Радиофизика и радиоастрономия, 1998, т. 3, №2, стр. 191-197

УДК 550.388

Flux Parameters of Energetic Particles Affecting the Middle Latitude Lower Ionosphere

L. F. Chernogor, K. P. Garmash, V. T. Rozumenko

Kharkiv State University
4 Svoboda Square, Kharkiv 310077, Ukraine

The paper is received by editor August 3, 1998, rewritten January 25, 1999

Electron concentration enhancement determined from partial reflection measurements in the D region at middle latitudes (~50^0 N) after a solar proton flare, rocket launch, high-power HF radio emission, and magnetic storms, is used for estimation and comparison of the parameters of possible precipitating energetic particle fluxes.

Introduction

The various mechanisms for energetic particle precipitation from the "slot region" between the radiation belts (the McElwain L-parameter ≈1.9÷2.5) are still not well defined.

The role of precipitating energetic particles in ionizing the high latitude (more than 65°) atmosphere is now reasonably well understood (see, e. g., [1,2]). This cannot be claimed concerning the middle latitude ionosphere. At the same time, the particles may play an important role in the ionization of the lower ionosphere during night and in the perturbations resulting from natural and anthropogenic sources of disturbance (see, e. g., [3,4]). Electron fluxes are produced by lightning discharges, VLF transmitter signals, harmonics in the kHz range radiated by electrical power transmission lines, and seismic activity (see, e. g., [5-8]). Electron precipitation is among the most important and well-known manifestations of magnetic storms (see, e. g., [9-12]). Except for radio-wave techniques and satellite in situ measurements, the instantaneous distribution of electron precipitation is determined with X-ray imagers (see, e. g., [13]).

The purpose of this study is to make estimates of the parameters of precipitating energetic particle fluxes produced by disturbances on the sun, rocket launches, and high-power radio waves, as well as magnetic storms in the ionospheric D region.

Instrumentation

The partial reflection facility at the Kharkiv State University Radiophysical Observatory near Kharkiv (L≈ 2.0) has been used for determining electron density profiles in the ionosphere, $N(z)$, under quiet and disturbed conditions. Its design specifications are as follows: 100-kW pulse transmitter, pulse length $\tau = 20 \div 100$ μs at $f = 1.5 \div 4.5$ MHz, pulse repetition rate $F = 1 \div 100$ per second, and transmitting antenna gain $G \approx 100$. The receiver has an intermediate-frequency half-power bandwidth of 60 kHz.

The data acquisition, control, display, and storage functions are performed by a computer system. This equipment makes it possible to operate the facility in a "raw data mode", in which the raw receiver voltage samples of the amplitudes A_0 and A_x of the ordinary and extraordinary, respectively, components of the partially reflected wave within an altitude range of 45 km to 115 km with an altitude resolution of 3 km are recorded on magnetic tape (dynamic range of 46 dB) for later processing and further analysis. To increase the signal-to-noise ratio, two to six samples of noise measurements are taken for each sounding pulse.

The NIRFI partial reflection facility near N. Novgorod (L≈2.45) with similar design specifications [14] was used in some experimental campaigns.

Lower Ionosphere and Particle Flux Parameters

In the ionospheric D region and, in particular, in its lower part where negative ions play the key role, chemical processes are not completely understood. The existing aeronomic schemes include a few tens of negative ion species and approximately a hundred chemical reactions. They are too complicated to obtain an analytical solution, to analyze the kinetics of charged particles, and to use them in practice. We assume that there is a single primary O_2^- negative ion species and the rest of the species are formed from it. Then the basic equations can be written as follows [15,16]:

$$\frac{dN}{dt} = q - \alpha_e N N^+ - \beta N + \gamma N^-,$$

$$\frac{dN^+}{dt} = q - \alpha_e N N^+ - \alpha_i N^- N^+,$$

$$N^+ = N + N^-,$$

where N is the electron number density, N^+ is the positive ion number density, N^- is the negative ion number density, q is the production rate, α is the effective coefficient of positive ion-electron recombination, α_i is the effective coefficient of the recombination of negative ions with positive ions, β is the effective rate at which the negative ions are formed by attachment of electrons to neutral constituents, γ is the effective rate at which negative ions are destroyed by electron detachment.

This set of equations has the well-known quasi-stationary solution:

$$N=\sqrt{\frac{q}{\alpha(1+\lambda)}}, \quad N^+=\sqrt{\frac{q(1+\lambda)}{\alpha}}, \; N^-=\lambda N, \quad (1)$$

where

$$\alpha=\alpha_e+\lambda\alpha_i, \; \lambda=\frac{\beta}{\gamma+\alpha_i N^+}. \quad (2)$$

Further, let $\alpha_i=6\cdot10^{-14}$ m^{3}s^{-1} and $\alpha_e\approx10^{-11}$ m^{3}s^{-1} at $z\leq85$ km altitudes where the predominant electron loss process is the recombination of ion clusters. The coefficient α_e gradually decreases from 10^{-11} m^{3}s^{-1} at 85 km to $2\cdot10^{-13}$ m^{3}s^{-1} 100 km. The latter is characteristic of the NO$^+$ and O_2^+ ion recombination [15,16].

The application of relations (1) and (2) to solving practical problems requires numerical values for λ. Their magnitudes depend on the resultant effective rate at which the negative ions are formed by attachment of electrons to O_2 molecules in triple collisions with O_2 and N_2 molecules [17], as well as on the effective rate at which negative ions are destroyed by electron detachment [17, 18]. They do not practically depend on N, N^- and N^+ but are associated with the chemical composition of the atmosphere and its temperature. Therefore, we assume that precipitating particles do not practically affect the values of λ. The daytime values of λ from [18] and the estimates of nighttime λ values made in this study are presented in Table 1.

Table 1. *Dependence of λ on altitude*

z, km	50	55	60	65	70	75	80	85
λ, day	70	15	4	1	0.3	0.1	0.02	0.003
λ, night	200	50	10	2.5	1	0.3	0.1	0.03

From relation (1) it follows that

$$q=(1+\lambda)\alpha N^2.$$

Under undisturbed conditions, i. e., before precipitation,

$$q_0=(1+\lambda_0)\alpha_0 N_0^2.$$

The change in the production rate is equal to

$$\Delta q=q-q_0.$$

We assume that the enhancement in electron concentration is caused by energetic particles precipitating from the magnetosphere. Neglecting atmospheric heating by precipitating particles and variations of λ, let $\alpha=\alpha_0$, $\lambda=\lambda_0$, and present Δq as

$$\Delta q\approx(1+\lambda)\alpha\left(N^2-N_0^2\right). \quad (3)$$

This quantity is related to the monoenergetic particle power density flux [19]

$$\Pi=2\varepsilon_i\Delta z\Delta q, \quad (4)$$

where $\varepsilon_i\approx35$ eV is the energy the precipitating particle expends per ion pair by collision [1,2], Δz is an altitude range where the energy is efficiently absorbed. It is of the order of a neutral scale height. Further, let $\Delta z\approx10$ km. On the other hand, the parameter Π is related to the particle flux p by

$$\Pi=\varepsilon p, \quad (5)$$

where ε is particle energy in a monoenergetic particle flux. Given Π, estimates can be made of power and energy of particles precipitating over the surface area S:

$$P=\Pi S, \quad E=P\Delta T, \quad (6)$$

where ΔT is the duration of the precipitation. The values of S and ΔT depend on the source of disturbance, and they are estimated in each case separately.

The technique for estimating the parameters of particle fluxes adds up to calculating first the value of Δq by Eq. (3) and then Π, p, P and E applying Eqs. (4)-(6).

Experimental Results and Model Estimates

We consider such disturbances as a proton flare, rocket launch, magnetic storms, and high-power radio waves.

Proton Flare. A class 1n solar proton event occurred on February 25, 1991, during the period of high solar activity (Wolf sunspot number $R \approx 400$, geomagnetic index $A_k \approx 5 \div 10$). The solar flare was observed from 07:35 UT to 07:45 UT with a maximum at the beginning of this interval. Several observatories of the former Soviet Union have detected unusually sharp power flux enhancement of 2-3 orders of magnitude in the 3÷15 GHz radio wave range during the 08:04 UT to 08:19 UT interval.

We have studied partially reflected signals using the NIRFI partial reflection radar at $f \approx 3$ MHz in the vicinity of N. Novgorod [14,20]. The partially reflected signals from all altitudes completely disappeared from 08:10 UT through 08:15 UT. In a few minutes, they began to appear: first, at the 72 km altitude at ~08:40 UT, and then higher, up to the 85 km altitude at 09:20 UT. It is important to note that solar X-ray bursts were not observed from 07:00 UT to 12:00 UT. Before (08:04 UT) and after (10:00 UT) the disturbance, $N_0 \approx 10^9$ m^{-3} at z=72.5 km. The most disturbed N value that we have managed to determine is approximately $6 \cdot 10^9$ m^{-3} at about 08:40 UT. After this moment, N slowly relaxed to the undisturbed value N_0. At the –3-dB point, the event had a duration of $\Delta T \approx 5 \cdot 10^3$ s.

The effects were detected with time delays of no less than 30 min with respect to the solar flare. If the solar corpuscles had been propagated along straight lines from the Sun to the Earth, then their velocity and energy would be equal to $6 \cdot 10^7$ m/s and 20 MeV, respectively. However, charged particles travel along curved interplanetary magnetic-field lines and cannot penetrate into the middle latitude sunlit ionosphere directly [1]. They may appear there only as a result of drift from the night sector of the magnetosphere into the dayside region propagating towards the Earth, and their initial energy may, therefore, be significantly greater. The fact that the particles have produced an increase in N by a factor of no less than 8 and even the full absorption (from 08:10 UT to 08:15 UT) at the 72.5 km and lower altitudes, provides an additional evidence for energies larger than 20 MeV. The precipitating particles correspond to the proton flux of smaller than $p \approx 10^7$ m^{-2} s^{-1} (Table 2).

Table 2. *Parameters of energetic particle fluxes under disturbed conditions of anthropogenic and natural origin*

Event	Proton flare	Magnetic storm	Magnetic storm	Rocket launch	High-power radio waves
Date	February 25, 1991	June 15, 1983	May 15, 1997	May 15, 1987	March 1, 1991
N_0, m^{-3}	10^9	10^8	$1.2 \cdot 10^9$	10^9	$4 \cdot 10^9$
N, m^{-3}	$6 \cdot 10^9$	$4 \cdot 10^8$	$1.7 \cdot 10^9$	$2 \cdot 10^9$	$7 \cdot 10^9$
q_0, m^{-3}s^{-1}	10^7	10^5	$1.4 \cdot 10^7$	$3 \cdot 10^6$	$1.3 \cdot 10^7$
q, m^{-3}s^{-1}	$3.6 \cdot 10^8$	$1.6 \cdot 10^6$	$2.9 \cdot 10^7$	$1.2 \cdot 10^7$	$4 \cdot 10^7$
Π, Jm^{-2}s^{-1}	$3.5 \cdot 10^{-5}$	$1.8 \cdot 10^{-6}$	$1.5 \cdot 10^{-6}$	10^{-6}	$2.7 \cdot 10^{-6}$
p, m^{-2}s^{-1}	$1.6 \cdot 10^9$ $(1.2 \cdot 10^7)$	$2.3 \cdot 10^7$ $(7.8 \cdot 10^5)$	$3.8 \cdot 10^8$	$2 \cdot 10^8$ (10^7)	$4.5 \cdot 10^8$
ε, MeV	0.15 (20)	0.5 (15)	0.06	0.08 (1.5)	0.04
S, m^2	10^{14}	10^{14}	10^{14}	10^{13}	10^{12}
P, W	$3.5 \cdot 10^9$	$1.8 \cdot 10^8$	$4.5 \cdot 10^8$	10^7	$3 \cdot 10^6$
ΔT, s	$5 \cdot 10^3$	$2 \cdot 10^5$	$4 \cdot 10^3$	10^3	$3 \cdot 10^2 – 3 \cdot 10^3$
E, J	$1.8 \cdot 10^{13}$	$3.6 \cdot 10^{13}$	$2 \cdot 10^{12}$	10^{10}	$10^9 – 10^{10}$
Energetic species	Electron (Proton)	Electron (Proton)	Electron	Electron (Proton)	Electron
Altitude, km	72.5	55–60	84	80	88

Magnetic Storm. We consider two characteristic magnetic storms of June 15, 1983, and of May 15, 1997 [21]. After the first of them, the electron density increased by a factor of 2÷5 at the 55÷65 km altitude, and after the second, by 30÷70 % in the 75÷85 km altitude range. The effects of precipitating protons were apparently observed during the first event when solar X ray bursts were absent, and precipitating electrons were observed during the second event. The parameters of these fluxes are also presented in Table 2. In particular, for these events $p \approx 7.8 \cdot 10^5$ m^{-2} s^{-1} (λ=10 averaged across the 55-60 km altitude) and $3.8 \cdot 10^8$ m^{-2}s^{-1} (λ=0.2), respectively. The first value is in good agreement with the simultaneous measurements made at the "Meteor" satellite [22] which showed $p \approx 7.7 \cdot 10^5$ m^{-2} s^{-1} that is 1 % less than the estimate in this study.

Generally, the response of the lower ionosphere to magnetic storms is similar to that reported in the literature [9-12] where VLF radio-propagation diagnostics were used to study precipitation effects. The authors of those papers have attributed the variations in the radio wave characteristics to $\varepsilon \geq 40$ keV electron precipitation from L shells of ~2.5÷3. Note that in our study $L \approx 2.0$ (Kharkiv).

Rocket Launch. The "Energia-Buran" space vehicle was launched from the missile-space-launch center at Tyuratam, on the Aral Sea at 17:30 UT on May 15, 1987; its engine power is ~10^{11} W, and the energy released is ~10^{13} J. The measurements were performed near Kharkiv at a distance of $R \approx 2{,}500$ km. Before the appearance of disturbance at $z \approx 80$ km, the electron density was $N_0 \approx 10^9$ m^3. In $\Delta t \approx 3$ min, the density increased by a factor of 4-5, and the enhancement persisted for a few minutes. The duration of the perturbation in N was $\Delta T \approx 10^3$ s, and $N/N_0 \approx 2$, on average. This enhancement in N could not be caused by events on the Sun because it remained quiet long before and till the lift-off of the rocket; the perturbation is most likely due to energetic electrons precipitating from the magnetosphere. The parameters of the particle fluxes are presented in Table 2. For electrons of $\varepsilon \approx 80$ keV, $p \approx 2 \cdot 10^8$ m^{-2}s^{-1}, for protons of $\varepsilon \approx 1.5$ MeV, $p \approx 10^7$ m^{-2} s^{-1}.

Our other papers (see, e. g., [23,24]) deal with the effects of rocket launch on the ionosphere as well.

Effects of High-Power Radio Waves. Disturbances in the ionosphere were produced by the f=5÷9 MHz heater system of the NIRFI Sura facility with a maximum equivalent power of PG=100÷300 MW used near N. Novgorod. The transmissions of disturbing pulses of 2÷10 min in length alternated with pauses of 3÷10 min in length. The radio wave instruments which provided a diagnostics for studies of large-scale ($R \approx 1000$ km) perturbations were located mainly at the Kharkiv State University Radiophysical Observatory, except for one measurement campaign in 1991 when the diagnostics were located near N. Novgorod. In the latter case, the distance between the heater and the partial reflection radar was approximately 100 km [25].

We have studied the parameters of similar large-scale perturbations since 1984 (see, e. g., [26-31]), and, in particular, we have revealed the 1.5÷3 factor enhancement in N at 75 to 85 km altitude. Because the enhancement appeared with a $\Delta t \approx 10 \div 15$ min delay after switching on the high-power transmitter, we explain them by the triggering of the energetic particle precipitation from the magnetosphere. If the precipitating particles are electrons, their energy is of the order of 10÷100 keV; for protons, ε~0.1÷1 MeV.

The estimates of electron flux parameters for the March 1, 1991, experiment are provided in Table 2. It is seen that at $z \approx 88$ km for $\varepsilon \approx 40$ keV, $p \approx 4.5 \cdot 10^8$ m^{-2} s^{-1}.

Discussion

The observations described above indicate that the electron concentration in the lower ionosphere can significantly increase during relatively short periods of time.

Further, it is necessary to address the following questions. What causes the increases in N? Can they be caused by precipitating particles? Are precipitation fluxes sufficiently large at middle latitudes? Are the flux parameters reasonable enough? What are the mechanisms for particle precipitation?

We shall try to give answers to these questions. The possible causes of increases in N may be the following: enhancement in the production rate q, changes in temperature dependent chemical reaction rates, and variations in the neutral and ion composition of the atmosphere. Changes of atmosphere temperature and chemical composition may be neglected because these processes are characterized by large time scales dependent on the transfer of matter and heat in the horizontal and, to some degree, vertical directions. They are of interest for meteorology.

We shall now in detail consider the mechanisms for changes in N caused by q variations. The major sources of ionization are the following [32].

1. X-Rays. They produce significant ionization only at $z \geq 85$ km altitudes.

2. Galactic Cosmic Rays. They produce ionization at $z \leq 65$ km. At latitudes of the order of 50°, the $j = q/N_n$ ratio (N_n is the neutral atmosphere number density) changes from $8 \cdot 10^{-18}$ s^{-1} to $14 \cdot 10^{-18}$ s^{-1} depending on solar activity [2]. Let us set $j = 10^{-17}$ s^{-1}, on average. Then the production rate $q = jN_n = 2.5 \cdot 10^5 \div 4 \cdot 10^4$ m^{-3} s^{-1} at z = 50÷65 km. In this case, $N = (1 \div 7) \cdot 10^7$ m^{-3}, according to formula (1).

3. Ionization of NO Molecules by the Solar Lyman α Radiation. The NO number density of the order of $10^{13} \div 10^{14}$ m^{-3} and the Lyman α radiation flux of $3 \cdot 10^{15}$ quantum·m^{-2}s^{-1} produce ionization observed at 70÷80 km altitudes. The nighttime values of N at the same altitudes caused by scattering of this line emission can be of the order of $10^7 \div 10^8$ m^{-3} [3].

4. Ionization of $O_2(^1\Delta_g)$ Molecules by 102.7÷111.8 nm Solar Emission. This mechanism begins to play role at 70-80 km at low NO concentrations.

5. Ionization by Energetic Particle Fluxes. This source at middle latitudes has been studied worse than the other. It is clear that this mechanism is not sufficiently efficient during daytime quiet conditions. Its role significantly increases during disturbed conditions, as well as during night at low NO concentrations.

6. Solar X-Ray Flares. During disturbed conditions, the enhancement of hard X-ray fluxes can intensely ionize the D region. In addition, protons of tens of MeV energy become significant mainly over the polar caps.

Next consider the ionization of the atmosphere by energetic particle fluxes in detail. This mechanism seems most appropriate for the explanation of observations of the large-scale and global-scale density enhancement caused by proton flares, rocket launches, and high-power radio wave emissions. Indeed, anthropogenic factors cannot in principle affect the efficiency of processes 1, 2, and 6, as well as the efficiency of processes 3 and 4 at least at distances of $R \sim 1000$ km from the sources of disturbance and especially with time delays of $1 \div 10$ min.

In order to understand to what extent the particle fluxes and other parameters presented in Table 2 are real, let us make estimates of these parameters for the quiet nighttime lower ionosphere conditions. The N values in Table 3 are assumed to be produced only by energetic particle fluxes from the radiation belts. This $N(z)$ profile is the lower boundary of a set of possible $N(z)$ dependences, and it is chosen taking into account the following considerations. Near $z = 60$ km altitude, $q = 10^2$ m^{-3}s^{-1} which is far less than the rate of production by galactic cosmic rays (approximately 10^5 m^{-3}s^{-1}). The production rate by Lyman α line emission is $q \sim 10^4 \div 5 \cdot 10^5$ m^{-3}s^{-1} [3], that by precipitating particles is $q \sim 10^2 \div 3 \cdot 10^5$ m^{-3}s^{-1} at $z \sim 70 \div 90$ km; thus, the latter is distinctly less than the former. This indicates that the chosen $N(z)$ profile adequately characterizes the ionization by precipitating energetic particles under quiet conditions, and it corresponds to relatively small electron fluxes of $p \sim 10^3 \div 10^7$ m^{-2}s^{-1} at $z \sim 60 \div 90$ km. Under disturbed conditions, the fluxes apparently increase to $p \sim 10^5 \div 10^8$ m^{-2}s^{-1} at the same altitudes (see, e. g., [3] and references there). But even such particle fluxes are significantly smaller than those in the high latitude ionosphere where electron fluxes of $p \sim 10^9 \div 10^{12}$ m^{-2}s^{-1} are observed at the same altitude interval (Table 4).

Table 3. *Parameters of energetic particle fluxes in the undisturbed mid-latitude nighttime ionosphere*

Parameter	60 km	70 km	80 km	90 km
N_0, m^{-3}	$3 \cdot 10^6$	$3 \cdot 10^6$	$3 \cdot 10^7$	$3 \cdot 10^8$
α_0, m^{3}s^{-1}	10^{-11}	10^{-11}	10^{-11}	$3 \cdot 10^{-12}$
q_0, m^{-3}s^{-1}	10^2	10^2	10^4	$3 \cdot 10^5$
Π, Jm^{-2}s^{-1}	10^{-10}	$2 \cdot 10^{-11}$	10^{-9}	$3 \cdot 10^{-8}$
p, m^{-2}s^{-1}	$1.5 \cdot 10^3$ (50)	$8 \cdot 10^2$ (20)	$7 \cdot 10^4$	$5 \cdot 10^6$
ε, MeV	0.5 (15)	0.2 (8)	0.1	0.04
S, m^2	10^{14}	10^{14}	10^{14}	10^{14}
P, W	10^4	$2 \cdot 10^3$	10^5	$3 \cdot 10^6$
ΔT, s	$4 \cdot 10^4$	$4 \cdot 10^4$	$4 \cdot 10^4$	$4 \cdot 10^4$
E, J	$4 \cdot 10^8$	$8 \cdot 10^7$	$4 \cdot 10^9$	$1.2 \cdot 10^{11}$
Energetic species	Electron (Proton)	Electron (Proton)	Electron	Electron

Table 4. *Parameters of energetic particle fluxes in the disturbed high-latitude ionosphere*

Parameter	60 km	70 km	80 km	90 km
N, m^{-3}	10^{10}	$3 \cdot 10^{10}$	10^{11}	$3 \cdot 10^{11}$
α, m^{3}s^{-1}	10^{-11}	$3 \cdot 10^{-12}$	10^{-12}	$3 \cdot 10^{-13}$
q, m^{-3}s^{-1}	10^9	$3 \cdot 10^9$	10^{10}	$3 \cdot 10^{10}$
Π, Jm^{-2}s^{-1}	$5 \cdot 10^{-4}$	$4 \cdot 10^{-4}$	10^{-3}	$3 \cdot 10^{-3}$
p, m^{-2}s^{-1}	$7.5 \cdot 10^9$ $(2.5 \cdot 10^8)$	$1.6 \cdot 10^9$ $(4 \cdot 10^7)$	$7 \cdot 10^{10}$	$5 \cdot 10^{11}$
ε, MeV	0.5 (15)	0.2 (8)	0.1	0.04
S, m^2	10^{13}	10^{13}	10^{13}	10^{13}
P, W	$5 \cdot 10^9$	$4 \cdot 10^9$	10^{10}	$3 \cdot 10^{10}$
ΔT, s	$4 \cdot 10^4$	$4 \cdot 10^4$	$4 \cdot 10^4$	$4 \cdot 10^4$
E, J	$2 \cdot 10^{14}$	$1.6 \cdot 10^{14}$	$4 \cdot 10^{14}$	$1.2 \cdot 10^{15}$
Energetic species	Electron (Proton)	Electron (Proton)	Electron	Electron

Table 5. *Experimental and model electron fluxes*

z, km	55-60	72.5	80	84	88
p, m^{-2}s^{-1}	$2.3 \cdot 10^7$	$1.6 \cdot 10^9$	$2 \cdot 10^8$	$3.8 \cdot 10^8$	$4.5 \cdot 10^8$
p_A, m^{-2}s^{-1}	$2 \cdot 10^5$	$6 \cdot 10^6$	$8 \cdot 10^7$	$1.5 \cdot 10^8$	$6 \cdot 10^8$

The power and energy input estimates presented above are made for particles precipitating over a surface area of 10^{14} m^2 at middle latitudes (40-65°) during 11 hours ($4 \cdot 10^4$ sec) at night, and at high latitudes (70-80°) over a surface area of 10^{13} m^2 during the same time interval.

The electron fluxes p from Table 2 are shown in Table 5 where they are compared with the fluxes p_A from model A of [3]. The latter is an approximation to the satellite measurements made by many researchers during "large precipitation" events, i. e., under disturbed conditions. As can be seen from Table 5, the fluxes p and p_A are of the same order of magnitude at 80-90 km, and significantly different at 60-70 km. This suggests that the ionization at the lower altitudes is produced by precipitating protons, and the measurements made at the "Meteor" satellite on June 15, 1983, provide evidence of this.

To what extent is particle precipitation real at middle latitudes? At present, there is no doubt that the precipitation exists. It occurs at least at 35-80° latitudes [3]. At Kharkiv latitude (~50° N), the flux is equal to $10^7 \div 5 \cdot 10^8$ m^{-2}s^{-1}. The magnitude of p varies with increasing latitude and attains a maximum value at high latitudes. This parameter also significantly varies with time, depending on disturbance level in near-earth space. As noted in Introduction, electron fluxes are produced by lightning discharges, VLF transmitter signals, harmonics in the kHz range radiated by electrical power transmission lines, seismic activity, and other processes, except for the disturbances discussed in this paper.

Now, let us consider the mechanisms for the electron precipitation from the inner radiation belt. These mechanisms are usually associated with geomagnetic disturbances, resonant wave-particle interactions, and cyclotron instabilities in the magnetosphere. They lead to the violation of particle adiabatic invariants, and thus to the pitch angle scattering and precipitation into the atmosphere. The final stage before the occurrence of precipitation is apparently the same for different sources of disturbance. The initial stage depends on the type of disturbance and on its parameters. These phenomena remain poorly understood at present, except for geomagnetic storms. For instance, the mechanism of [25,33] and the quasi-steady electric fields of ionospheric origin may apparently play an essential role in high power HF effects. This suggests that the variations in quasi-steady electric and magnetic fields may result in particle precipitation after rocket launches.

The reason why the proton flare caused the particle precipitation at middle latitudes remains not understood. Generally, the proton precipitation at middle latitudes is still a poorly understood phenomenon.

Conclusions

1. Using the partial reflection technique, the existence has been confirmed of the enhancement in the electron density N in lower part of the mid-latitude D region by up to a factor of 10 after solar proton events and magnetic storms, as well as an increase in N by a factor of several times at 80-90 km altitude after some other geomagnetic storms.

2. The variations revealed in N can be explained by the enhancement in proton fluxes in the lower D region and by electron fluxes in the higher its part. The flux values are $p \sim 10^6 \div 10^7$ and $10^8 \div 10^9$ m^{-2}s^{-1}, respectively.

3. Rocket launches and high-power radio wave emissions are accompanied by the transient (minutes to tens of minutes) enhancement in electron density in the upper part of the D region on characteristic spatial scales of up to a few thousand kilometers. Most likely, the processes of the natural origin are triggered, and, ultimately, the precipitation of energetic particles from the magnetosphere occurs.

4. During such ionospheric perturbations at a distance from artificial disturbances, electron fluxes of $10 \div 100$ keV and $p \sim 10^8 \div 10^9$ m^{-2} s^{-1} have been observed.

5. Because of the limited duration and surface area, the energetics of the precipitation caused by anthropogenic effects is generally less than the energetics of the precipitation caused by natural processes.

Acknowledgments. The authors have been supported by Science and Technology Center in Ukraine (STCU) Agreement No. 471 to Kharkiv State University.

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Параметры потоков энергичных частиц, воздействующих на среднеширотную нижнюю ионосферу

Л. Ф. Чорногор, К. П. Гармаш, В. Т. Розуменко

На основе измеренных при помощи метода частичных отражений увеличений электронной концентрации оцениваются и сравниваются параметры потоков энергичных частиц, которые могли возникать в D-области ионосферы средних широт (~50° с. ш.) после протонной вспышки на Солнце, магнитной бури, старта ракеты и воздействия мощного декаметрового радиоизлучения.

Параметри потоків енергійних частинок, які діють на середньоширотну нижню іоносферу

Л. Ф. Чорногор, К. П. Гармаш, В. Т. Розуменко

На основі вимірювань за допомогою методу часткових відбиттів збільшень електронної концентрації оцінюються і порівнюються параметри потоків енергійних частинок, які могли виникнути в D-шарі іоносфери середніх широт (~50° п. ш.) після протонного спалаху на Сонці, магнітної бурі, старту ракети та під дією потужного декаметрового радіовипромінювання.