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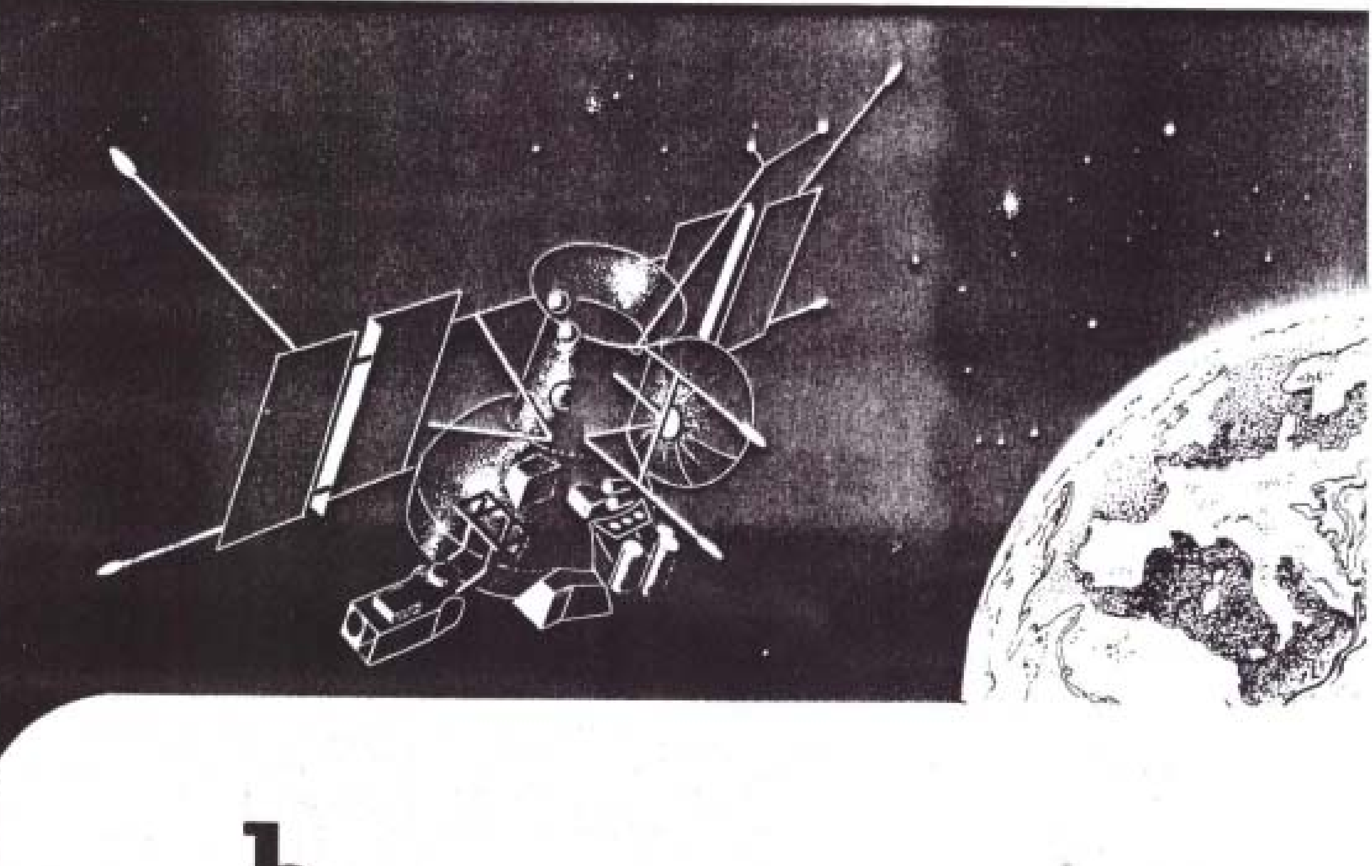

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Experimental Investigations of Electron Density Variations in the Middle Latitude Ionospheric D-Region During REmotr Strong Earthquakes

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Using a technique of partial reflections the changes it electron density, N, in the ionospheric D-region after remote strong earthquakes were experimentally investigated. An electron dencity increase of more than 50–100% was observed during 10–20 min at interval of few minutes after an earthquake moment. In order to explain the experimental results, it was applied a hypothesis of electrons precipitating from radiation belts, which was initiated by a MHD-wave generated under certain conditions in the ionosphere during an earthquake.

1. Introduction.

In Gokov and Gritchin [1996]; Gokov and Tyrnov [1997]; Gokov and Tyrnov [2000] using the technique of partial reflections (PR), there were investigated effects of distant strong earthquakes on temporal characteristics of radio noise at f = 2-4 MHz, reactions of the ionospheric D-region of the middle latitudes to such events being considered as well. It has been found that near the earthquake's moment (for a few minutes after it), considerable (several times larger) temporal variations of radio noise amplitudes, A_{no}, A_{nx}, and amplitudes of mixing PR signals and radio noise of the ordinary, A_o, and extraordinary, A_x, polarization's are observed. To a certain extent of probability, such events take place for earthquakes having energy $E > 10^{12}$ J, both under sea and by land. The experimental data bank, if compared with that in Gokov and Gritchin [1996]; Gokov and Tyrnov [1997]; Gokov and Tyrnov [2000], was increased by more than 40%. A statistics of the events given in Gokov and Gritchin [1996] is on the whole confirmed. In connection with this, there appeared a necessity of investigating possible electron density changes during such events. The results of our investigations are given in this paper.

2. Investigation methods and experimental equipment.

The investigations of amplitudes of PR signals of the ordinary, A_o, and extraordinary, A_x, polarizations and noise, A_{no}, A_{nx}, were carried out by means of the equipment given in Tyrnov et. al. [1994] in the vicinity of Kharkov, Ukraine ($\varphi = 49.5^o N$, $\lambda = 36.4^o E$) at a period from 1983 to 1999 for earthquakes having $E > 10^{12} J$ occurred at ranges of R_l = 1-17 Mm both by land and under sea. As earlier in Gokov and Gritchin [1996]; Gokov and Tyrnov [1997]; Gokov and Tyrnov [2000], the following retrospective analyzing of the data was used. There were analyzed height-time variations of the amplitudes $A_{no,nx}(t)$ and $A_{o,x}(z,t)$ (z being the height above the Earth's ground, t being the

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time), obtained at f = 2,1-3,5 MHz for distant strong earthquakes. Duration periods of the continuous records of $A_{no,nx}(t)$ and $A_{o,x}(z,t)$ were units-tens of hours and covered the whole range in the ionospheric D-region with 3 km height samples. Records obtained over tens of minutes-hours before and after the earthquake were analyzed. The information on the earthquakes was taken from the World Data Centers using WWW-Internet.

To analyze the electron dencity changes, $N(z,t)$, in the ionospheric D-region in the course of earthquakes the recording were taken with the inherent responces (or without them) at the $A_{n0,nx}(t)$ and $A_{0,x}(r,t)$ dependences, for which the calculation was carried out the height-time variations of $N(z,t)$ [1].

Under the $N(z,t)$ profile calculations by the differential absorption procedure [5,6] we used the following the expression:

$$R(z)=\frac{<A_x^2>-<A_{nx}^2>}{<A_o^2>-<A_{no}^2>}$$

Averaging the amplitudes was carried out with intervals of 5 or 10 min. The error in the $N(z,t)$ calculations increases considerably for the smaller averaging intervals. An inverse problem in the PR technique is incorrect, in order to increase reliability of the N-values obtained, they were made more precise by means of the methods from [7] using regularization. This allows to decrease a statistical error in constructing $N(z)$ using $R(z)$ and increase a height range where the construction is possible. A profile model from [8] was used as a profile of the electron collision frequency, $\nu(z)$. The error in $N(z,t)$ calculations did not exceed 50 or 30% for averaging on intervals of 5 or 10 min, respectively.

3. Experimental results and discussion.

Fig. 1 shows examples of the height-time $N(z,t)$ changes ($N(z,t)$ dependencies were obtained for intervals of 5 or 10 min), and Fig. 2 shows $A_x(z,t)$ values corresponding to them (1 min averaging). The information on the earthquakes is presented in Table 1.

Table 1. Data on earthquakes

Data	UT	Latitude, longitude	Magnitude	Depth, km
24.03.1992	13.01.49	20.59^{O}N, 146.97^{O} E	5.1	33
20.03.1995	10.48.54	3.37^{O} S, 135.2^{O} E	5.5	33
28.02.1996	09.44.11	1.81^{O} N, 126.06^{O} E	6.4	105
19.02.1997.	10.28.57	19.19^{O} N, 64.4^{O} W	5.4	33
24.08.1997	13.15.22	29.99^{O} N, 68.11^{O} E	5.6	33

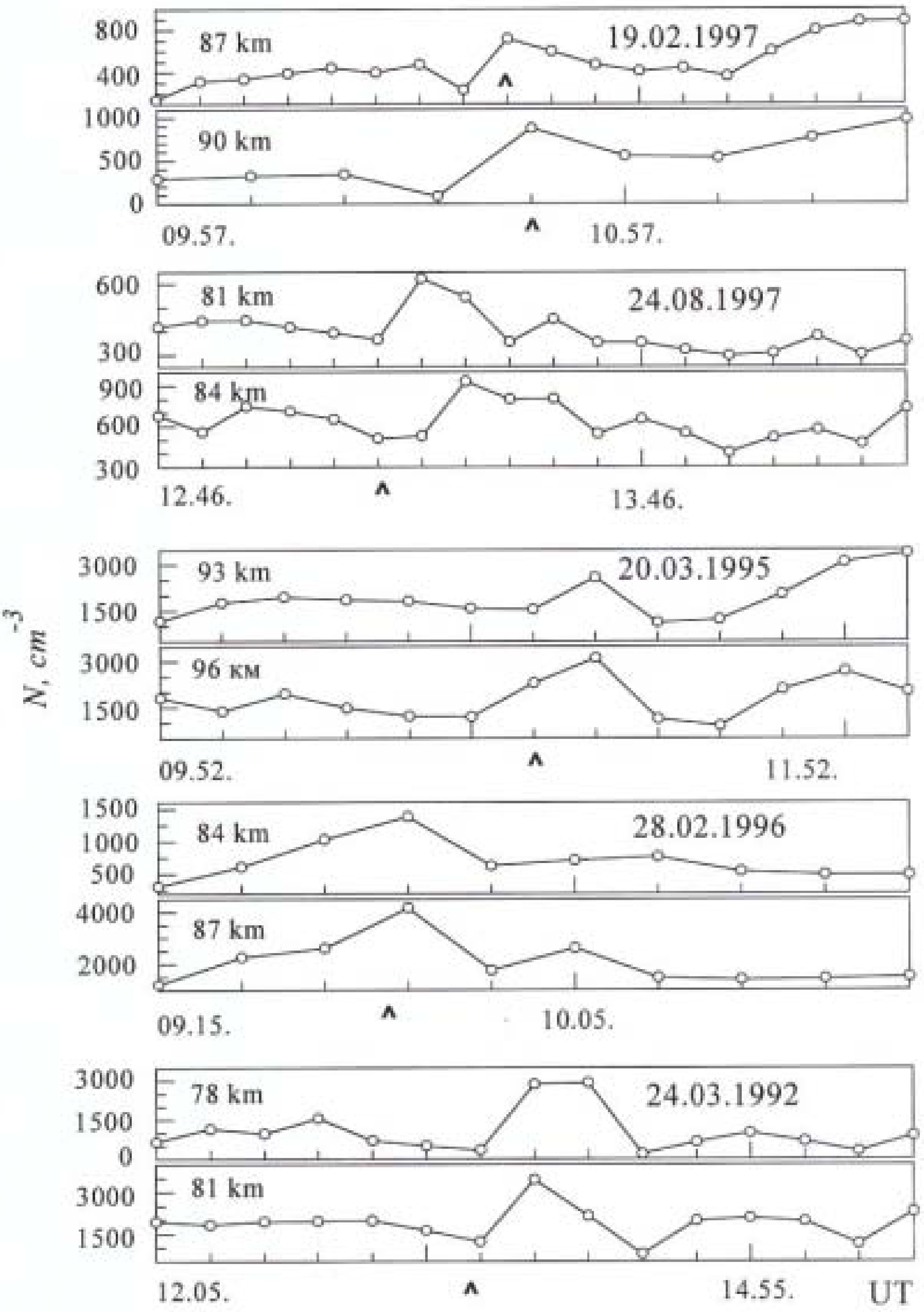
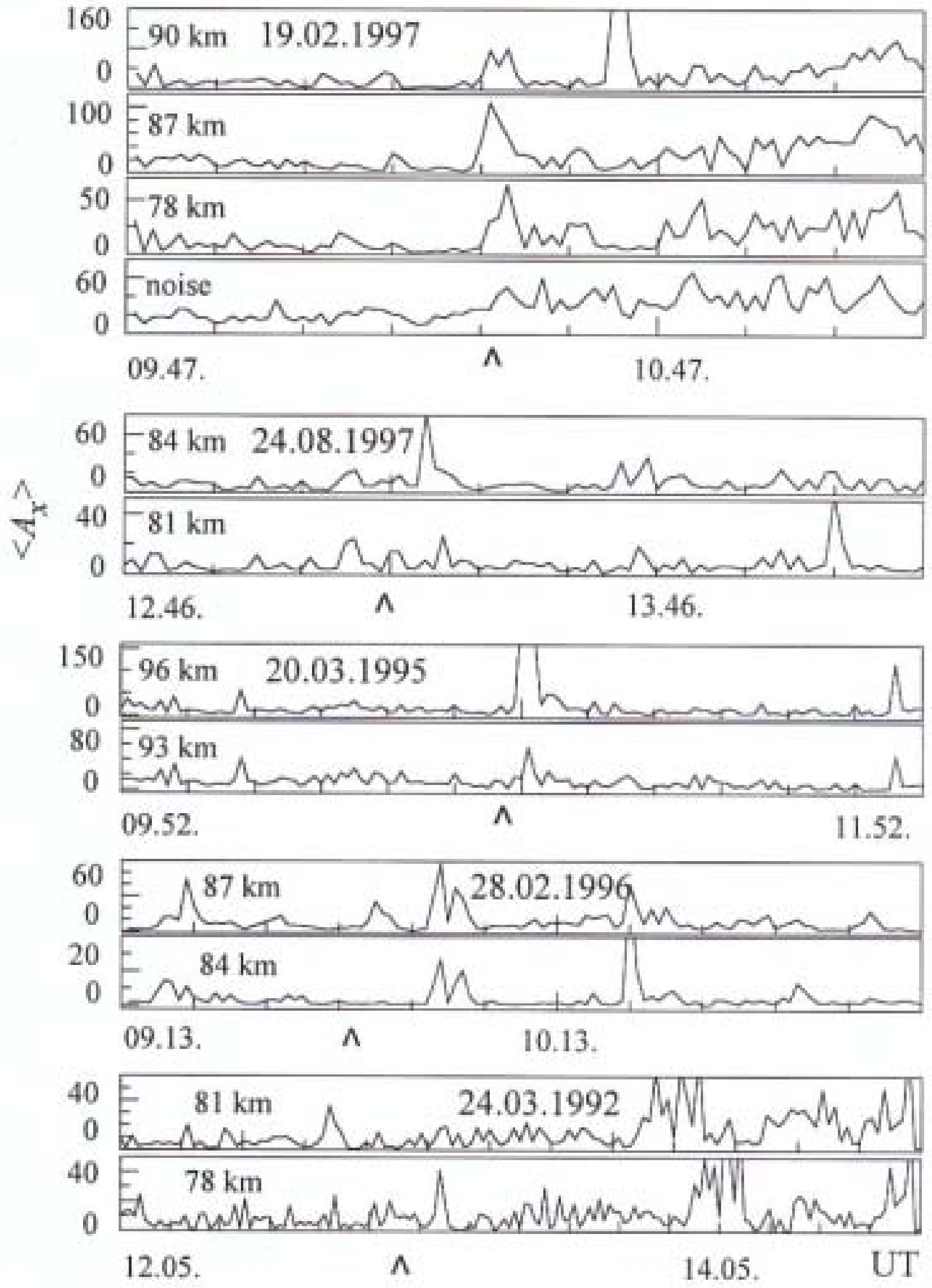


Fig. 1 Examples of the height-time dependences, $N(z,t)$, obtained over the period of strong distant earthquakes (earthquake time being marked with an arrow).



c. 2 Examples of the $A_{nx}(t)$ and $A_x(z,t)$ dependences obtained during strong distant earthquakes.

Note the main peculiarities in $N(z,t)$ behavior near the earthquake's moment in the ionospheric D-region. It has been apparent from data (including those not given here) that in 25 percent situation the $N(z,t)$ is lowered more then 50% during 5–10 min before the earthquake and on the moment one (see examples in Fig. 1, data for 19.02.1997 and 24.03.1992). In 5-10 min after the earthquake the sharp increase in $N(z,t)$ by ~50-200 % was observed to compare with the undisturbed values for 10-20 min (sometimes even more). The $N(z,t)$ relaxation occurred, as a rule, during 10-15 min. We experimentally observed such $N(z,t)$ behavior within a range of z = 78-96 km (at z < 78 km, no characteristic peculiarities in $N(z,t)$ changes were found). It should be noted that we observed $N(z,t)$ behavior similar to that described above in about 50% of the cases; it was observed both for the earthquakes occurred by land and under sea at different depths. It is also characteristic that the given peculiarities in $N(z,t)$ behavior correlate with the characteristic "splashes" of $A_{no,nx}(t)$ and $A_{o,x}(z,t)$ described by Gokov and Gritchin [1996]; moreover, they are still observed when there are no "splashes" of $A_{no,nx}(t)$ and $A_{o,x}(z,t)$ (see examples in Fig. 1,2).

Additional investigations are necessary to construct an adequate model of spreading disturbances into the ionospheric plasma, caused by the earthquakes. Nevertheless, it does follow from the available data that the considered peculiarities in the $N(z,t)$ behavior in D- region of the ionosphere near the moment of the distant powerful earthquake, may be explained on the basis of a mechanism of generating MHD-waves in the ionospheric plasma during the earthquakes. As shown by Gokov and Gritchin [1996], under certain conditions in the ionospheric plasma, the MHD-waves are disturbed. Velocity thereof is equal to the Alfen one $V \approx V_A$ = 100 km/sec [Sorokin and Fedorovich, 1982; Rudenko, 1985]. Such waves may transfer the information on disturbances with minimum delay times, Δt~ 10-100 sec, which was recorded in Gokov and Gritchin [1996] in minimum delay times $\Delta t \sim 10-100$ sec, which was recorded by Gokov and Gritchin [1996] in changes of $A_{no,nx}(t)$ and $A_{o,x}(z,t)$. Assuming such a mechanism of transferring disturbances, one may explain the increase of $A_{no,nx}(t)$ and $A_{o,x}(z,t)$ after the earthquake by different delays (for the equal V-values) for different R_i ranges of the observation station from the earthquake places. In this case, the MHD-wave may be as a trigger factor affecting the magnetosphere magnetic field and causing the height energy charged particles to precipitate from the radiation belt into the Earth atmosphere. These particles cause an ionization increase in the lower ionosphere for temporal intervals of about 1-10 min, which leads to both changes in the height-time dependence of the electron density, $N(z,t)$, described above and changes in $A_{no,nx}(t)$ and $A_{o,x}(z,t)$ described earlier in [1,3]. First of all the probability of generating MHD-wave depends, first of all, on the ionospheric conditions and on the earthquake parameters also (the power, depth, place, etc.). Moreover, the MHD-wave seems not always to cause precipitating of electrons (it depends both on a state of the radiation belt and characteristics of the MHD-wave itself). Also, there are cases when an observation station is out of the cone of precipitating electrons coming from of the radiation belt. Therefore, the peculiarities of the height-time $N(z,t)$ changes described above, are recorded not in all the experiments.

On the basis of the suggested mechanism of precipitating high energy electrons from the radiation belt, let us estimate parameters of the flows similarly to the way given in [11] for sources of ionospheric disturbances of another nature: the start of the rockets, magnetic storm, heating of the ionosphere by powerful radio radiation. Using the experimental electron density values under the undisturbed N_0 and disturbed N conditions, we shall estimate the ionization rates, $q_0 = \alpha_0 N_0^2$ and $q = \alpha N^2$ (the «0» index corresponds to the undisturbed conditions). Assume that the electron recombination with NO^+ and O_2^+ ions is the main recombination process [12] and the atmosphere heating-up is negligibly small on precipitating electrons $(\alpha \approx \alpha_0)$. Under these circumstances the α changes approximately from 10^{-11} to $2 \cdot 10^{-13}$ m^{3}sec^{-1} at $z > 75$ km in the ionospheric D-region. We shall define the density of the flow P_1 of the power P of the particles having energy w as follows [13]

$$P_1 \cong 2 w_i \Delta z \Delta q = wp \,,$$

where $\Delta q = q - q_0$, $w_i \approx 35$ eV is the energy of one ionization act [14], Δz is the height range of the effective absorption of the flow p for the electrons with the given energy w (this expression is valid if the precipitating electrons disturbed with respect to their energies are neglected). The power P and energy E of the electrons precipitating over the square S under the duration of precipitation Δt may be esteemed using the relationships

$$P = P_1 S \text{ and } E = P \Delta t \,.$$

We reasoned $\Delta t = 1{,}2\ 10^3$ sec in the calculations on the basis of behavior of PR signals and $N(z,t)$. The calculation results of the mentioned values for the experiments discussed are presented in Table 2 (for the calculation convenience, we adopt $\Delta z = 10$ km; we believed also the energy of the precipitating electrons to be $w > 40$ keV, which seems to be quite grounded (see, for instance, the data for solar flares and magnetic storms [12–18]).

Table 2. Estimations of electron flow parameters

Data	24.03.1992	20.03.1995	28.02.1996	19.02.1997	24.08.1997
z, km	81	93	84	90	84
N_0, m^{-3}	1,9 10^9	1,5 10^9	5 10^8	3 10^8	6 10^8
N, m^{-3}	3 10^9	3,1 10^9	1,1 10^9	8,7 10^8	9 10^8
q_0, m^{-3}sec^{-1}	4,0 10^7	2,3 10^6	1,5 10^6	0,3 10^6	2,2 10^6
q, m^{-3}sec^{-1}	9,9 10^7	9,6 106	7,3 10^6	2,3 10^6	4,9 10^6
P_1, J m^{-2}sec^{-1}	4,1 10^{-6}	5,1 10^{-7}	4,1 10^{-7}	1,4 10^{-7}	1,9 10^{-7}
p, J m^{-2}sec^{-1}	1,8 10^8	3,4 10^8	2,8 10^7	9,4 10^7	1,3 10^7
w, MeV	0,15	0,01	0,1	0,01	0,1
S, m^2	10^{14}	10^{14}	10^{14}	10^{14}	10^{14}
P, W	4,1 10^8	5,1 10^7	4,1 10^7	1,4 10^7	1,9 10^7
E, J	4,9 10^{11}	6,1 10^{10}	4,9 10^{10}	1,7 10^{10}	2,3 10^{10}
Δt , sec	1,2 10^3	1,2 10^3	1,2 10^3	1,2 10^3	1,2 10^3

It is seen from the table that the flow parameters of the precipitating electrons have a reasonable spreading, which seems to be conditioned by different factors: for instance, by ionospheric conditions, a state of the radiation belts, power of the source (of the MHD-wave), location of the observation station, etc. The absolute values of the precipitating electron parameters as a whole do not contradict to well-know data obtained experimentally or estimated from the disturbances of various nature, such as the solar flares and magnetic storms [14–18], rocket starts [11,19], ets.

It should be noted that for the earthquakes having $E < 10^{12}$ J, according to the registration analysis of the data bank of Kharkov National University, obtained by the PR technique, no effects described above were found (more than 70 experiments were analyzed for different conditions).

4. Conclusions.

1. 1.Using the measurements conducted by the partial reflection technique, it has been found that during the remote strong earthquakes having $E > 10^{12}$ J in the middle latitude ionospheric D-region at $z > 78$ km, an increase in N by 50-200% with the duration $\Delta t \approx 10$-20 min may be observed.
2. The $N(z,t)$ variations observed may be explained by the precipitating flows of high energy electrons from the radiation belt of the Earth caused by the MHD-wave generated under certain conditions in the ionosphere and propagating in the ionospheric plasma with $V \approx 100$ km/sec.

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