Ionospheric Storms Associated with Geospace Storms as Observed with the Kharkiv Incoherent Scatter Radar

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Abstract. This paper is concerned with the Kharkiv incoherent scatter radar (ISR) measurements taken during the September 25, 1998, March 20–21, 2003, May 29–30, 2003, and November 7–10, 2004 storms. The storms have been shown to be accompanied by significant disturbances in the ionospheric parameters in midlatitude Central Europe. The disturbances are interpreted in terms of thermospheric disturbances, Joule heating, particle precipitation, the penetration of magnetospheric electric fields to midlatitudes, and the shift of the auroral oval and other polar region structures to the Kharkiv radar field of view. The analysis has permitted the regular and specific features of the evolution of the ionospheric storms to be distinguished and separated into two groups.

Keywords: incoherent scatter radar (ISR), ionospheric storms, geospace storms

Introduction

Ionospheric storms are one of the manifestations of space weather disturbances. The analysis of each storm provides valuable information for forecasting of the regional ionospheric response to disturbances on the Sun. The aim of this paper is to present the main features of ionospheric storms observed by the Kharkiv (49°40' N, 36° 18' E) incoherent scatter radar (ISR) [1, 2]. The ionospheric, magnetic, atmospheric, and electric storms are a manifestation of the geospace storm [3 – 5]. Their studies contribute enormously to understanding of coupling between the subsystems in the Sun-Earth system [3 – 5].

The magnetic storm of September 25, 1998

The severe magnetic storm of September 25, 1998 (Dst = – 200 nT, Kp= 8+) followed the M6/3B solar flare on September 23, 1998 and was initiated by the arrival of the interplanetary shock on September 24, 1998 at ~23:00 UT (Fig. 1). The strong negative ionospheric storm commenced soon after 01:00 UT on September 25, 1998 and persisted at least to the end of the measurement campaign. The storm was accompanied by a decrease in the ionospheric F2 peak electron density (NmF2) during the main phase of the storm by a factor of 3–3.5 and the uplifting of the F2 region by 100 km at night and 50 km near noon (Fig. 2).

The analysis has revealed that one of the causes of the decrease in NmF2 could be an equatorward shift of the main ionospheric trough. This conclusion has been confirmed by the analysis of global total electron content (TEC) maps derived from arrays of GPS receivers.

Fig. 1 shows the peak density of the daytime F2 layer (NmF2) and the altitudes of the F2 and F1 peaks as measured by the Kharkiv incoherent scatter radar (ISR) during the magnetic storm of September 25, 1998. The vertical plasma drift velocities Vz and the estimated vertical component of the diffusion velocity Vdz, the meridional component of the neutral wind velocity Vnx, and the velocity W that takes account of both electric field and neutral wind effects at an altitude of 300 km are presented in Fig. 2.

The prominent feature of this storm is an unusual increase in the upward plasma drift velocity in the morning hours on September 25, 1998 up to a value of Vz ≈ 50 m/s, whereas on the quiet day September 23, 1998, Vz ≈ –25 m/s (Fig. 3). The Vz disturbance is shown to be an equatorward storm-induced surge in the meridional component of a neutral wind of Vnx ≈ 270 m/s induced by a traveling atmospheric disturbance (TAD) and/or an electric field pulse with the eastward zonal component of Ey ≈ 12–13 mV m–1.

The magnetic storm of March 20-21, 2003

The minor magnetic storm of March 20–21, 2003 (Dst =–57 nT, Kp = 5) occurred against the background of high Solar flare activity, but the geoefficiency of the flares was low (Fig. 4).

The ionospheric storm of March 20–21, 2003 occurred during a minor geomagnetic storm and exhibited a two-phase character, an initial positive phase (an increase in NmF2 by a factor of 1.5) and a subsequent deep negative phase (a decrease in NmF2 by a factor of 5), Fig. 5 and 6. The analysis of the event has shown that the destabilizing impact of the electric field pulse and the traveling atmospheric disturbance generated by the magnetospheric substorms could be the cause of the phase change in the ionospheric storm that occurred during the sunset period.

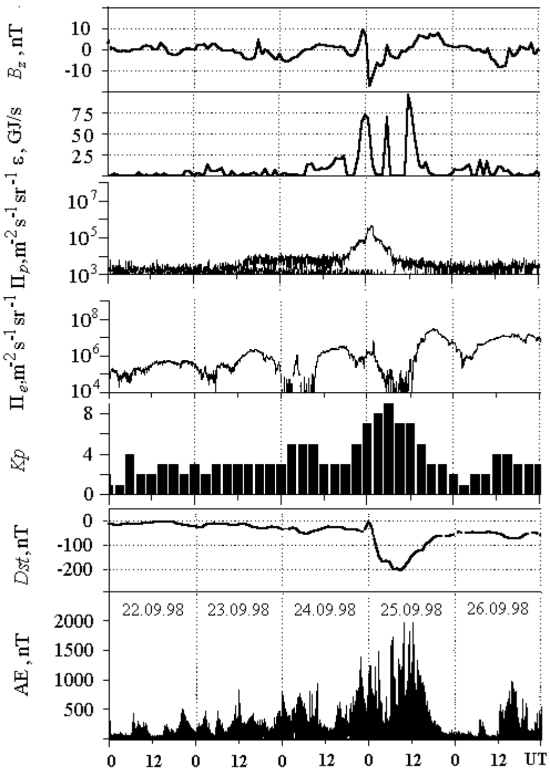

Fig. 1. The solar-geophysical conditions on September 22-26, 1998: B_z-component of the IMF (the ACE Satellite magnetometer), the Akasofu function ε (energy injected by the solar wind into the Earth's magnetosphere per unit of time), the proton fluxes Π_p (GOES 8 (W75)), the electron fluxes Π_e (GOES 8), the planetary *Kp* index (http://spidr.ngdc.noaa.gov/spidr/index.jsp), the hourly *Dst* indices (WDC-C2 for Geomagnetism, Kyoto University), and the *AE* index (WDC Kyoto). Here, the proton fluxes are presented with energies greater than 10, 50, and 100 MeV, and the electron fluxes with energies greater than 2 MeV.

Figure 3 shows time variations in the deviations of the critical F2-layer frequencies from the median values, the ionospheric F2 peak densities (NmF2), and the altitude of the F2 peak (hmF2) before, during, and after the magnetic storm of March 20–21, 2003. The variations of the electron density (log Ne), the electron Te and ion Ti temperatures, and the vertical plasma drift Vz are presented in Fig. 4.

The positive storm phase on March 20, 2003 lasted approximately for 6 hours, and it could be caused by the enhanced equatorward meridional wind related to high-latitude thermospheric heating (Fig. 4).

The magnetic storm of May 29-30, 2003

This severe magnetic storm (Dst =–108 nT, Kp= 8+, Fig.7) was caused by the arrival of two interplanetary shocks from the X1.3 and X3.6 flares on May 27–29, 2003.

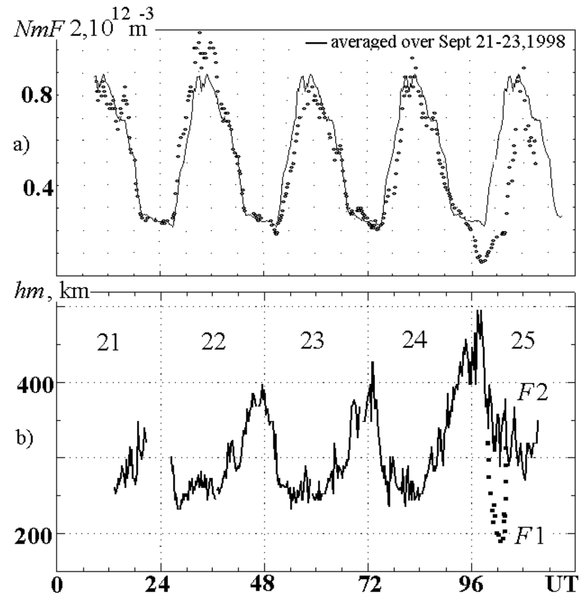

Fig. 2. Time variations of (a) ionospheric F2 peak densities N_mF2 and (b) heights h_m above the Kharkiv ISR on 21-25 September 1998 starting from the midnight on 21 September (heights h_m less than 200 km are attributed to the F_1-layer peak altitude). LT ≈ (UT + 02:25).

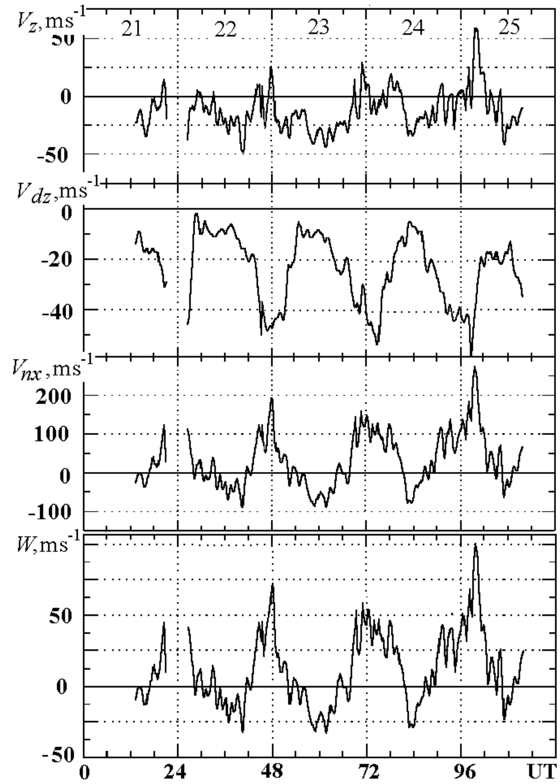

Fig. 3. The measured vertical plasma drift velocity V_z (the radar data acquired on 21-25 September 1998) and the calculated vertical component of the velocity due to diffusion V_{dz}, meridional component of the neutral wind velocity V_{nx}, and the velocity W that takes account of both electric field and neutral wind effects at an altitude of 300 km.

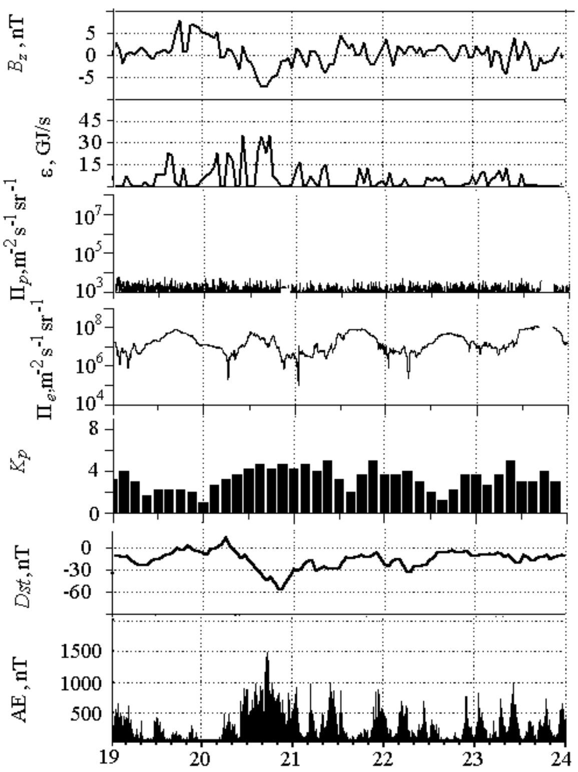

Fig. 4. The solar-geophysical conditions on March 19–23, 2003.

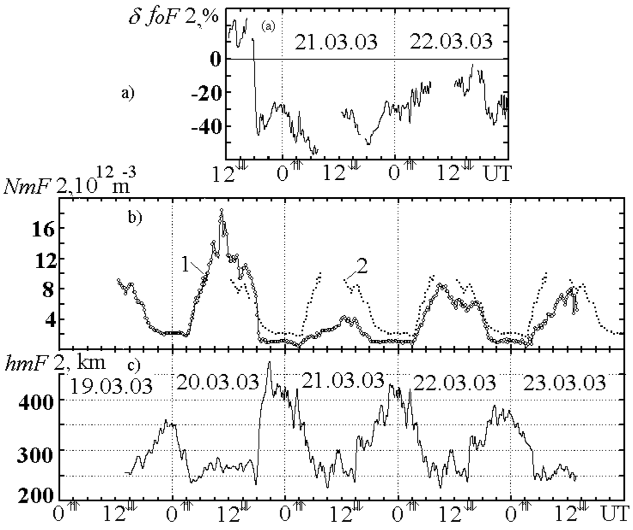

Fig. 5. Time variations (a) in the deviations of critical F2-layer frequencies f_oF2 measured with the Kharkiv ionosonde in comparison with a reference day data during the two-phase ionospheric storm of March 20–22, 2003; (b) in ionospheric F2 peak densities N_mF2 calculated for 19-23 March 2003 from the Kharkiv ionosonde data (curve 1) and calculated for the reference day 19 March 2003 from the ionosonde data at San Vito (over the 0000–0730 UT interval) and at Kharkiv (over the 1230–2400 UT interval) (curve 2); and (c) ionospheric F2 peak heights h_mF2 from the Kharkiv ISR data. LT ≈ (UT + 02:25).

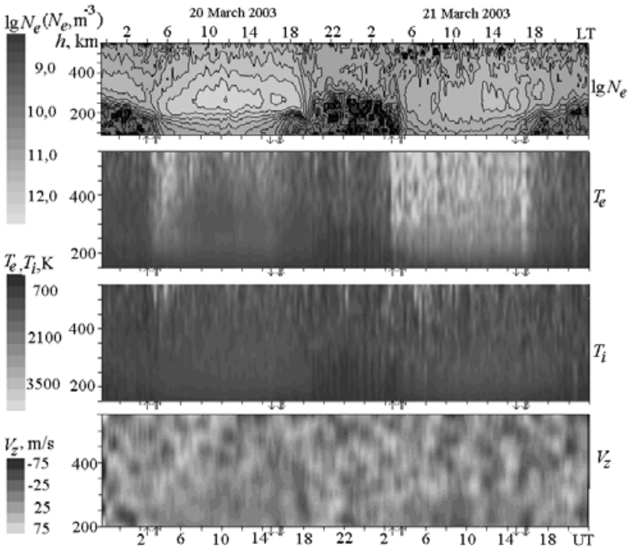

Fig. 6. Variations of the ionospheric parameters on March 20–21, 2003: the electron density (log N_e), the electron T_e and ion T_i temperatures, and the vertical plasma drift V_z.

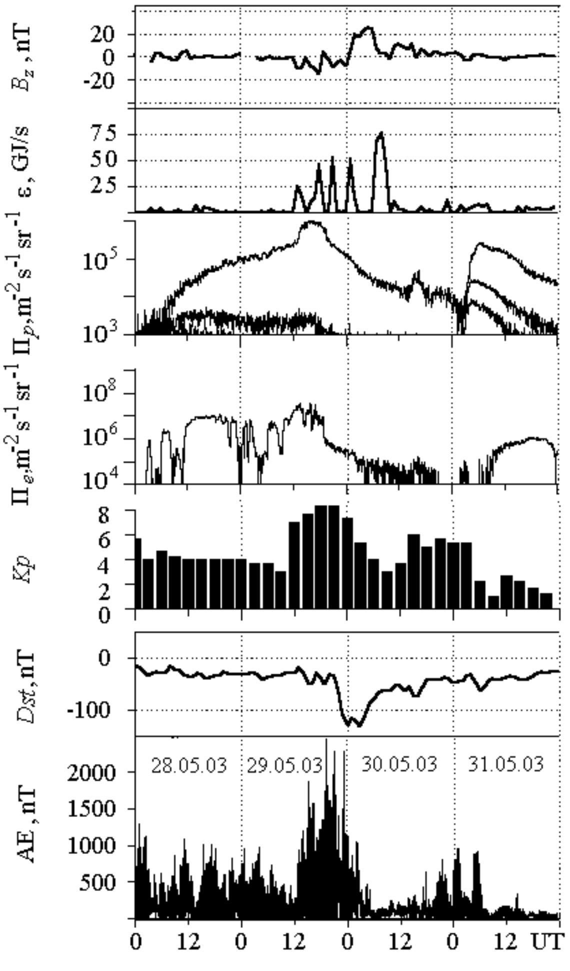

Fig. 7. The solar-geophysical conditions on May 28–31, 2003.

The magnetic storm was accompanied by a decrease in NmF2 by a factor of 4, unusual plasma heating at night on May 29–30, 2003, an uplifting of the ionospheric F2 region by 160 km at night and by 70 km near noon, and a decrease in the N(H+)/Ne ratio more than by an order of magnitude (Fig. 8). One of the causes of these phenomena could be the shift of the main ionospheric trough, the light ion trough, and elevated electron temperatures associated with the sub-auroral red arc thermal phenomenon towards the Kharkiv radar site (geomagnetic latitude of 45.7°). The equatorward shift of these structures was indirectly confirmed by the maximum values of the POES Auroral Activity Level equal to 10, [http:\\www.sec.noaa.gov\Aurora\ index.html], which could manifest the shift of the auroral oval equatorward boundary towards geomagnetic latitudes ≈ 51–45°. Thus, the Kharkiv radar could be situated within the trough close to the midnight sector during the storm main phase.

The variations in the electron density (log Ne), the electron Te and ion Ti temperatures, the relative hydrogen ion densities N(H+)/Ne, and the vertical component of the plasma drift velocity Vz are presented in Fig. 5 for the 29–31 May 2003 storm. Figure 6 shows the vertical profiles of electron density Ne obtained at dawn and the subsequent time period in 15 min during disturbed day on May 30, 2003.

The geomagnetic storm was accompanied by a strong negative ionospheric storm when a depletion of NmF2 by a factor of up to 4 during the storm main phase occurred. Unusual plasma heating was observed during the night of May 29–30, 2003 when the ion and electron temperatures increased up to the daytime values of 1200–2400 K at 300-km altitude and 2000–3200 K at 800-km altitude, whereas the values of these temperatures were about 800 K at night under quiet conditions.

The magnetic storms of November 7-10, 2004

This magnetic storm presents a sequential occurrence of two severe magnetic disturbances on November 7–8, 2004 and November 9–10, 2004 (Dst = –373, –289 nT, Kp = 8+, 9–, respectively, Fig. 9).

Fig. 7 shows time variations in electron density, the electron Te and ion Ti temperatures, the relative hydrogen ion densities N(H+)/Ne, as observed on November 8–13, 2004.

The main features of the November 7–10, 2004 strong negative ionospheric storm include a decrease in the electron density by a factor of up to 6–7, an uplifting of the ionospheric F2 region by 300 km at night and by 150–180 km in the daytime, unusual nighttime heating of the plasma, and a decrease in the N(H+)/Ne ratio by a factor of up to 3.5 due to the emptying of the magnetic flux tube passing over the Kharkiv radar. During the main phase of the storm of November 9–10, 2004, the effects observed by the Kharkiv radar were characteristic of the high-latitude ionosphere, which include coherent backscatters at oblique incidence even in the daytime. The observations could indirectly manifest an equatorward shift of the large-scale structures of the high-latitude ionosphere, including the auroral oval, the main ionospheric trough, the light ion trough, and elevated electron temperatures associated with the sub-auroral red arc thermal phenomenon towards the Kharkiv radar field of view.

A depletion of NmF2 by a factor of 7 during the storm main phase occurred on November 8, 2004 during the main phase of the storm. On November 11, 2004, the storm began to abate and a gradual recovery of NmF2 continued up to the end of the measurements.

During the storm, the contribution of diffusion processes into ionospheric vertical density profiles Ne changed with altitude.

Discussion

The ionospheric storms under study may be divided into two groups.

The ionospheric storms accompanying the severe magnetic storms (Kp ≥ 8) form the first group. Such magnetic storms occurred on September 25, 1998, May 29–30, 2003, and November 7–10, 2004 (the Kp indices attained the maximum values of 8+, 8+, 9–). They had long-lasting (6–12 hours) periods of high geomagnetic activity (Kp ≥ 8), a minimum in the Dst index reached –210, –131, and –383 nT, respectively.

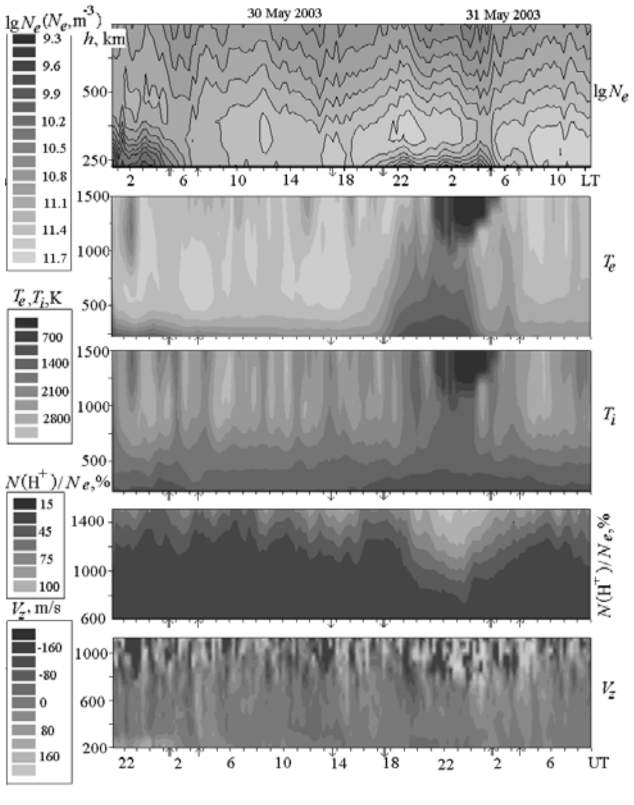

Fig. 8. Variations of the ionospheric parameters on 29–31 May 2003: the electron density (log N_e), the electron T_e and ion T_i temperatures, the relative hydrogen ion densities N(H+)/N_e, and the vertical component of the plasma drift velocity V_z. LT ≈ (UT + 0325). In this image, arrows at the abscissa indicate the moments of sunrise (upwards) and sunset (downwards) at Kharkiv (double) and in the magnetically conjugated point (single) at the surface of the Earth. The magnetically conjugated point for Kharkiv is located in the vicinity of Madagascar.

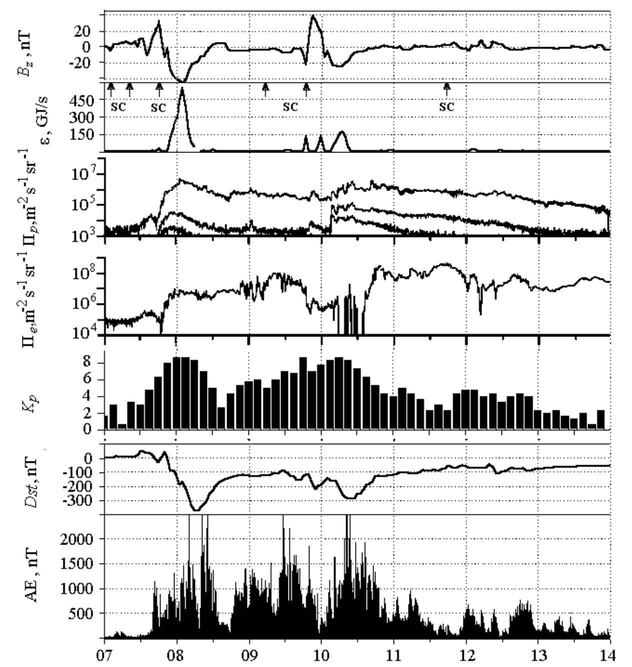

Fig. 9. The solar-geophysical conditions on November 7-13, 2004. Arrows at the abscissa mark the moments of the substorm sudden commencements (SC).

The magnitude of the energy injected by the solar wind into the Earth's magnetosphere per unit of time for this group of magnetic storms was significant, ε ≥ (75–550) GJ/s.

The magnetic storms commenced both at night and in the daytime. It is important that the main phase of the storms developed quickly, with maximum values of the derivative |Dst/dt| = 35–65 nT hr–1 and fell during the time interval when the Kharkiv radar was in the midnight-to-predawn sectors.

The ionospheric storms that accompanied these magnetic storms are characterized by considerable disturbances that rarely occur in the midlatitude ionosphere. The disturbances include a decrease in electron density by a factor of up to 3.5–7, an uplifting of the ionospheric F2 region by up to 150–300 km at night and by 100–180 km in the daytime, unusual nighttime heating of the plasma up to 2400–3200 K, an increase in the neutral temperature by more than 200 K, a rise in the thermospheric temperature to altitudes not less than 400 km, and a significant decrease in the hydrogen ion abundance N(H+)/Ne during the storm main phase with its subsequent increase during the recovery phase. One of the causes of these disturbances could be the shift of such polar region structures as the main ionospheric trough, the light ion trough, and elevated electron temperatures associated with the sub-auroral red arc thermal phenomenon to midlatitudes where the Kharkiv radar located at the L≈1.9 geomagnetic shell deep within the inner plasmasphere.

During the main phase of the magnetic storm of November 9–10, 2004 (Kp = 9–), coherent backscatters were observed from the oblique ranges of R ≈ 400 and 650–1200 km, which are more typical of the high latitude ionosphere. Such a seldom event was registered on November 10, 2004 even in the daytime when the Dst index reached a minimum of – 289 nT. It should be also noted that the Ne(h) profiles contaminated by the coherent backscatters were accompanied by spread F in ionograms over the Kharkiv radar (Fig.10). The coherent backscatters at oblique incidence could be caused by the scattering of the radar signals by small-scale field-aligned irregularities of the electron density produced by the two-stream or/and gradient-drift instabilities in the ionospheric plasma at E region altitudes in the vicinity of the equatorward boundary of the auroral oval shifted to midlatitudes.

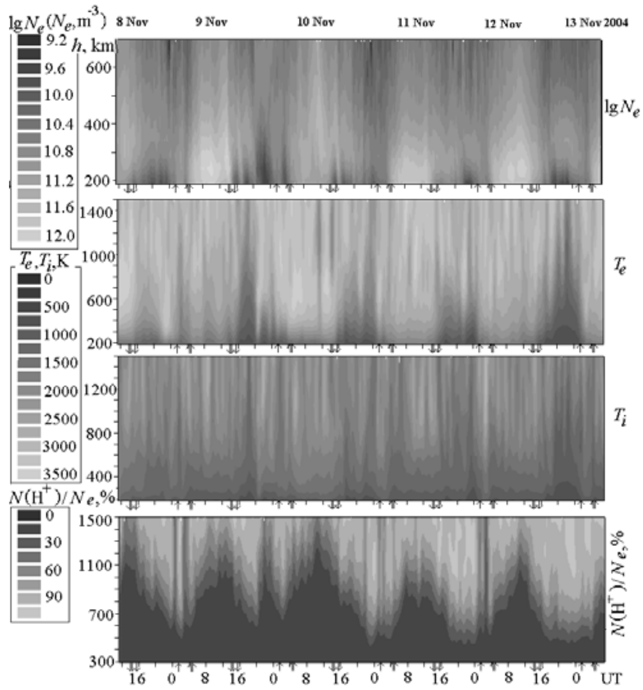

Fig. 10. Time variations in electron density in logNe (drawn without smoothing), the electron Te and ion Ti temperatures, the relative hydrogen ion densities N(H+)/Ne (running means over an interval of 75 min in time steps of 15 min) on November 8-13, 2004.

The ionospheric effects produced by transient magnetospheric electric fields penetrating to midlatitudes and by energetic particles precipitating from the magnetosphere were observed during the storms under consideration.

The ionospheric storms accompanying severe magnetic storms (Kp ≥ 8) comprise the first group. These magnetic storms occurred on 25 September 1998, 29–30 May 2003, and November 7–8, 2004. They had long-lasting (6–9 hours) geomagnetic activity enhancements (Kp ≥ 8), the main phase of the storms developed quickly, with maximum values of |Dst/dt| = 35 − 65 nT h−1, and occurred during the time interval when the Kharkiv radar was in the midnight-to-predawn sector. The ionospheric storms associated with these magnetic storms are characterized by considerable disturbances: a decrease in electron density by a factor of up to 3–4, a rise in ionospheric F2 peak heights hmF2 by 100–160 km, nighttime plasma heating up to 2400–3200 K, an increase in the neutral temperature by 200–350 K, and a depletion of hydrogen ion densities N(H+)/Ne by more than an order of magnitude during the storm main phase with its subsequent recovery during the recovery phase. The nonstationary disturbances in magnetospheric electric fields accompanying an intensification of the auroral electrojets during a substorm and energetic particle precipitations from the magnetosphere could lead to the penetration of magnetospheric electric fields to middle latitudes and destabilize the state of the ionosphere.

The second group includes the ionospheric storm that accompanied a minor magnetic storm of March 20–21, 2003 (Kpmax = 5). The magnetic storm was a response of the geomagnetic field to the input of a small amount of solar wind energy into the magnetosphere, Akasofu function ε ≈ 35 GJ/s. The magnetic storm began at 04:45 UT, the main phase developed slowly (|Dst/dt| ≈ 5 nT h−1) and reached a minimum of Dst = −57 nT at 20:00 UT. The ionospheric storm had a two-phase character and began with a positive phase. However, the prominent feature of this storm was that its negative phase, which occurred against the background of low geomagnetic activity, was characterized by very large ionospheric disturbances: a decrease in NmF2 by a factor of up to 5, an electron temperature increase up to 2400–3500 K at altitudes of 300–500 km, and an uplifting of the F2 region by more than 100 km during the night of March 20–21, 2003 and near sunrise. The reversal of the storm phase occurred during less than an hour near dusk and was, apparently, caused by a superposition of the effects of two destabilizing factors generated by the magnetospheric substorms: the passage of a traveling atmospheric disturbance and a storm-induced electric field penetrating the inner magnetosphere and the ionosphere over Kharkiv, whose Ey component changed the direction from the westward to the eastward and the value from −10 to +15 mV m−1.

The data acquired show that intense geomagnetic disturbances (on September 25, 1998 and May 29–30, 2003, Kp was approximately equal to 8) may be accompanied by phenomena of rare occurrence at mid-latitudes (e.g., a decrease in the electron density by a factor of up to 7, uplifting of the ionospheric F2 region by up to 300 km at night and 180 km in the daytime, unusual nighttime electron and ion heating of the plasma up to daytime temperatures, a decrease in the hydrogen ion abundance more than by an order of magnitude, coherent backscatters at oblique incidence, etc.), which may be related to an equatorward shift of polar region structures. These disturbances could produce considerable changes in the structure of the mid-latitude ionospheric F region and thermal and dynamical regimes of the charged and neutral components of the Earth’s upper atmosphere.

The observations and modeling of the dynamical processes in the ionosphere show that even a minor geomagnetic storm (as on March 20–21, 2003, Kp=5) is capable of causing a strong negative ionospheric storm accompanied by considerable variations in ionospheric parameters at middle latitudes. The reversal of the storm phases can be caused by superposition of two destabilizing factors: an electric field pulse and a traveling atmospheric disturbance, both factors being generated by magnetospheric substorms.

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