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SOME FEATURES OF THE LOWER IONOSPHERE DYNAMICS, CAUSED BY THE MORNING SOLAR TERMINATOR

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Abstract. Using a partial reflection technique, there are carried out experimental investigations of electron density variations in the middle latitude D-region of the ionosphere during the morning solar terminator passage. The electron density was found to increase by about 50-150% both during the terminator passage and after it. In order to explain such events, a hypothesis of electrons precipitating from the magnetosphere, which is caused by the solar terminator, was suggested.

Key words: solar terminator, partial reflections, electrons precipitating, lower ionosphere, electron density.

1. Introduction

The morning solar terminator (henceforward the terminator) is a moving with the Earth velocity region of sharp changes in atmospheric equilibrium; therefore it is reasonable to expect that the terminator is a powerful natural source of various spatial-temporal disturbances in the Earth's ionosphere and atmosphere. A number of papers deal with investigating such phenomena (see, e.g. Antonova et al. (1988); Beley et al. (1983a, 1983b); Bezrodny et al. (1977); Belikovich and Benediktov (1986); Gokov and Gritchin (1994); Somsikov (1983, 1991, 1992)). On the basis of analyzing data on the Doppler frequency shift of a low frequency transmitter during the terminator passage across a radio wave path, it has been found in Bezrodny et al. (1977) and Beley et al. (1983a, 1983b), that the terminator causes a quasi-periodic electron-density structure in the ionosphere, which moves in the wake of the terminator. The later papers deal mainly with studying parameters of the wave disturbances in the E- and F- regions of the ionosphere and investigating the atmosphere turbulence generation (see reviews in Somsikov (1991, 1992)). The terminator influence on the lower ionosphere D-region parameters is the least studied one, which is explained by difficulty in conducting long-time continuous (hours-days) systematic measurements. Along with other effects, we demonstrated increase in the electron density N in the D-region for the terminator passage (Gokov and Gritchin (1994)).

This paper gives results of experimental investigations of the electron density changes in the middle latitude ionospheric D-region during the morning terminator passage; these results being obtained by means of a partial reflection (PR) technique (Belrose (1970)). A possibility of electrons precipitating from the magnetosphere, which is caused by the terminator, has been considered.

2. General Information on the Terminator

It should be noted that the optical terminator width set by a time interval of the full solar disk appearing above the horizon in an optical range, is about 100 km, therefore a characteristic period of the optical terminator passage is ~ 5 min. Transitional processes in the terminator range, setting changes in the atmospheric temperature, have a larger period, which is determined by a height distribution character of the atmospheric components absorbing solar energy, and therefore the terminator range width, L, will be significantly larger (L ~1000 km), a characteristic time of the passage being Δt ~30 min in the near-equator region (Somsikov (1992)). During the morning hours, the terminator passage is accompanied by a number of physical processes in the atmosphere due to rapid increasing in the solar radiation flow. Their energy is rather high. In a similar way as it is done in

Gokov and Chernogor (2000) for the solar eclipse, we estimate changes in internal energy of atmospheric gas having the volume V and mass m:

$$\Delta E = Cm\Delta T = C\rho V\Delta T = \frac{\pi}{4}C\rho d^2 \Delta z \Delta T ,$$

where ρ is the air density, Δz is the thickness of a heated air layer, C is the specific heat of air. Assuming that near the Earth $\rho \approx 1.3$ kg/m^3, $d \approx 1000$ km, $C \approx 10^3$ J/(kg·K), $\Delta z \approx H \approx 8$ km (H being the scale height), $\Delta T \approx 5$ K, we obtain $\Delta E \approx 4.1 \cdot 10^{18}$ J. We are going to believe that temperature increasing occurs within Δt not less than 30 min. At the same time, the average power, $P = \Delta E / \Delta t$, is about $2.3 \cdot 10^{15}$ W. The estimated ΔE exceeds the energy of a 200-megaton super-atomic bomb, the estimation of P being more than an order of magnitude larger than the power used by the mankind in 2000. As seen from these comparisons, the energy and power of a heat source of disturbances, caused by the morning terminator, are rather considerable.

Evaluations of changes in the specific internal energy, $\Delta\varepsilon$, and the specific power, p, of this source give $\Delta\varepsilon = \Delta E / V \approx 4.5 \cdot 10^3$ J/m^3 and $p = P / V \approx 2.5$ V/m^3. Powerful squalls and hurricanes (typhoons) have approximately the same specific characteristics but their energy release related to air mass motions.

The evaluations given are related to a near-equator region. At the middle latitudes, a size of the region disturbed by the terminator is larger (Somsikov (1992)) due to an inclination of the Earth rotation axis. Moreover, there exists dependence of the terminator parameters on the season. Thus, according to Somsikov (1983), at a certain latitude the terminator region width changes approximately by 10% from summer to winter. As there are different temperatures on the both sides of the terminator surfaces, i.e. in the illuminated and darkened regions, which also depend on the season, the amplitude of the disturbance and its other characteristics should also change during a year.

Taking into account that the duration, Δt, of the air temperature increase is about 30-60 min, a longitudinal size of the disturbed atmospheric region is $L \approx V_t\, \Delta t$. Assuming that at the middle latitudes the terminator velocity is $V_t \approx 350$ m/sec, we obtain $L \approx 1300$ km. Let a transverse size of this region be of the same order. Then, a change in the internal energy in the atmospheric region with the radius of $L/2 \approx 700$ km, under the average value of $\Delta T \approx 5$ K, is $2 \cdot 10^{19}$ J. The average power of $6 \cdot 10^{15}$ W corresponds to it. The largest cyclone (Chernogor (1998)) has approximately the same energy, and its power is about $3 \cdot 10^{14}$ W, which is more than an order less than the power given above.

With increasing the height z, energy characteristics decrease proportionally to the gas density, $\rho \propto \exp(-z/H)$. Thus, for instance, in the ozonosphere (the average height being 45 km) ρ decreases by the order of three. For the same ΔT and H, the energy characteristics of the process related to the terminator also decrease by the order of three.

Thus, the energy, power and their specific values of the atmospheric processes caused by the morning terminator have large values. Therefore there are grounds to believe that the terminator may cause disturbances in the atmosphere not only in the shadow or light shadow but far beyond their boundaries. As in the latitude region of $\pm 45^\circ$, the terminator velocity is larger than the acoustic velocity, then in this case there is generated a shock density wave. Moreover, for the passing terminator, one should expect displaying (or enhancing) of atmospheric-ionospheric-plasmospheric relationships.

3. Equipment, methods of data measuring and processing

In order to sound the ionospheric D-region during the terminator passage, there was used a partial reflection 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 $P_t = 150$ 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} .

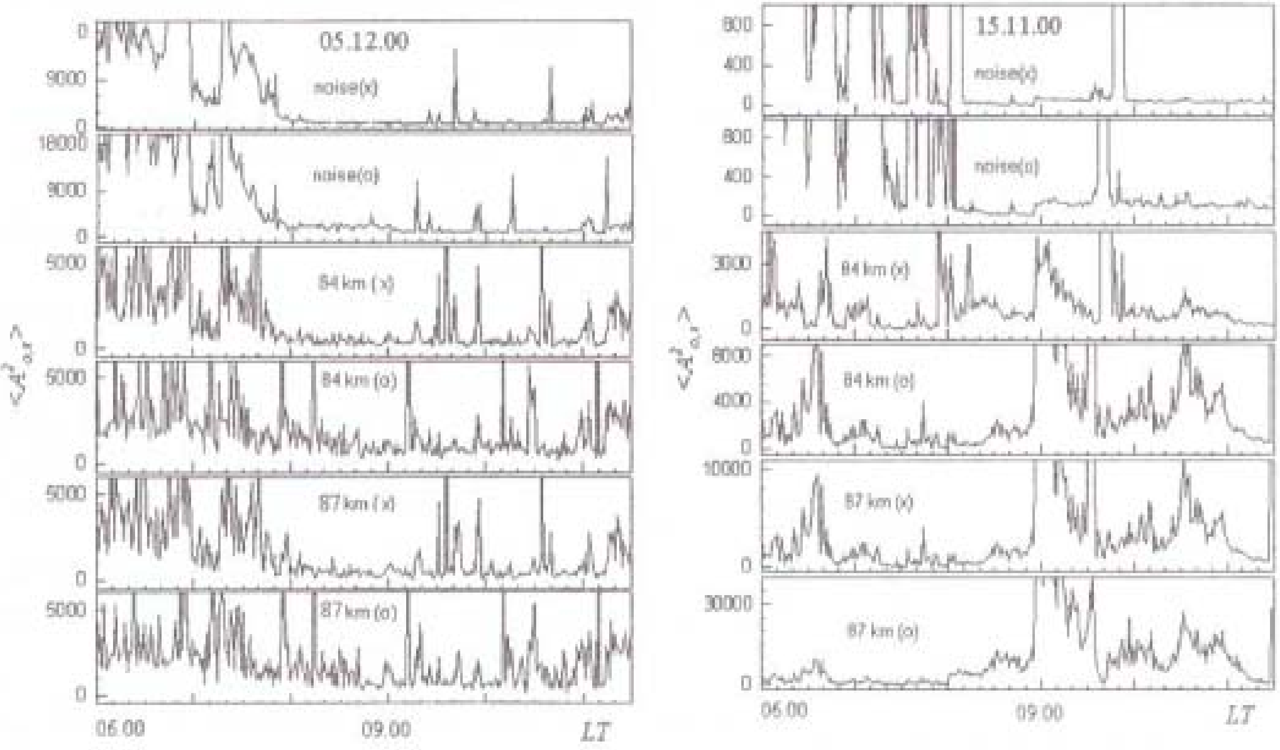
The measurements of A_{mo} , A_{mx} and A_{no} A_{nx} noise were carried out within a height range of 60-111 km for different seasons in the middle latitude near Kharkiv City (geographic coordinates: φ = 49.5°N, λ = 36.3°E) over 1990-2000. The duration of continuous measurements was not less than 5-8 hours (both 2-4 hours before and after the terminator passage). The total number of observations is about 200.

Estimating of 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, there was 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 (1970)) using the regularization algorithm (Garmash and Chernogor (1996); see also Gokov and Tyrnov (2000)) according to Tikhonov et al.(1990). 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.

4. Experimental results

Our analysis of the $N(z,t)$ value has shown that in ~ 25% of the cases during the terminator passage or soon after it (in ~30-60 min), increasing in the electron density by 50-150% takes place.



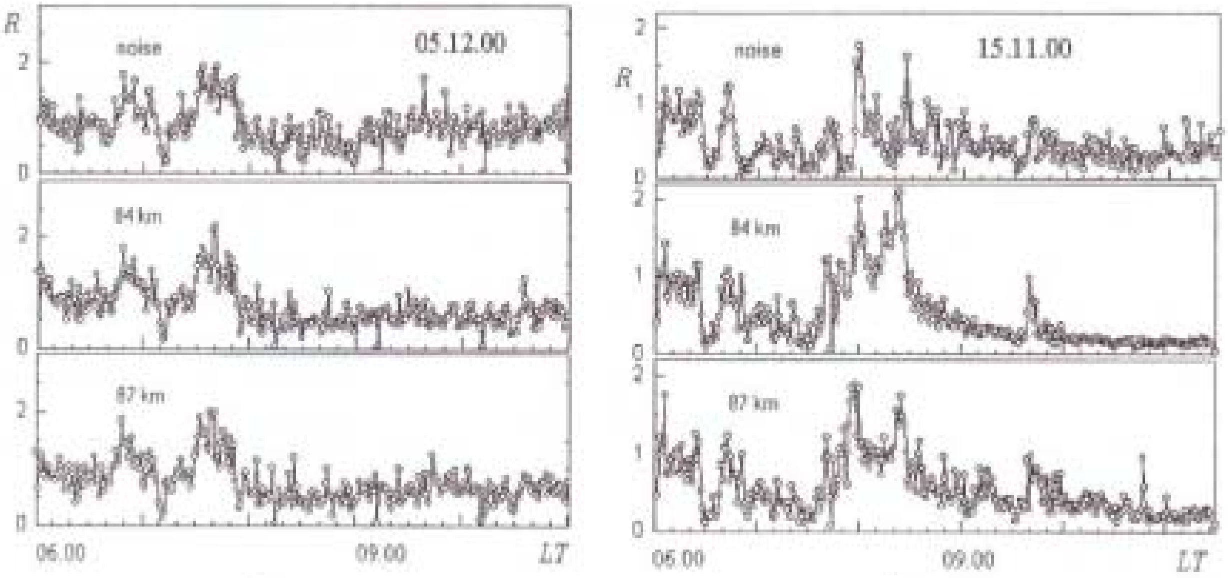
a

b

Fig. 1. Temporal dependences of radio noise and partial reflection signal intensities at the morning terminator passage.

As a typical example, we consider two experiments (on 15.11.00 and on 05.12.00) where we observed unusual behaviour of characteristics both of PR signals and noise and the electron density in the upper part of the ionospheric D-region.

Figs. 1 a,b show time changes in $<A^2_{a,x}>$, Figs. 2 a,b show *R(t)* dependences corresponding to them, and Fig. 3 shows examples of height-time changes in *N* (the moment of the terminator passage is marked with a vertical line).



a

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Fig. 2. Temporal dependences of radio noise and partial reflection signal intensities ratio, $R = <A^2_x> / <A^2_a>$, at the morning terminator passage.

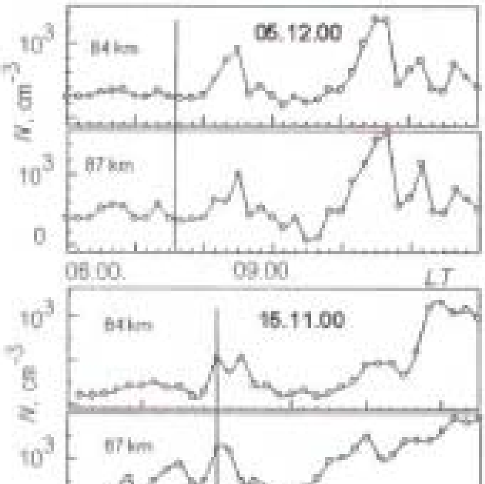

Fig. 3. Temporal variations of electron density at the morning terminator passage.

Note the main special features characteristic of other experiments as well.

1. Intensity of noise and their dispersion being several times smaller. This process starts just after the beginning of the terminator passage or some time before it (~30 min).
2. Increasing in the average intensities of a PR signal and its dispersion just after (sometimes in 10-30 min) or approximately 20-30 min before the terminator passage of ~ 30-90 min.
3. The *R* ratio being 1.5-2 times smaller after the moment of the terminator passage, and the presence of quasi-periods in the *R(t)* dependences before this moment.
4. *N* increasing during the terminator passage (in the experiment on 15.11.2000, the *N* increase is observed near the moment of the terminator passage, and on 05.12.2000 40 min after it). The duration of such events is ~ 30-90 min.

Fig. 4 shows *N(z)* profiles obtained on 22.03.1989 after the terminator passage (curves 1-3 were obtained in succession within 30 min). It is seen from the figure that over this time interval, the *N(z)* profiles did not sufficiently change.

5. Calculation results. Discussion.

Let us discuss processes in the ionospheric D-region, accompanying the terminator passage.

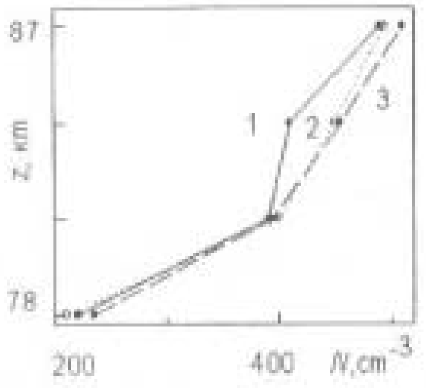

Fig. 4. Sample of $N(z)$ profiles obtained on 22.03.89 after the terminator passage.

Decreasing in the average intensities of noise and its dispersion may be explained as follows. The noise within ~2-3 MHz is a superimposition of signals from radio devices working in this range. The terminator passage is accompanied by increasing in both the electron density and radio signal absorption in the ionosphere over large areas having the characteristic size, L, of several thousand kilometers. Increasing in the absorption leads to weakening noise received by both the main lobe and lateral ones of the directivity pattern of the PR radar antenna system consisting of orthogonal vertical rhombs. An opposite effect occurs before the evening.

In order to explain the increasing in the average intensity of the PR signal and its dispersion, we take into account that (see, for instance, Chernogor (1985))

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

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

The terminator passage causes the following processes: 1) increasing in N and hence in $K_{x,o}$; 2) increasing in gas temperature and hence in ν; 3) considerable increasing in $\overline{\Delta N^2}$ (see Chernogor (1985)). All these three factors cannot fully explain the observed increasing in $<A^2_{o,x}>$. For this, it is necessary to have the contribution of the latter to be more than those of the first two. Such a situation is possible for a strong turbulization of the medium, which may be caused, for instance, by the flows of precipitating charged particles. Increasing in the dispersion of signal intensities is caused by a rate of change in the processes and also by incomplete subtracting of the noise. The noise dispersion over the same intervals increased as well.

The third effect is decreasing in the ratio of intensities, R, and of its dispersion, σ_R, after the terminator passage. As

$$R = \frac{< A^2_x >}{< A^2_o >} = \frac{\Omega^2_+ + \nu^2}{\Omega^2_- + \nu^2} \exp\{-4(K_x - K_o)\}$$

and $\Omega^2_+ >> \nu^2$, $\Omega^2_- >> \nu^2$ in the larger part of the ionospheric D-region ($z \approx 75 - 90$ km),

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

When the terminator passes, N and $K_{x,o}$ are increased. This leads to decreasing the R value. Besides, the R value becoming 2 times smaller during the terminator passage is caused by increasing in N on the average by 30 % at 70 – 80 km. The σ_R increase is related to increasing of nonstationarity of the medium.

The N increase observed during the terminator passage and after it may be aroused by the following causes:

1) ionization of NO molecules by means of scattered radiation in the Lyman-α; at the same time, $\Delta N \leq 10^7$-10^8 m^{-3}, which cannot explain the N increase observed;

2) ionization of $O_2(^1\Delta_g)$ molecules by means of scattered solar radiation at the wave length of 102.7-11.8 nm; at the same time, $\Delta N \leq 10^7$ m^{-3}, which is also small;

3) motions of the region of strong gradients of the atmospheric parameters;

4) the terminator interaction with atmospheric irregularities;

5) radiation instability caused by the large gradient of the radiation flow;

6) increasing in Railey-Taylor instability in the terminator region;

7) the presence of the magnetically-conjugated terminator causing a strong photoelectron flow from the magnetically-conjugated region;

8) ionization by means of energetic electron flows.

Out of the given sources, a flow of electrons from the radiation belt seems to be the most possible. Importance of the middle latitude particle precipitation was repeatedly discussed (see, for instance, Garmash et al (1999); Gokov and Gritchin (1996); Gokov and Tyrnov (2000); Lastovicka and Fedorova (1976); Knut and Fedorova (1977); Hargreaves (1979)). 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. Moreover, in the process of forming and relaxing disturbances of the conductivity tensor of the ionospheric plasma, the polarization field, E_p, has a vortical component, E_r, as well. The latter mechanism is considered in Garmash et al. (1998); Garmash and Chernogor (1989); Garmash and Chernogor (1995); Garmash and Chernogor (1998). Under the terminator passage considerable changes in the ionospheric plasma conductivity tensor and variations of the electric field components E_p and E_r are possible and hence the $\varepsilon_\perp$ components are possible as well.

On the basis of the suggested mechanism of high energy electrons 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); Gokov and Chernogor (2000); Lyatsky and Maltsev(1983); Lastovicka and Fedorova (1976); Knut and Fedorova(1977); Knut and Vurzburger (1976); Hargreaves (1979) for ionospheric disturbance sources of different 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, $q_o = \alpha_o N_0^2$ 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, 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. (1988)) $P_1 \approx 2\varepsilon_i \Delta z \Delta q = \varepsilon p$, 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 durations, Δt, may be estimated for the relationships of $P = P_1 S$ and $E = P \Delta t$. In calculations on the basis of analyzing PR signals and $N(z,t)$, there was used $\Delta t = 1{,}2\ 10^3$ sec.

Calculation results of the given values for the experiments discussed are presented in Table 1.

For convenience of the calculations, we took Δz =10 km, it was also assumed that the energy of precipitating electrons was ε >40 keV, which was rather correct (see, for instance, 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 increasing in the electron density, N, observed at 81-87 km. Estimations of E_p and E_r using method from Garmash et al. (1988); Garmash and Chernogor (1998), with account of the calculations conducted, showed that the mechanism discussed might be used for explaining the observed N changes.

Table 1. The electron flow parameters.

Date	05.12.00		15.11.00	
z, km	84	87	84	87
N_0, m^{-3}	3.5 10^{8}	4.2 10^{8}	2.5 10^{8}	3.5 10^{8}
N, m^{-3}	7.5 10^{8}	8.0 10^{8}	4.8 10^{8}	8.0 10^{8}
q_0, m^{-3}sec^{-1}	0.7 10^{6}	1.8 10^{6}	0.4 10^{6}	1.3 10^{6}
q, m^{-3}sec^{-1}	3.4 10^{6}	6.4 10^{6}	1.5 10^{6}	6.4 10^{6}
P_f, J m^{-2}sec^{-1}	1.9 10^{-7}	5.1 10^{-7}	4.1 10^{-7}	1.4 10^{-7}
p, J m^{-2}sec^{-1}	1.8 10^{7}	3.4 10^{8}	2.8 10^{7}	9.4 10^{7}
ε, MeV	0.1	0.04	0.1	0.04
S, m^{2}	10^{14}	10^{14}	10^{14}	10^{14}
P, w	2.9 10^{8}	5.1 10^{7}	4.1 10^{7}	1.4 10^{7}
E, J	3.1 10^{11}	6.1 10^{10}	4.9 10^{10}	1.7 10^{10}
Δt, sec	1.2 10^{3}	1.2 10^{3}	1.2 10^{3}	1.2 10^{3}

6. Conclusion

1. An increase in the electron density by ~50-150% was experimentally found both during the morning solar terminator passage and after it.

2. Within the hypothesis of electrons precipitating from the magnetosphere, calculations were carried out, and the possibility of electron precipitation caused by the morning solar terminator was shown.

3. The estimations of the electron flows densities with energies of 40-80 keV leads to the values of 10^7-10^8m^{-2}sec^{-1}.

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