
7	12.04.2001	During the day	28	07:30:00-16:20:00
8	17.05.1993	During the day	21	12:00:00-15:30:00

Using the $< A^2_{o,x} >$ values obtained, there was calculated their ratio, $R(z)=< A^2_x >/< A^2_o >$, (at the fixed heights with a step of $\Delta z = 3$ km). these results used further to obtain height profiles of the electron density, $N(z)$, by means of the differential absorption methods [30-32]. The height $R(z)$ profiles were calculated over the average intervals of $\Delta t = 5$ and 10 min, then being smoothed using three points. The $R(z)$ dependences obtained in such a way were used in order to construct $N(z)$ profiles (the $N(z)$ profiles were corrected by means of a technique in [33]). When calculating the $N(z)$ profiles, there was used a profile model of the electron-neutral molecule collision frequencies, $\nu(z)$ [34].

The error in the $N(z)$ profile calculation over the average intervals of 10 or 5 min was not more than 30% or 50%, respectively.

The $A_{m,x}(z,t)$ and $A_{w,x}(z,t)$ measurements were made by means of continuous measurements lasting units-tens of hours (before and after the *spe* events). The number of such observations was 8. The information on the experiments and *spe* events is summarized in Table 2.

The information on the precipitating protons was taken from the Internet: www://solar.sec.noaa.gov; gopher://solar.sec.noaa.gov. The duration of the proton precipitations was tens of minutes-hours. In the Table, the proton flow is given in terms of *pfu*; for the flows with $\varepsilon > 10$ Mev, the 5 min averaging was carried out.

Period estimating of the $A_{m,x}(z,t)$ and $A_{w,x}(z,t)$ variations was made by means of the fast Fourier transformation over the time intervals of 30 min. At the same time, the temporal series was formed out of the $A_{m,x}(z,t)$, $A_{o,x}(z,t)$ and $A_{w,x}(z,t)$ values recorded every second.

The comparison was made with the data obtained by the same equipment as that used on the magnetically quiet days (the control days). Controlling over the ionosphere state was carried out by means of an ionosonde.

3. Experimental results and discussion

The analysis of the experimental data have shown that, for the events considered, there occur typical features both in the behaviour of PR signals and noise and in the height-time variations of the electron density. Let us consider them in detail using the data obtained in the typical experiments. Figs 1-4 show examples of the height-temporal variations of the $A_{m,x}(z,t)$, $A_{w,x}(z,t)$ and $N(z)$ values obtained in the experiments of 20.02.2002, 17.03.2002, 24.04.2002 and 24.01.2003.

In the first experiment, the intensive proton precipitation began at 07.00 UT, going on for several hours. Within 11.15-12.55 UT at $z = 72$-81 km, there were recorded intensive PR signals (the $< A^2_{o,x} >$ values became tens of times larger, exceeding the radio noise level several times (Fig. 1)). The PR signals escaped detection at the height more than $z > 81$ km. Note that we do not observe so intensive PR signals at these operating frequencies at the middle latitude under undisturbed conditions (at heights $z < 80$km). The electron density in the given height interval increased by more than 150% over this period. (The $N(z)$ increasing began at about 10.00 UT when the PR signals were still comparable to the noise as to the order of magnitude).

In the experiment of 17.03.2002, increasing (units-tens of times) of the PR signal intensities was recorded for about 15-20 min within 72-84 km 25-30 min after the beginning of the proton precipitation (it is significant that the intensity of the noise and its dispersion decreased over this interval of time). The electron density increased by 50-100% over this period of time in this part of the ionospheric D-region (see Fig. 2).

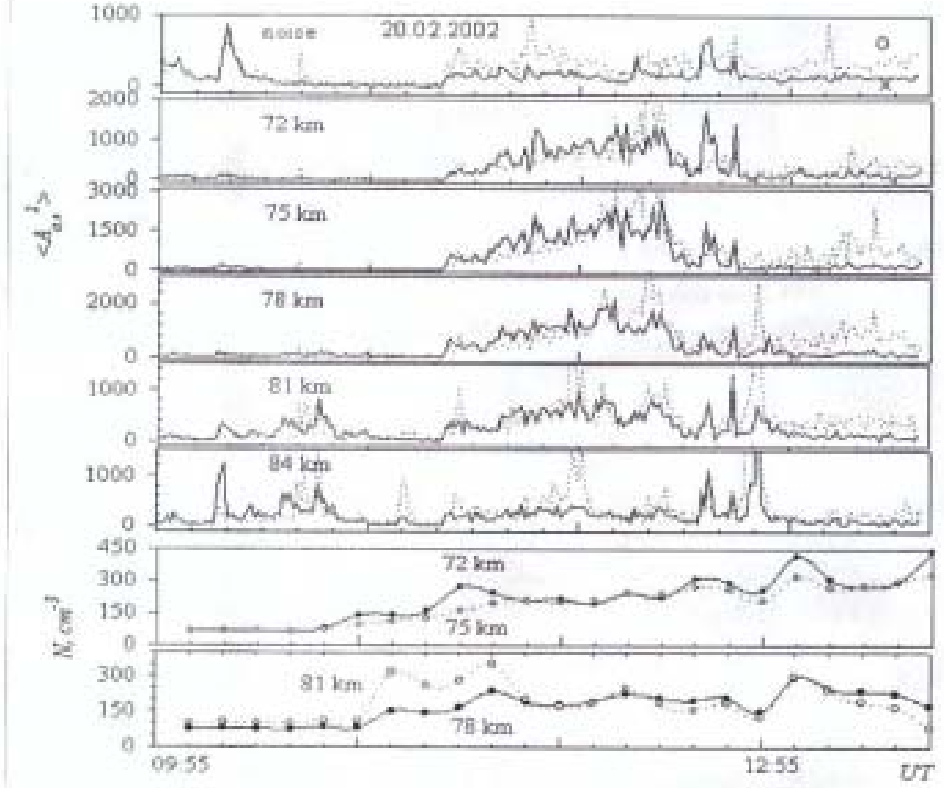

Fig. 1. Height-temporal dependences of one-minute averaged intensities of partial reflection signals $A_{o,x}(z,t)$ and noise $A_{no,x}(t)$ and changes in the electron density, $N(z,t)$, in the middle latitude lower ionosphere D-region, obtained in the experiment of 20.02.2002 during proton precipitations.

We direct our attention to the experiment of 24.04.2002. Note that the precipitations of protons having $\varepsilon > 10$ Mev, started on 21.04.2002 and went on till 26.04.2002. Intensive signals were recorded about 5-10 min after the *spe* commencement over 50-60 min within 69-75 km. At $z > 78$ km there were no PR signals. This situationwere not observed before the event (the $< A^2_{o,x} >$ values became tens of times larger). The electron density within this height interval increased by about 50% over this period (see Fig. 3). At $z = 84$, 87 km over this time interval, the changes in the electron density corresponded to the typical diurnal variation (the $N(z)$ increase at 04.20-05.00 UT being related to the high-energy electron precipitation after the magnetic storm on 12.04.2002; detailed consideration not falling within this paper's purpose). Note also that over the growth period of the PR signal intensities and about the hour after, the intensity of the noise and its dispersion decreased with a following recovery of the typical diurnal variation.

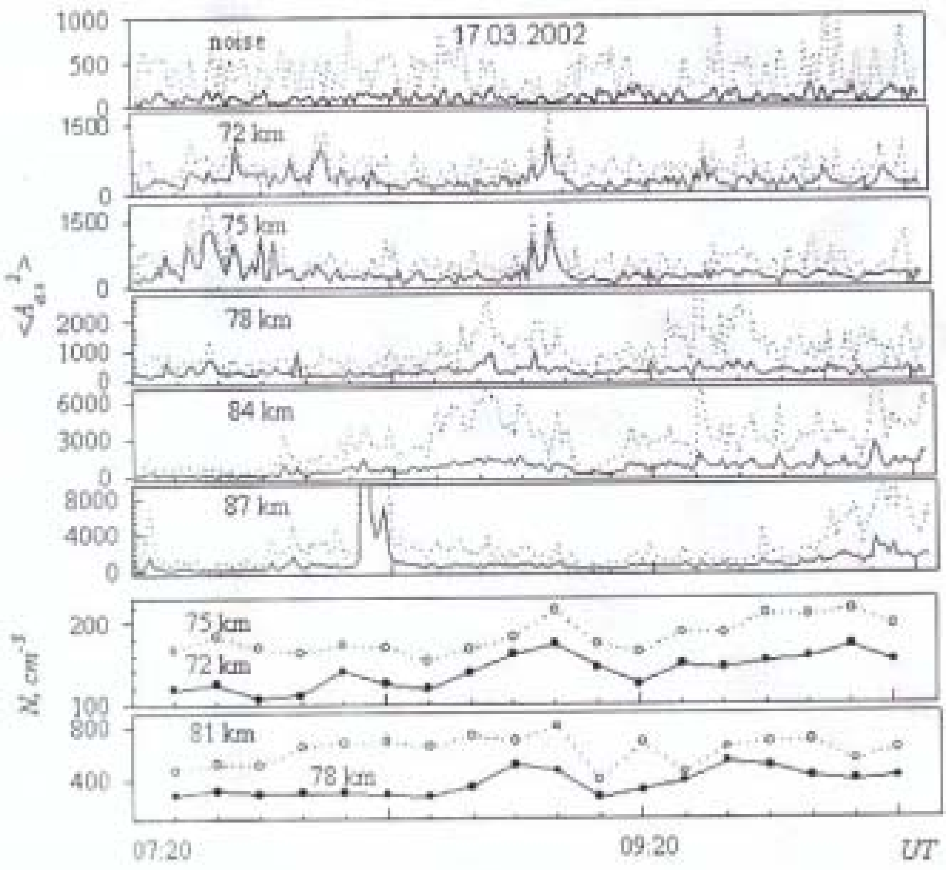

Fig. 2. Height- temporal dependences of one-minute averaged intensities of partial reflection signals $A_{o,x}(z,t)$ and noise $A_{no,x}(t)$ and changes in the electron density, $N(z,t)$, in the middle latitude lower ionosphere D-region, obtained in the experiment of 17.03.2002 during proton precipitations.

In the experiment of 24.01.2003, the precipitations of the protons with $\varepsilon > 10$ Mev were going on for a day. Within 09.20-12.00 UT at 72-81 km, we recorded intensive PR signals (the signal/noise ratio being more than 10). The electron density over this height interval increased by more than 100% for this time period (see Fig. 4). After 14.20 UT over this height interval, there were also recorded the intensive PR signals but the noise level was considerably higher than in the first case (the signal/noise ratio being ~1, and therefore the error in calculating the $N(z)$ value is here $\geq 50\%$).

Fig. 5 shows the height-time $N(z)$ dependences obtained in other experiments not considered above, which also illustrate the electron density increase in the lower part of the middle latitude ionospheric D-region during the *spe* events: on 17.05.1993, the electron density increased by more than 50% at about 10.00-11.00 UT; on 20.03.2002, the $N(z)$ increase by 100-300% was more short duration being of a 20-minute (the periodic proton precipitations were recorded by a satellite for a few hours); on 12.04.2001, the $N(z)$ increase by 50-100% occurred after 04.50 UT; on 17.04.2002, the electron density increased by 100-300% about an hour after the start of recording the proton precipitation sharply decreasing down to the ground values about 140 min later. It should be noted here that in these experiments, and the ones mentioned above, over the $N(z)$ increase periods in the lower D-region of the ionosphere, there were recorded PR signals which were several times larger than the noise level.

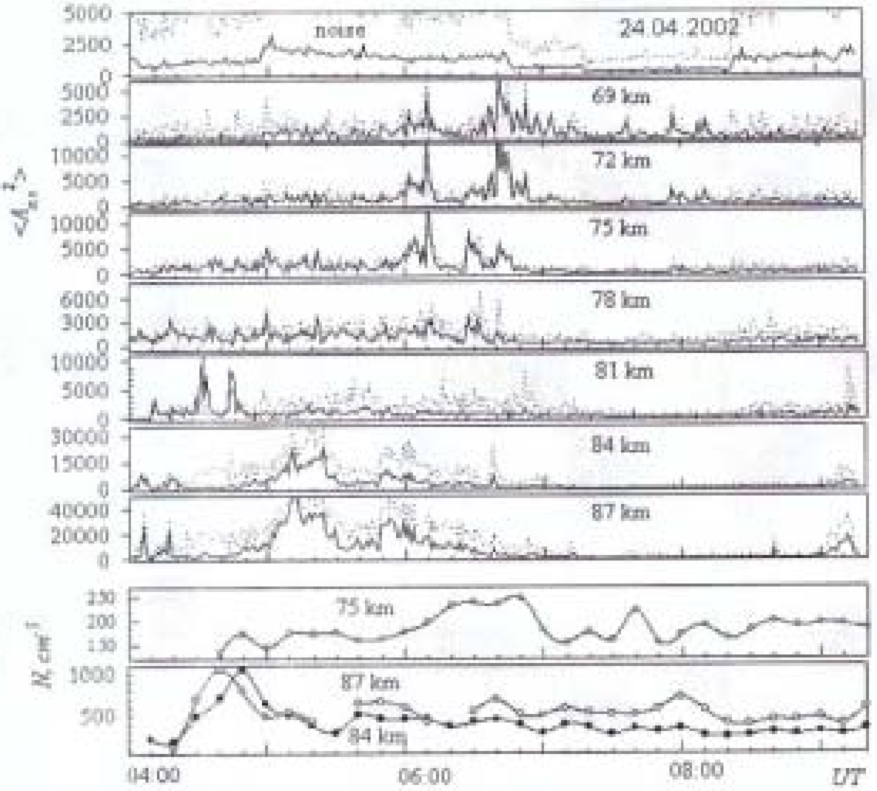

Fig. 3. Height- temporal dependences of one-minute averaged intensities of partial reflection signals $A_{o,x}(z,t)$ and noise $A_{no,x}(t)$ and changes in the electron density, $N(z,t)$, in the middle latitude lower ionosphere D-region, obtained in the experiment of 24.04.2002 during proton precipitations.

As a rule, the main special features of the experimental data at the time of such events are as follows:

1. appearing intensive PR signals (the $< A_{o,x}^2 >$ values became units-tens of times larger) from 69-81 km for a few tens of minutes;
2. the electron density increasing by more than 50-100% in this height interval;
3. the intensity of the noise and its dispersion decreasing and their following recovery of the typical diurnal variation.

Let us consider the effects enumerated above.

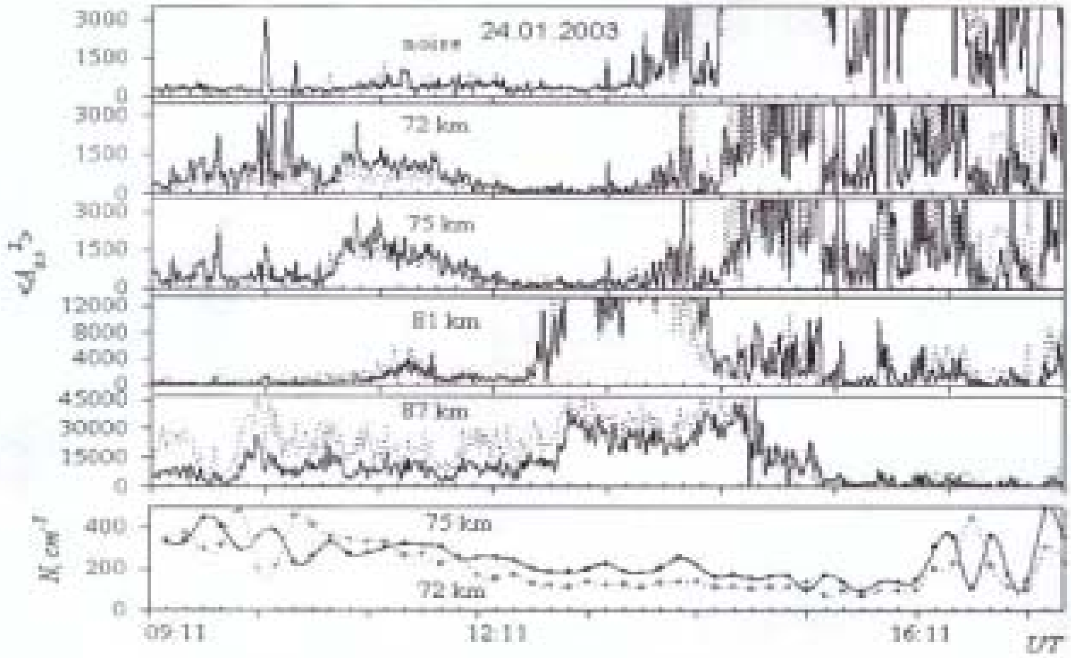

Fig. 4. Height-temporal dependences of one-minute averaged intensities of partial reflection signals $A_{o,x}(z,t)$ and noise $A_{no,x}(t)$ and changes in the electron density, $N(z,t)$, in the middle latitude lower ionosphere D-region, obtained in the experiment of 24.01.2003 during proton precipitations.

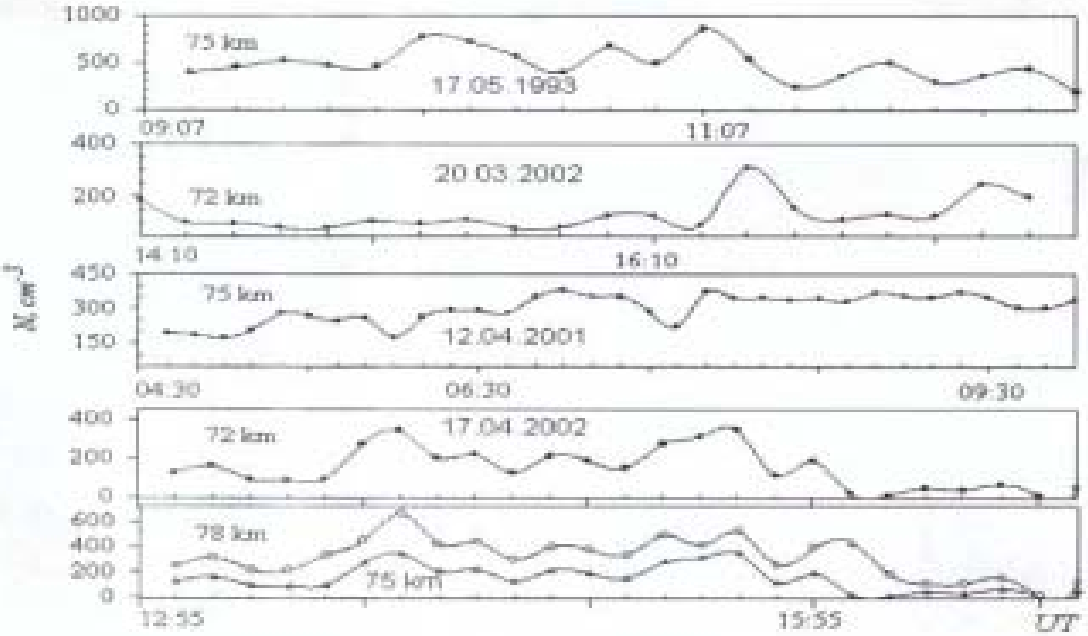

Fig. 5. Height-temporal dependences of the electron density in the middle latitude lower ionosphere D-region.

The decrease in the noise intensity and its dispersion some time after precipitating protons occurred may be explained as follows. The noise within about 2-3 MHz is superimposing of signals coming from the radio facilities operating over this range. Over the period of the noise decrease, there was observed the electron density increase (see Fig. 3), which was accompanied by the radio signal absorbed in the ionosphere over considerable areas with the characteristic size L of several thousands of kilometers. Increasing in the absorption leads to decreasing in the noise received by both the main lobe and the lateral ones of the antenna pattern of the PR radar system consisting of the orthogonal vertical rhombs. An inverse effect, being pronounced more strongly, occurs in the twilight after sunset for the evening terminator passing.

In order to explain the variations (increasing and decreasing) of the average values of the PR signal intensity and its dispersion, we take into account that (see, e.g., [35])

$$< A^2_{x,o} > \propto \frac{\overline{\Delta N^2}}{\Omega^2_\pm + \nu^2} \exp\{-4K_{x,o}\}, \tag{1}$$

where $\overline{\Delta N^2}$ is the intensity of N fluctuations, $\Omega_\pm = \omega \pm \omega_L$, $\omega_L = 2\pi f_L$, $f_L = f_B \cos\theta \approx 1.3$ MHz, f_B is the electron gyro-frequency, θ is the angle between a vertical and a vector of the geomagnetic field induction, ν is the electron-neutral collision frequency, and $K_{x,o}$ is the integral absorption coefficient of the PR signals of x- and o- polarizations.

Over the period of the events considered, there are the following processes: 1) variations (increasing and decreasing) of N and hence $K_{x,o}$; 2) considerable $\overline{\Delta N^2}$ variations (possible under strong turbulization of the medium, which may be caused, for instance, by a proton flow increase). These factors may completely explain both increasing and decreasing in $< A^2_{o,x} >$. As to the increasing dispersion of signal intensities, it shows non-stationary of the processes and incomplete "subtraction" of the noise as well.

The electron density increase at 72-81 km seems to be related to the precipitating protons having more than 10 Mev [10,27].

Using the experimental data on temporal changes in the electron density (see Figs. 1-5), we estimate the rate changes in forming electrons at these heights. From the electron density balance equation for a quasi-stationary case ($|dN/dt| << \alpha N^2$), we have $q = \alpha N^2$ where q is the ionization rate, α is the effective recombination coefficient.

Transport processes (wind, ambipolar and turbulent diffusions) are not taken into account here as their characteristic times are much larger than $(\alpha N)^{-1}$. Before the event of precipitating protons, the ionization rate is $q_0 = \alpha_0 N_0^2$. Then, neglecting the atmosphere heating at $\alpha \approx \alpha_0$, we have $N/N_0 = \sqrt{q/q_0}$. In this case, for instance, for the experiment of 12.04.2002 at $z = 75$ km, $N_0 \approx 160$ cm^{-1}, $N \approx 380$ cm^{-3}, $q/q_0 = 5,64$; for the experiment of 20.02.2002 at $z = 72$ km, $N_0 \approx 100$ cm^{-3}, $N \approx 400$ cm^{-3}, $q/q_0 = 4,0$ and for the same experiment at $z = 78$ km, $N_0 \approx 100$ cm^{-3}, $N \approx 510$ cm^{-3}, $q/q_0 = 26,01$.

We estimate the proton flow parameters using the methods from [10], on the basis of a mechanism for precipitation of the high energy particles (electrons, protons). Using the electron density magnitudes under the undisturbed N_0- and disturbed N-conditions (Figs. 1-5), there were estimated ionization rates of $q_0 = \alpha_0 N_0^2$, $q = \alpha N^2$, where α_0 and α are the corresponding recombination coefficients.

Table 3.

Parameters of proton flows

Date	17.05.93	17.03.02	20.03.02	12.04.02	24.04.02	20.02.02		17.04.02		24.01.03
z, km	75	72	72	75	75	72	78	72	75	75
N_0, m^{-3}	4.5×10^8	1.0×10^8	0.7×10^8	1.6×10^8	1.6×10^8	1.0×10^8	1.0×10^8	1.2×10^8	1.1×10^8	1.2×10^8
N, m^{-3}	8.5×10^8	1.7×10^8	3.0×10^8	3.8×10^8	2.5×10^8	$4.\times410^8$	5.1×10^8	3.2×10^8	3.0×10^8	5.0×10^8
q_m, $\text{m}^{-3}\text{sec}^{-1}$	2.0×10^6	1.0×10^5	0.5×10^5	2.6×10^5	2.6×10^5	1.0×10^5	1.0×10^5	$1.\times510^5$	1.2×10^5	1.4×10^5
q, $\text{m}^{-3}\text{sec}^{-1}$	7.2×10^6	2.9×10^5	9.0×10^5	14×10^5	6.3×10^5	1.9×10^6	2.6×10^6	1.0×10^6	9.0×10^5	2.5×10^6
Δq, $\text{m}^{-3}\text{sec}^{-1}$	5.2×10^6	1.9×10^5	8.5×10^5	1.1×10^6	3.8×10^5	1.8×10^6	2.5×10^6	8.8×10^5	3.8×10^5	2.3×10^6
P_1, $\text{Jm}^{-2}\text{sec}^{-1}$	1.8×10^{-5}	9.8×10^{-7}	2.9×10^{-6}	3.7×10^{-6}	1.3×10^{-6}	6.2×10^{-6}	8.5×10^{-6}	3.0×10^{-6}	2.6×10^{-6}	7.8×10^{-6}
p, $\text{m}^{-2}\text{sec}^{-1}$	6.0×10^6	3.3×10^5	9.8×10^5	1.3×10^6	4.4×10^5	2.1×10^6	2.9×10^6	1.0×10^6	0.9×10^6	2.7×10^6
ε, Mev	20	20	20	20	20	20	20	20	20	20
P, wt	1.8×10^9	9.8×10^7	2.9×10^8	3.7×10^8	1.3×10^7	6.2×10^8	8.5×10^8	3.0×10^8	2.6×10^8	7.8×10^8
E, J	9.0×10^{12}	4.9×10^{11}	1.2×10^{12}	5.6×10^{12}	6.5×10^{11}	4.5×10^{12}	6.1×10^{12}	2.2×10^{12}	1.9×10^{12}	3.1×10^{12}
ΔT, sec	5.0×10^3	5.0×10^3	4.0×10^3	1.5×10^4	5.0×10^3	7.2×10^3	7.2×10^3	7.2×10^3	7.2×10^3	4.0×10^3

For convenience, as earlier, we shall neglect the atmosphere heating at the moment of precipitating particles and assume that $\alpha \approx \alpha_0$. It is also assumed that at the lower heights there predominates a recombination of electrons with ion-bonds, for which $\alpha \approx 10^{11}\text{m}^3\text{sec}^{-1}$. It is valid at $z \leq 75$-90 km under conditions of a weakly disturbed ionosphere for the day- and night- time, respectively [10]. At the higher heights, the α-value decreases from 10^{-11} down to $2\cdot10^{-13}$ $\text{m}^3\text{sec}^{-1}$. The latter value is inherent the recombination of electrons with ions NO^+ and O_2^+. If the energy distribution of particles (which is unknown for the ground observations) is neglected, then the flow density of the particle power, $P_1 \approx 2\varepsilon_i \Delta z \Delta q$, where $\Delta q = q - q_0$, $\varepsilon_i \approx 35$ ev is the energy lost in one ionization act, Δz is the height range where the flow of the particles of the given energy ε is absorbed. Further we assume that $\Delta z = 10$ km. On the other hand, the P_1 parameter is connected with the particle flow p: $P = \varepsilon p$. When having P_1, one can estimate the power and energy of the particles precipitating over the area S: $P = P_1 S$, $E = P\Delta T$ where ΔT is the precipitation duration. The methods of estimating the particle flow parameters consist in calculating the Δq value, the P_1, p, P and E values being calculated as well.

The calculation results are summarized in the Table 3 ($S = 10^{14} \mathrm{m}^2$ being assumed in the calculations). They agree rather well with the known data on the proton flows, obtained experimentally or estimated during disturbances of a different nature [4-8, 10, 24, 27]. Unfortunately we cannot compare the obtained values of the proton flows with those obtained over the observation periods in the satellite measurements. It is caused by the fact that there are no reliable methods of recalculating the proton flows, obtained in the satellite measurements at $z > 200$ km, into ones for the lower ionosphere considered.

4. Conclusions

1. We found and explained the increases of units-tens times in the average intensities of the partial reflection signals from the middle latitude ionospheric D-region at heights $z \approx 70$-80 km and the changes in the radio noise, and their dispersions at the moment of precipitating protons.
2. At the time of the proton events, *spe*, there was experimentally found the electron density increase by more than 50-100% in the lower part of the middle latitude ionospheric D-region ($z \approx 70$-80 km) for several tens of minutes. The changes in the ionization rate were estimated.
3. On the basis of the experimental data on changes in the electron density over the periods of precipitating protons, the corresponding flows were estimated, being $\sim 10^6$-$10^7 \mathrm{m}^{-2} \mathrm{sec}^{-1}$. The calculations of the proton flows from the experimental data agree well with those theoretically known.

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