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Studies of the structure and dynamics of the *D* region of the polar ionosphere during solar flares in April 2004

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[1] The results of observations of the polar lower ionosphere by the partial reflection method during moderate solar flares in April 2004 are presented. The structure of the electron concentration profile in the ionospheric *D* region and the effects of the impact on it of X-ray radiation of the flares both in quiet and disturbed conditions are considered. It is shown that at altitudes below 75 km the electron concentration is proportional to the intensity of X-ray radiation from a solar flare. This manifests the existence of a linear recombination law at these heights. *INDEX TERMS:* 2479 Ionosphere: Solar radiation and cosmic ray effects; 2435 Ionosphere: Ionospheric disturbances; 2419 Ionosphere: Ion chemistry and composition; *KEYWORDS:* Lower ionosphere; Solar flares; Electron concentration.

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1. Introduction

[2] For the creation of a dynamical model of the lower ionosphere a detailed study of spatial–time variations in the ionospheric *D* region caused by disturbances of various nature is needed. Chromospheric solar flares are among the most important natural sources of disturbances [*Mitra*, 1974]. In the ground-based observations, solar flares are manifested as a result of pulse ionizing impact on the atmosphere of the Earth: splashes of X-ray and ultraviolet emissions, cosmic ray fluxes, subrelativistic protons of the polar cap, and auroral electrons. Their interaction to the atmosphere leads to a series of effects: sudden increase of the electron concentration in the lower ionosphere, changes in the *D*-region structure, increase in the absorption of MF and HF radio waves, and others [*Al'pert*, 1972; *Belikovich et al.*, 1975; *Garmash et al.* 1999; *Mitra*, 1974]. Occurrence of the flare is detected on the basis of such radio events as solar radio emission bursts, sudden phase anomaly (SPA) at a very low frequency, sudden enhancement in atmospherics (SEA) and sudden absorption of the sudden cosmic noise absorption (SCNA) [*Davies*, 1990; *Hargreaves*, 1995; *Hunsucker and Hargreaves*, 2003].

[3] Studies of these effects provide information on the main physical and chemical processes occurring in the ionosphere under the influence of the ionizing radiation of solar flares. For example, measurements of the electron concentration vertical profiles and fluxes of X-ray radiation from solar flares make it possible to find the effective recombination coefficient [*Belikovich and Itkina*, 1972; *Belikovich et al.*, 1976; *Hunsucker and Hargreaves*, 2003; *Mitra*, 1974]. The analysis of the simultaneous measurements of the effective loss rate of electrons and the electron concentration observed experimentally during flares led to the conclusion on the significant role of cluster ions in the loss processes [*Danilov*, 1989; *Mitra*, 1974]. However, there are still very few such measurements during flares, especially at high altitudes. Moreover, every solar flare presents a unique event. Therefore, in order to increase the reliability of the available information on the main parameters and processes in the lower ionosphere an increase in the observations is needed. The goal of this paper is studying of the reaction of the polar lower ionosphere to solar flares of the M class using the data of the partial reflection installation of the Polar Geophysical Institute.

2. Installation Parameters and Method of Studies

[4] The method of partial reflections is one of the ground-based methods of quantitative studies of the flare effects in the lower ionosphere [*Mitra*, 1974]. The characteristics and structural scheme of the measuring partial reflections installation of PGI were described by *Tereshchenko et al.* [2003]. The installation is located in the vicinity of Tumanny town of the Murmansk Region (69.0°N, 35.7°E). The observations

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were conducted at frequencies of 2.65–2.78 MHz at the pulse power of the transmitter about 60 kW and pulse duration of 15 μs. The reception of the scattered signals was conducted by receiving-transmitting antenna with the directivity diagram of $19 \times 22^\circ$ at the half-power level. Two circular polarizations were received in turn and were amplified by the receiver with the band of 40 kHz. The registration of the signal amplitudes was performed in the height interval 50–146 km. The step of the data reading was 1.5 km. The receiving instrumentation was equipped by a quick-operating multichannel analog-digital transformer and computer for reception, processing, and analysis of the data. The amplitudes of the ordinary and extraordinary components of the signal were averaged over every minute at all registered altitudes. These data were used for the general estimation of the observation results and then were averaged over time intervals 5–15 min. Using the averaged data, the electron concentration profile $N_e(h)$ was calculated by the method of differential absorption of radio waves described by *Belikovich et al.* [2003a, 2004].

[5] To obtain the concentration as a function of height in the differential absorption method [*Belrose and Burke*, 1964], the difference in absorption along the trajectory of propagation of ordinary and extraordinary waves is used. It is assumed that the electron collision frequency vertical profile is known from some other independent data. The method makes it possible to calculate the vertical profile with a vertical shift of $\pm 1 - 2$ km relative to the corresponding profile of the amplitudes of the scattered signal.

[6] Extra geophysical equipment was used at carrying out the measurements: the installation for ionospheric drift measurements on the basis of the space diversity reception of the scattered signal, magnetometer, and riometer at a frequency of 32 MHz.

3. Results of Measurements

[7] During the period of measurements from 31 March to 14 April 2004 several chromospheric flares occurred on the Sun (the data are taken from ftp://ftp.ngdc.gov/stp/solar.data). The strongest of them were observed in the following moments and were characterized by the following fluxes of the X-ray radiation in the 1–8 Å range: (1) beginning on 5 April at 0533 UT, maximum at 0555 UT, end at 0614 UT, the flux 0.028 erg cm^{-2} s^{-1}; (2) beginning on 6 April at 1230 UT, maximum at 1328 UT, end at 1344 UT, the flux 0.032 erg cm^{-2} s^{-1}; (3) beginning on 8 April at 0953 UT, maximum at 1019 UT, end at 1047 UT, the flux 0.015 erg cm^{-2} s^{-1}; and (4) beginning on 11 April at 0354 UT, maximum at 0419 UT, end at 0435 UT, the flux 0.013 erg cm^{-2} s^{-1}.

[8] Figure 1 shows time-altitude dependence of the amplitude of the reflected extraordinary wave A_x and electron concentration N_e in the ionospheric D region during the flare on 5 April 2004. The flare duration is shown in Figure 1 by the segment of direct line. The values of the electron concentration were found using 5-min averaging and the inverse function. Figure 1 shows that during the flare at heights of the D and E regions there occurs a considerable depletion of the intensity of the radio echo of extraordinary polarization. The electron concentration in the lower ionosphere increases.

[9] The measurements period was characterized by fairly high solar and geomagnetic activity. Because of this the majority of days in Tumanny town was characterized by auroral disturbances. Only 2 April and 14 April were quiet days and that made it possible to use these days for the comparison.

[10] Figure 2 illustrates the influence of the M-class solar flare on the structure of the D region of the polar ionosphere. The values of the electron concentration were obtained with 1-min averaging. Dashed curves in Figure 2 show the time profile of the solar X-ray radiation (according to the data of the GOES 10 satellite). The maximum values of the flux on 5 April were 2.9×10^{-6} W m^{-2} and 1.63×10^{-5} W m^{-2} in the ranges 0.5–3 Å and 1–8 Å, respectively. Figure 2 shows that the flare produced a considerable increase in the electron concentration at altitudes below 85 km. The increase of the electron concentration was accompanied by changes in the lower ionosphere structure, in particular, by appearance of a two-layer region of additional ionization observed during 40 min. The time behavior of the additional ionization corresponded to the variations in the intensity of the X-ray radiation of the flare in the ranges 0.5–3 Å or 1–8 Å. Calculations of the electron concentration profiles based on theoretical models of the ionization [*Smirnova et al.*, 1988] before and during the flare in question confirm the statement that the effect of sudden ionospheric disturbances in the D region is actually caused by the solar hard X-ray radiation.

[11] Figure 3 shows vertical profiles of the electron concentration averaged over 10 min in quiet conditions (dashed curves) and at the maximum intensity of the solar flares on 5, 6 and 8 April (solid curves). The flares on 5 and 6 April occurred in the conditions of relatively weak auroral disturbance. On the background of this disturbance the additional ionization produced by the flare was distinctly seen. The maximum electron concentration was $(0.7 - 1.0) \times 10^3$ cm^{-3} and $(1.5 - 2.7) \times 10^3$ cm^{-3} in the height ranges 64–70 km and 77–79 km, respectively. During the flares on 8 and 11 April, an auroral disturbance occurred in Tumanny. The electron concentration in the lower D region reached values of 1.7×10^3 cm^{-3} and the additional ionization of the flares almost was not seen.

[12] The increase of the ionization in the lower D region is in a good qualitative agreement with the well-known effect of the increase of the amplitude of long radio waves [*Al'pert*, 1972; *Belikovich et al.*, 1975; *Mitra*, 1974] and of the changes in their phase height [*Davies,* 1990; *Hargreaves*, 1995].

[13] Figure 4 shows the power spectrum of the fluctuations of the electron concentration during the flare on 5 April 2004. The power spectrum of the fluctuations was calculated using the direct Fourier transformation of the autocorrelation function for the 60-min series of the data and was smoothed using the Tiuki spectral window [*Jenkins and Watts*, 1969, 1970]. One can see a manifestation of wave-like variations in the isolines of the electron concentration in Figure 2. Variations of the ionization in the polar lower ionosphere during the flares were accompanied by generation of atmospheric waves with periods longer than 3 min.

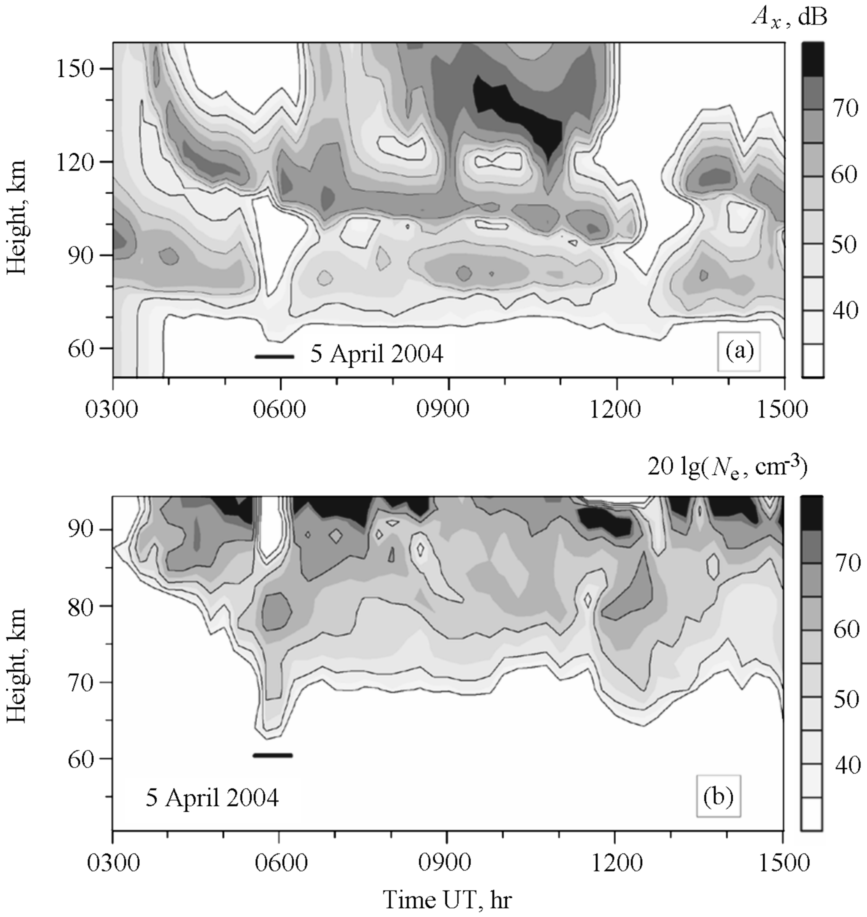

Figure 1. (a) Amplitude of radio echo of the extraordinary wave and (b) the electron concentration as a function of time and height.

[14] According to the data of space diversity reception of the scattered radio waves during the flare a drift of ionospheric irregularities with a velocity of not more than 100 m s^{-1} was detected. The presence of the horizontal velocity shear and the change of the direction of its azimuthal component to the opposite one was an interesting feature of the observed drifts in the moment of the flare maximum intensity.

[15] Figure 5 shows the riometer recordings at the frequency of 32 MHz containing splashes of the space radiation

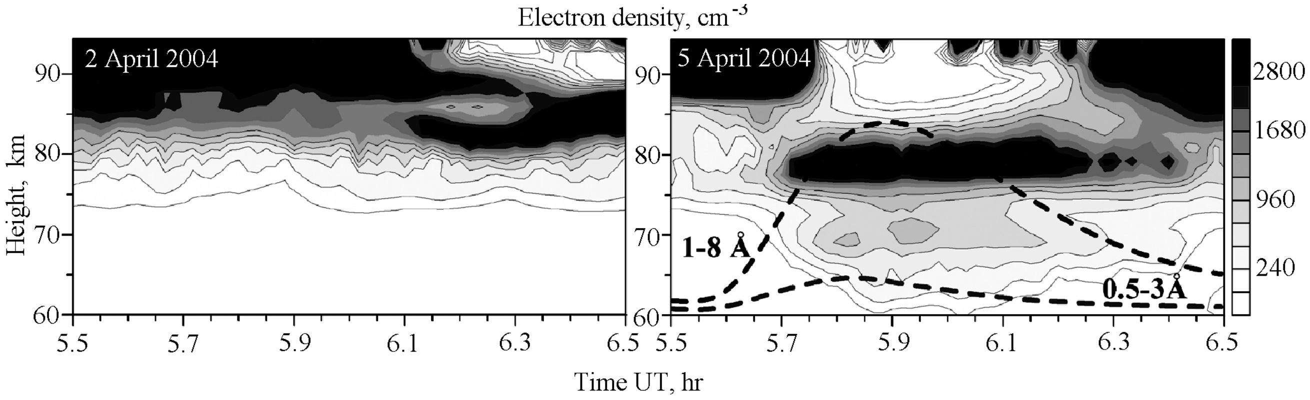

Figure 2. Time-altitude dependence of the electron concentration in a quiet day on 2 April and during the X-ray solar flare on 5 April 2004.

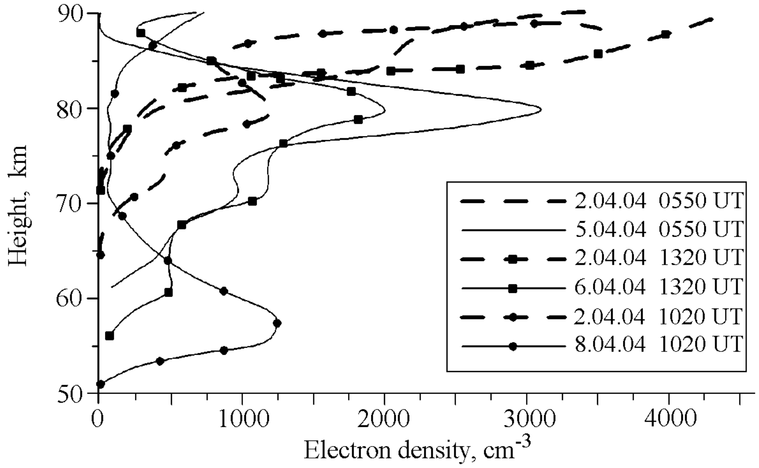

Figure 3. Vertical profiles of the electron concentration at maximum intensity of solar flares on 5, 6, and 8 April and in quiet conditions on 2 April 2004.

during solar flares. The vertical segment in Figure 5 shows the scale of the relative measurements of the cosmic noise level. It is worth noting that similar recordings of "interferences" to riometer operation in a wide frequency range were detected also at the Finnish chain of riometer stations [*University of Oulu*, 2004]. The comparison of the splashes in the riometer recordings at remote stations at several frequencies with the solar phenomena occurring during this time makes it possibly to conclude that the "interferences" to riometers are not of a local origin but are generated by solar sporadic radiation. In the considered cases the splashes occurred at the phase of development of a solar flare and lasted about 10–15 min. (0540–0550 UT on 5 April, 1230–1245 UT and 1310–1325 UT on 6 April). Such splashes of the space radioemission in the meter and decameter ranges were numerously observed at high-latitude riometer stations [*Brunelli and Los'*, 1973; *Hunsucker and Hargreaves*, 2003]. It is assumed [*Akasofu and Chapman*, 1975] that these splashes are produced by synchrotron radiation of high-energy particles emitted by the disturbed regions on the Sun. Therefore such parts of the recordings may be used for obtaining of additional information on the fluxes of high-energy solar particles.

4. Analysis

[16] The relation between the intensity of the X-ray radiation of the flare and anomalous ionization in the ionospheric *D* region needs more detailed consideration. To do this, it is interesting to compare the changes in the electron concentration Ne with the behavior of the intensity of the flare X-ray radiation I and a square root of the intensity $I^{0.5}$. For calculation of the dependencies at fixed altitudes of the *D* region, the 5-min data of the X-ray radiation flux and electron concentration were used. As an example, Figure 6 shows such dependencies for the X-ray radiation flux in the range 1–8 Å from the flare on 5 April 2004 at altitudes of 72.4 and 77.5 km. At these altitudes the significance coefficients were the maximal and equal to 0.98 and 0.94, respectively. The calculations show that at altitudes below 74 km the significance coefficient for the $N_e(I)$ dependence is higher then the coefficient for the $N_e(I^{0.5})$ relation, that is there presents a linear relation in the considered region between the intensity of the X-ray radiation (proportional to the ionization rate) and electron concentration. At altitudes from 75 km to 81 km the significance coefficient is

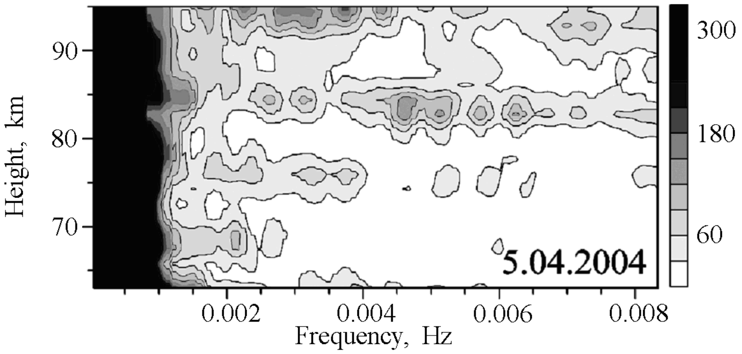

Figure 4. Hourly spectrum of the power of fluctuations in the electron concentration in the ionospheric *D* region during the solar flare on 5 April 2004.

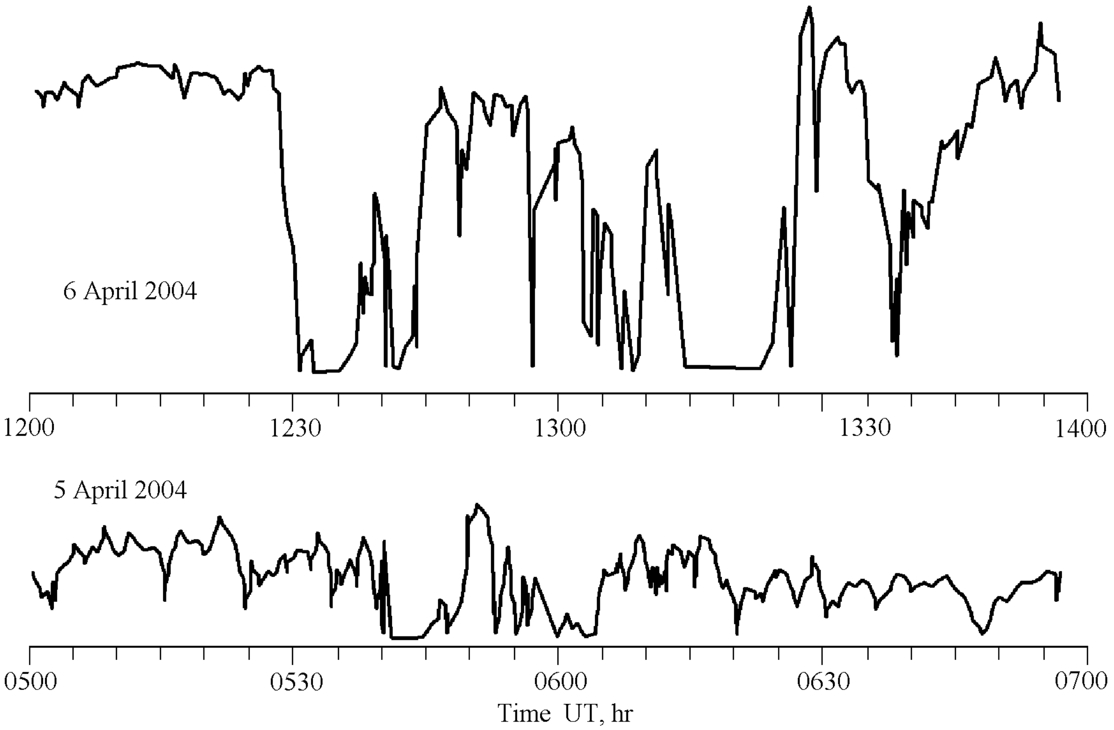

Figure 5. Riometer recordings at a frequency of 32 MHz in Tumanny during solar flares.

higher for the $N_e(I^{0.5})$ dependence; that is, a quadratic recombination law is observed. Thus linear recombination law and quadratic recombination law are observed in the lower part of the D region and at higher altitudes, respectively. It should be noted that the conclusion on the linear relation between the ionization rate and electron concentration variations in the daytime has been earlier obtained by *Belikovich et al.* [2003b].

[17] According to *Belikovich et al.* [2005] the linear recombination law in the D region may be explained on the basis of the hypothesis of intense recombination of positive and negative charges on dust-like particles. The number of

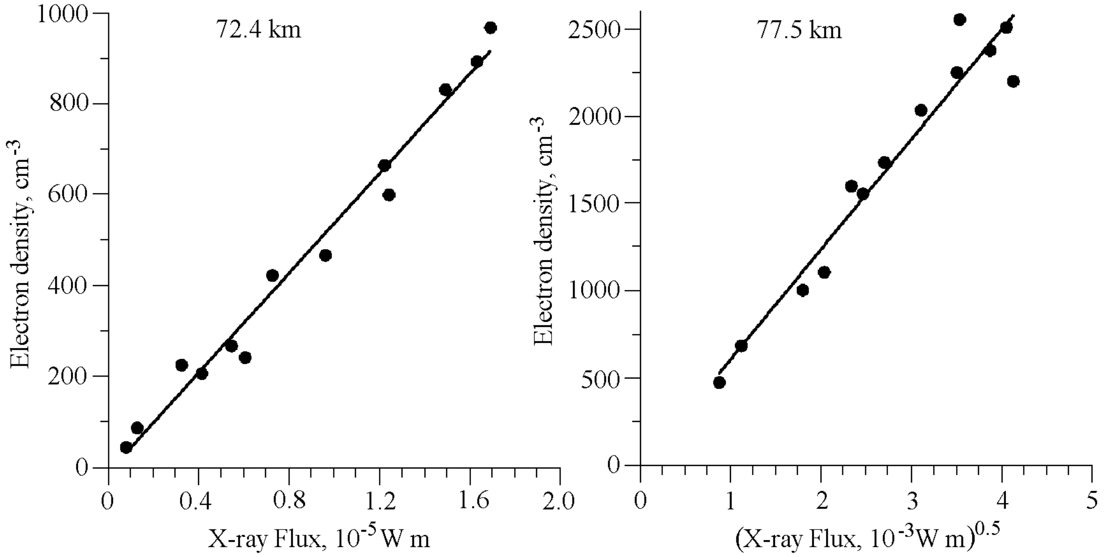

Figure 6. Dependence of the electron concentration on the intensity of the X-ray radiation of a solar flare in the 1–8 Å range.

particles in a volume unit is limited and is not related to the value of the electron concentration. The term prevailing in the balance equation and containing the concentration of dust-like particles leads to the linear recombination law. Above 80 km atomic oxygen presents in the atmosphere and prevents cluster formation. Because of that the quadratic recombination law begins to work.

[18] One can explain the increase in the electron concentration during flares by variations in the ion composition of the ionospheric *D* region. It is known [*Danilov*, 1989; *Mitra*, 1974] that the portion of the rapidly recombining complex clustered ions in the total amount of positive ions decreases. Theoretical models of the ion composition based on the ion chemistry [*Smirnova et al.*, 1988], in particular conditions of the polar ionosphere, lead to the same conclusion. The calculations show that considerable destruction of clustered ions under the action of an X-ray solar flare of the M importance occurs in the lower ionosphere below 70 km. The depletion of the clustered ions content leads to a significant depletion of the effective recombination coefficient at altitudes of 65–95 km. The decrease in the effective recombination coefficient is accompanied by an increase in the electron concentration.

[19] The trough in the electron concentration vertical profile at a height of 80 km (see Figure 3) during the maximum of the 5 April flare can be related to the instrumental features of the partial reflections method and conditions in the environment. Apparently, the existence of high electron concentration and strong absorption during a solar flare limits the height up to which the data could be obtained by this method at a single frequency. However, the latter assumption requires a thorough checking.

5. Conclusions

[20] Thus a two-layer region of additional ionization with the maximum electron concentration of 2.7×10^3 cm^{-3} is detected during moderate solar flares in the polar ionosphere at heights below 85 km. Ionospheric effects of the X-ray solar flares were accompanied by an intensification of the MF radio wave absorption, splashes of the meter space radiation, and generation of infrasound waves with a period of about 3 min and more. The effects of solar flares depend on geophysical conditions in the ionosphere. They are manifested in the most visual way at the absence of disturbances. It is shown that at heights below 75 km the electron concentration is proportional to the intensity of X-ray radiation, the fact indicating that there is a linear recombination law and dust-like particles play a significant role. The detected features in the electron concentration behavior during solar X-ray flares need further experimental studies and theoretical explanation.

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