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International Symposium

Solar Extreme Events

Fundamental Science and Applied Aspects

Nor-Amberd, Armenia
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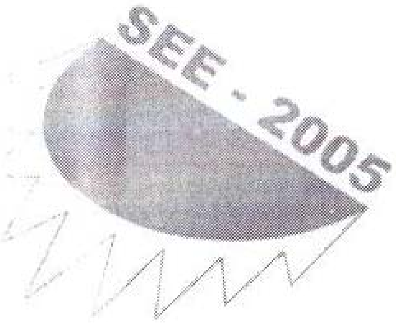

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Foreword

From September 26 to 30, 2005, 75 scientists and students from 11 countries attended the second conference on Solar Extreme Events (SEE-2005) at Nor Amberd, Armenia.

Investigation of Solar Extreme Events is important for several reasons:

- It provides unique information about violent processes in the solar corona, including mechanisms of particle acceleration and Coronal Mass Ejection (CME);

- The study of propagation of huge amounts of solar plasma in the interplanetary space can shed light on its interactions with Interplanetary Magnetic Field (IMF) and ambient population of the Galactic Cosmic Rays (GCR);

- Interplanetary shocks and CMEs, along with solar particle and electromagnetic emissions, trigger various dynamic processes in the Earth's magnetosphere, causing global geo-effective events, including geomagnetic storms, heating of the upper atmosphere, changes in the electrodynamic properties of ionosphere, and creation of geomagnetically-induced surface currents. All this constitutes Space Weather (SW) conditions that change dramatically with SEE development.

- Space Weather can have a negative impact on the performance and reliability of space-borne and ground-based technology systems and endanger human health and life. It is of paramount importance to establish accurate methods for monitoring and forecasting SW disturbances and to identify the mechanisms of various SW effects.

The solar extreme events of October-November 2003, known as the Halloween events, have provided us with valuable information we can use to achieve better understanding of space weather. The SEE-2004 symposium in Moscow in July 2004 focused on comprehensive discussions of solar/heliospheric and magnetospheric aspects of these events. The data obtained onboard numerous satellites and from ground-based observatories were presented, discussed and interpreted both from experimental and theoretical points of view. Meetings during the COSPAR Assembly (Paris, July 2004) and the European Cosmic Ray Symposium (Florence, September 2004) revealed the substantial interest of the scientific community in the Halloween events as well as its continuous efforts to understand them in detail. New attempts to develop analytical techniques to incorporate data from space-borne and surface instruments have created new perspectives for understanding and forecasting the consequences of SEEs.

In 2004 several extreme events from the end of July to mid-November provided new examples of severe Geospace Storms and Forbush decreases. However, the 23rd solar cycle reserved its most severe events for the descending phase. The Ground Level Enhancement (GLE) from the event of January 20, 2005 , the largest one in nearly half a century, caused gigantic count rate increases on the neutron monitors of South Pole. The event displayed very complicated behavior, revealing diversity of particle acceleration mechanisms and the importance of numerous factors influencing particle transport, composition and event geo-effectiveness. The analysis of these events is underway; it will provide an extremely interesting basis for the understanding of SEEs and their effects.

The aims of SEE-05 were twofold:

(1) To provide a wide forum for discussion of recent Solar Extreme Events and their impact on technological systems and human environment, and

(2) To discuss directions of future research.
while promoting cooperation between groups with different research interests from different countries.

The scientific program was divided into three major areas:

- Energetic processes on the Sun during extreme events
- Magnetospheric response to solar extreme events
- Violent conditions of space weather
  and possibilities for its forecasting.

The conference sessions consisted of invited talks and contributed papers presented at poster sessions. High-quality invited talks were given by Vahe Petrossian, Igor Veselovsky, Riho Nymmik, Vladimir Kuznetsov, Galina Bazilevskaya. Leonid Lazutin, Yuri Stozhkov, Yuri Yermolaev, Erwin Flueckiger, John Bieber. Anatoly Belov, Michail Panasyuk, Frank Jansen andYasushi Muraki. The review talks highlighted how the Sun affects heliosphere and the Earth's environment, putting particular emphasis on energetic particle storms, solar eruptions producing these storms and their impact on Earth.

The conference reports demonstrated that integrated information about the consequences of Extreme GLEs and Geomagnetic Storms, including spectral forms, amplitudes and anisotropies of ion fluxes in the vicinity of Earth, strength and direction of the interplanetary Magnetic Field and the state of the magnetosphere, is indispensable for testing solar ion acceleration and propagation models as well as for early diagnostics of the expected impact of violent solar eruptions on technology.

New types of particle monitors, measuring secondary cosmic ray fluxes with inherent correlations are necessary for establishing world-wide networks for Space Weather forecasting. The International Heliophysical Year should provide an excellent opportunity for establishing these networks as well as involve participation of developing countries and, of course, European Space Weather initiatives.
The conference site was located near experimental facilities of Aragats Space Environmental Center (ASEC). The operation of ASEC monitors was demonstrated to the conference participants. In addition, the data base of solar extreme events detected by ASEC monitors was available in the computer class. The prototype detectors developed by Cosmic Ray Division of Alikhanyan Physics Institute (the conference host) were demonstrated during the poster sessions. It is planned to use these detectors for the new Space Weather network. Participants from Croatia, Bulgaria and Costa Rica expressed a wish to become a part of the new network by installing detectors in their countries. Negotiations concerning the formal aspect of this cooperation are underway.

The conference was supported by COSPAR, International Science and Technology Center (ISTC), National Foundation of Science and Advanced Technologies and WEB limited.

We thank Andranik Oganesyan, Veronika Moiseenko and Arthur Reimers for their help in preparing the volume of the SEE-2005 proceedings.

Ashot Chilingarian, Mikhail Panasyuk

August, 2005

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

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Using a partial reflection technique, there were experimentally investigated changes in the electron density in the ionospheric D-region at the time of solar proton events. Increasing by more than 50-100% in the electron density in the lower D-region of the ionosphere (~70-80 km) was observed for 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 ~107m-2sec-1.

Introduction

At present, a part of the corpuscular ionization played in the middle latitude ionospheric D-region was confirmed in an experimental way (see, e.g., [1-9]). The charged particles (electrons and protons) may play a significant part in the lower ionosphere ionization at z<90-100 km 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.) and an artificial character (industrial explosions, space rocket launches, powerful heating stands operating in the radio-frequency range, radiating high-voltage transmission lines, etc.) At present, 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 □ 80-100 km [1-5]. Moreover, over the periods of solar flares and magnetic storms, the increased (often several orders higher) - if compared with the undisturbed conditions – 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. However, there are considerable difficulties in measuring flows of precipitating charged particles at the middle latitudes and in obtaining correct estimations of their energy contribution at $z <$ 90-100 km, using the satellite measurements made at the considerably larger heights ($z >$ 200 km). Possible effects of proton flows on the middle latitude D-region of the ionosphere have been studied insufficiently: there are only episodical experimental investigations (see, e.g., [2,5]); therefore there is necessity of carrying on with experimental investigations and collecting 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 tasks of radio communication, radio-navigation, etc. This paper deals with experimental results obtained by the partial reflection (PR) technique at a middle latitude for some solar proton events (*spe*) over the periods of solar flares and magnetic storms.

Equipment, methods of measuring and data processing

The experimental investigations were carried out by means of the complex equipment [10] using the PR technique at the V.Karazin Kharkiv National University Radiophysical Observatory situated near the city of Kharkiv. For the analysis, out of the University experimental data bank, PR signal records made during some events of protons precipitating into the Earth ionosphere were selected. 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. In 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 "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 in a 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 in 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. 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) used further to obtain height profiles of the electron density, *N(z)*, by means of the differential absorption methods [11]. 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 [12]). 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 $A_{so,x}(z,t)$ and $A_{no,x}(z,t)$ 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 presented in Table 1. 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.

TABLE I

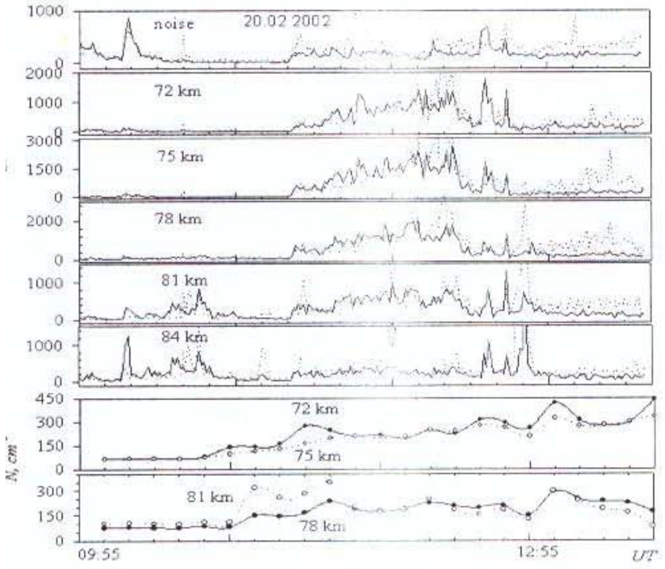
Information of the experiments and *spe* events

Date	Time of the *spe* event, UT	Proton Flow, pfu
24.01.2003	During the day	13
17.04. 2002	12:00-15:40(max)-18:00	24
24.04.2002	05:50-06:50(max)-	16
17.03.2002	08:20-08:50(max)-	13
20.03.2002	15:10-15:25(max)-	19
20.02.2002	07:30-07:55(max)-	13
12.04.2001	During the day	28
17.05.1993	During the day	21

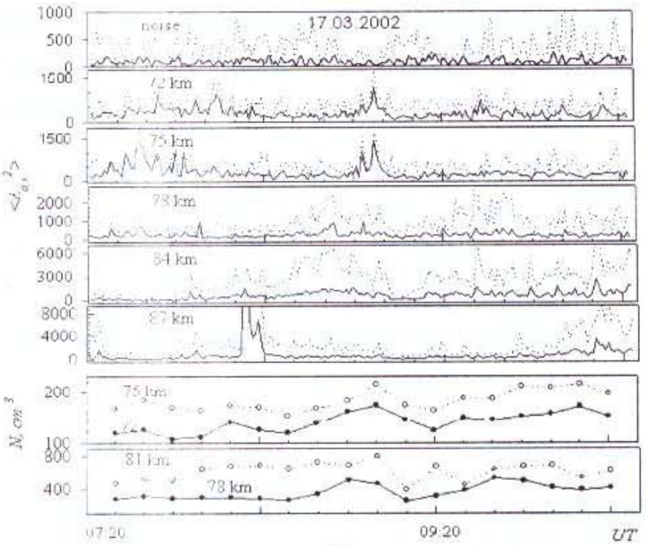
Period estimating of the $A_{so,x}(z,t)$ and $A_{no,x}(z,t)$ variations was made by means of the fast Fourier transformation over the time intervals of 30 min. At the same time, a time series was formed out of the $A_{so,x}(z,t)$, $A_{o,x}(z,t)$ and $A_{no,x}(z,t)$ values recorded every second. The comparison 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.

Experimental results. 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 show examples of the height-time variations of the $A_{no,x}(z,t)$, $A_{no,x}(z,t)$ 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 $z \approx$ 72-81 km, there were recorded intensive PR signals (the $< A_{o,x}^2 >$ values became tens of times larger, exceeding the radio noise level several times (Fig. 1a)).



a)



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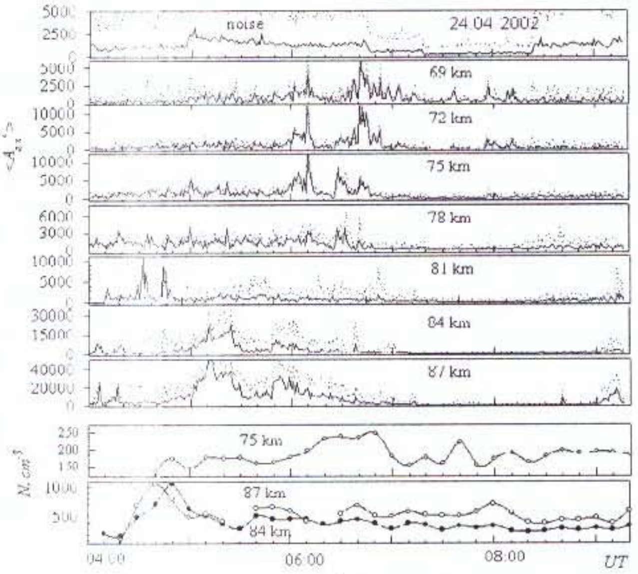

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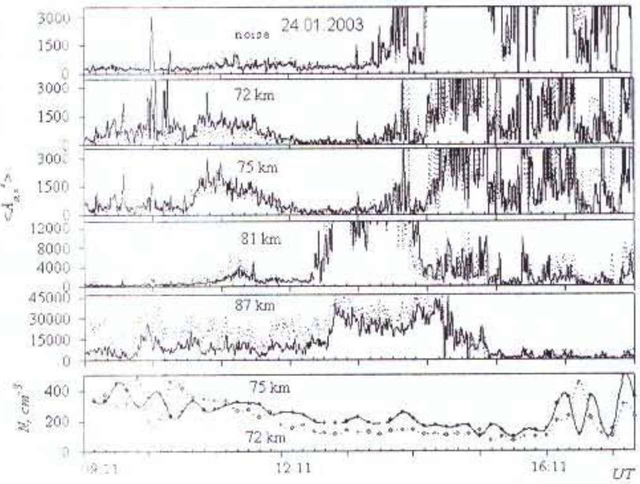

d)

Fig. 1. Height-time dependences of one-minute averaged intensities of partial reflection signals $A_{o,x}(z,t)$ and noise $A_{n\,o,x}(z,t)$ and changes in the electron density in the middle latitude lower ionosphere D-region, obtained in the experiments during proton precipitations.

At $z > 81$ km, there were no PR signals. 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 in this part of the ionospheric D-region increased by 50-100% over this period of time (see Fig. 1b)). In 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) about 5-10 min after the *spe* commencement over 50-60 min within 69-75 km, there were recorded intensive signals (at $z > 78$ km there were no PR signals), which were not observed before the event (the $< A_{o,x}^2 >$ values became tens of times larger).

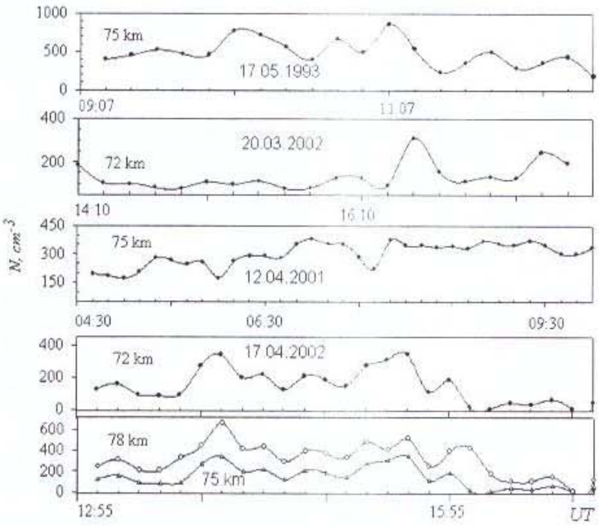

Fig. 2. Height-time dependences of the electron density in the middle latitude lower ionosphere D-region.

The electron density within this height interval increased by about 50% over this period (see Fig. 1c). 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 for the about an hour after, the intensity of the noise and its dispersion decreased with a following recovery of the typical diurnal variation. 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 for this time period increased by more than 100% (see Fig. 1d). After 14.20 UT over this height interval, there were also recorded the intensive PR signals but the noise level was considerably higher than it was in the first case (the signal/noise ratio being ~1, and therefore the error in calculating the $N(z)$ value is here ≥50%). Fig. 2 shows the height-time $N(z)$ dependences obtained in other (not considered above) experiments, 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 shorter, being of a 20-minute duration (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. 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 given above.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 directive 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., [13])

$$< A_{x,o}^2 > \propto \frac{\overline{\Delta N^2}}{\Omega_\pm^2 + \nu^2} \exp\left\{-4K_{x,o}\right\}, \qquad (1)$$

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, $K_{x,o}$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.

Using the experimental data on temporal changes in the electron density (see Figs. 1-5), we estimate rate changes in forming electrons at these heights. For instance, for the experiment of 12.04.2002 at $z = 75$ km, $N_0 = 160$ cm^{-3}, $N = 380$ cm^{-3}, $q/q_0 = 5{,}64$; for the experiment of 20.02.2002 at $z = 72$ km, $N_0 = 100$ cm^{-3} , $N = 400$ cm^{-3}, $q/q_0 = 4{,}0$ and for the same experiment at $z = 78$ km, $N_0 = 100$ cm^{-3}, $N \approx 510$ cm^{-3}, $q/q_0 = 26{,}01$. Using the methods from [5], on the basis of a mechanism for precipitation of the high energy particles (electrons, protons), we estimate the proton flow parameters. 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 $\Delta q = q - q_o$, $\varepsilon_i \approx 35$ 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 given in Table2. They agree rather well with the known data on the proton flows, obtained experimentally or estimated during disturbances of different nature [1–9]. The pity is that 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.

TABLE 2
Parameters of proton flows

Date	z, km	P_1, Jm^{-2}sec^{-1}	p, m^{-2}sec^{-1}	P, wt	E, J
17.05.93	75	1.8×10^{-5}	6.0×10^{6}	1.8×10^{9}	9.0×10^{12}
17.03.02	72	9.8×10^{-7}	3.3×10^{5}	9.8×10^{7}	4.9×10^{11}
20.03.02	72	2.9×10^{-6}	9.8×10^{5}	2.9×10^{8}	1.2×10^{12}
12.04.02	75	3.7×10^{-6}	1.3×10^{6}	3.7×10^{8}	5.6×10^{12}
24.04.02	75	1.3×10^{-6}	4.4×10^{5}	1.3×10^{7}	6.5×10^{11}
20.02.02	78	8.5×10^{-6}	2.9×10^{6}	8.5×10^{8}	6.1×10^{12}
17.04.02	75	3.0×10^{-6}	1.0×10^{6}	3.0×10^{8}	2.2×10^{12}
24.01.03	75	7.8×10^{-6}	2.7×10^{6}	7.8×10^{8}	3.1×10^{12}

Conclusions

1. We found and explained 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 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. 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, corresponding flows were estimated, being ~10^6–10^7m^{-2}sec^{-1}. The calculations of the proton flows from the experimental data agree well with those theoretically known.

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