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SPACE PHYSICS

Features of the Ionospheric Storm on December 21–24, 2016

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Abstract—The purpose of this work is to investigate the response of the F region and topside ionosphere to the moderate geomagnetic storm on December 21, 2016 ($K_{p\,\max} = 6$). The subject of the study is the height–time variations in the parameters of the ionospheric plasma over Kharkiv. Experimental data were obtained using vertical sounding and incoherent scatter methods by the ionosonde and incoherent scatter radar. The presented results are based on the correlation analysis of the incoherent scattered signal. The ion and electron temperatures, as well as the ionospheric plasma velocity, were determined from a set of measured correlation functions of the incoherently scattered signal. The electron density was calculated using the following parameters measured for a number of ionospheric heights: power of the incoherent scatter signal, ion and electron temperatures, and the electron density at the ionospheric F2 layer peak, which is calculated from the critical frequency measured by the ionosonde. The moderate geomagnetic storm was accompanied by an ionospheric storm over Kharkiv with sign-variable phases (first positive and second negative). The peak increase in the electron density was 1.8 times and decrease was 3.4 times. The negative phase was accompanied by a slight rise of the F2 layer (by 20–28 km), which could be due to a decrease in the vertical component of the plasma velocity and an increase in the electron temperature by 600–800 K and ion temperature by 100–160 K. Effects of strong negative ionospheric disturbances were registered during the subsequent magnetospheric disturbance of December 22–24, 2016, with a decrease in electron density at the F2 layer peak up to 2.5–4.9 times. The effects of negative disturbances manifested themselves in the variations of temperatures of electrons and ions. In general, the moderate magnetic storm caused significant changes in the electron density in the ionospheric F2 layer peak, which were accompanied by heating of the ionospheric plasma as well as changes in variations of the vertical component of the ionospheric plasma velocity and the height of ionization during the main phase of the magnetic storm.

Keywords: space weather, geomagnetic storm, ionospheric storm, incoherent scatter radar, ionosonde, positive and negative storm phases, electron density, electron and ion temperatures, plasma velocity

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INTRODUCTION

Studying the state of space weather and its influence on processes in the Earth's magnetosphere is one of the important and urgent problems of solar-terrestrial physics [1, 2, 10, 11, 13]. Despite the fact that a large number of experiments and theoretical results have been accumulated to date, there are still questions in predicting the response of the ionosphere depending on the level of solar activity. Complexity and variability of the physical processes forming an ionospheric storm and the dependence of contribution of different physical mechanisms on the geographical region lead to a large variety of the observed phenomena in different regions of the Earth. Of special interest in the study are also moderate or weak magnetic storms, which can cause strong ionospheric disturbances. Analysis of each storm provides valuable information for further investigation and modeling of physical processes in the Sun–interplanetary medium–geospace–atmosphere–Earth system as well as for predicting the response of the ionosphere of a specific region to disturbances on the Sun [1].

STATE OF SPACE WEATHER

In general, solar activity was low during the considered period from December 18 to 24, 2016: the radio emission flux at a wavelength of 10.7 cm ($F_{10.7}$) was in the range of 72–75 and there were no flares [http://ftp.swpc.noaa.gov]. During December 18–20, 2016, values of the proton density in the solar wind flux n_{sw} (Fig. 1) varied significantly from 5×10^6 m^{-3} to ~13×10^6 m^{-3} as a result of a large coronal hole in the Sun's atmosphere [http://spaceweather.com]. On December 20, the solar wind velocity V_{sw} averaged approximately 350 km/s.

On December 21, after 05:00 UT (Universal Time, hereafter UT), the velocity began to increase gradually, and it exceeded 650 km/s after 12:00 UT. The values of solar wind temperature T_{sw} also changed significantly: they increased sharply from $(0.5–1) \times 10^5$ K to $(3–4) \times 10^5$ K and sometimes exceeded 5×10^5 K. As the velocity V_{sw} increased on December 21, the n_{sw} density values began to decrease and were ~6×10^6 m^{-3} after 12:00 UT.

The dynamic pressure p_{sw} values during December 18–20, 2016, varied accordingly to the change in density n_{sw} during this period reaching 3 nPa at night. On December 21, 2016, against the background of the increasing solar wind velocity and temperature, p_{sw} exceeded 4.5 nPa between 13:00 and 19:00 UT and reached a maximum of 4.8–4.9 nPa. The second significant increase in p_{sw} to 4.2–4.7 nPa was observed in the time interval 23:00–24:00 UT on December 21, 2016, against the background of a sharp temperature jump T_{sw} at the same time.

The B_z-component of the interplanetary magnetic field turned sharply southward after 09:00 UT on December 21, 2016. The first minimum extreme value, –10.4 nT, was observed at 09:35 UT, and the second, –10.6 nT, was around 10:00 UT. A weakly pronounced onset of the magnetic storm occurred at approximately 10:00 UT on December 21, 2016 (see Fig. 1 for variations of the D_{st} index). After 12:00 UT on December 21, 2016, the *AE* auroral index began to increase rapidly and reached a maximum value of 1932 nT at 16:10 UT. In turn, the K_p index in the time interval 12:00–15:00 UT increased from 3 to 3.3, and its extreme value was $K_{p\ \max} = 6$ from 15:00 to 18:00 UT, which is characteristic of moderate magnetic storms according to the Space Weather Scales of the National Oceanic and Atmospheric Administration (NOAA). At the same time, D_{st} index values were –33 and –38 nT at 17:00 and 18:00 UT, respectively. The extreme $D_{st\,\min} = -40$ nT was recorded at 21:00 UT, which marked the end of the main phase of the magnetic storm.

Solar wind velocity remained high ~(650–700) km/s throughout the subsequent period of December 22–24, 2016, sometimes exceeding 700 km/s. The temperature T_{sw} fluctuated between $(2–3) \times 10^5$ K. In turn, n_{sw} density values decreased to $(3–4) \times 10^6$ m^{-3}.

The values of the K_p and D_{st} indices show that the Earth's magnetosphere remained in a disturbed state until the end of the observation period. On December 22, $K_{p\ \max} = 4.7$ in the time interval 00:00–03:00 UT, $K_p = 4.3$ from 03:00 to 06:00 UT, and $K_p = 4.0$ from 18:00 to 21:00 UT. On December 22, 2016, at 03:00 UT, the D_{st} index deviated to –39 nT, the minimum value of –40 nT was recorded from 07:00 to 08:00 UT. On December 23, 2016, $K_p = 4$ in time intervals 03:00–06:00 UT and 18:00–21:00 UT, D_{st} remained below –20 nT and reached –40 nT at 21:00 UT. On December 24, 2016, the K_p index reached 3–3.3, and the D_{st} index remained negative and was –30 nT about 10:00 UT.

Let us estimate the energy of the moderate magnetic storm on December 21, 2016. Its energy E_{ms} was determined by the value of the $D_{st\ \min}$ index [6]:

$$E_{ms} = \frac{3}{2} E_M \frac{\left|D_{st}^*\right|}{B_0},$$

where $B_0 \approx 3 \times 10^{-5}$ T is the value of the magnetic field induction at the equator, $E_M \approx 8 \times 10^{17}$ J is the energy of the Earth's dipole magnetic field. The corrected value $D_{st}^* = D_{st\min} - bp^{1/2} + c$. Here $b = 5 \times 10^5$ nT/(J m^{-3})$^{1/2}$, $c = 20$ nT, $p = n_p m_p V_{sw}^2$, n_p and m_p are proton density and mass, and V_{sw} is the solar wind velocity.

The extreme values of the geomagnetic activity indices during the magnetic storm were: $AE_{\max} = 1932$ nT, $K_{p\ \max} = 6$, and $D_{st\min} = -40$ nT. For a moderate storm for $\left|D_{st}^*\right| \approx 49.1$ nT, its energy was ~2×10^{15} J, which is consistent with the classification of magnetic storms [5–7, 11, 12].

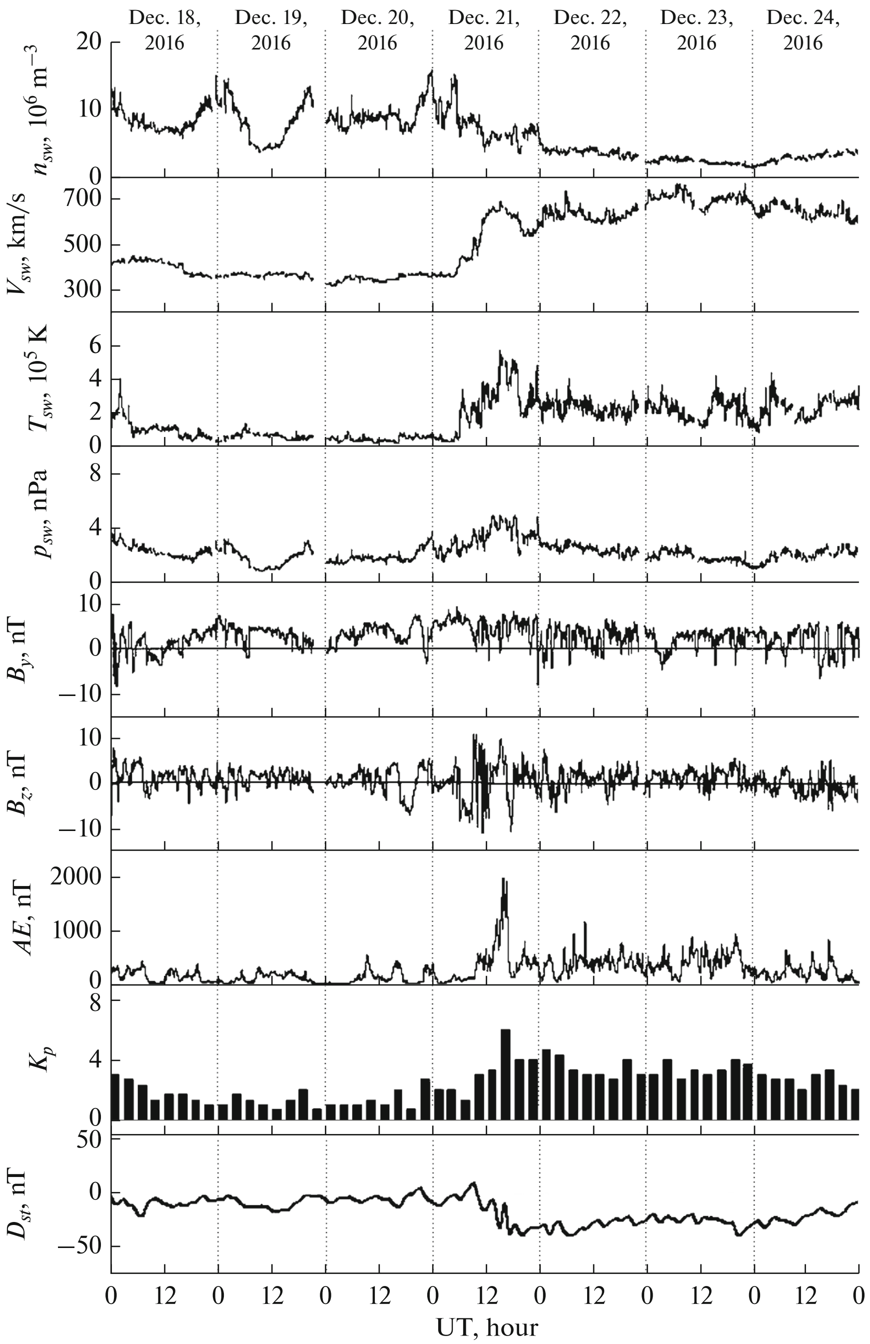

Fig. 1. Temporal variations of solar wind parameters: density n_{sw}, radial velocity V_{sw}, temperature T_{sw} and calculated values of dynamic pressure p_{sw}, B_y- and B_z-components of the interplanetary magnetic field, AE index (WDC Kyoto), K_p index (http://spidr.ngdc.noaa.gov/spidr/index.jsp), hourly value of the D_{st} index values (WDC-C2 for Geomagnetism, Kyoto University) on Dec. 18–24, 2016.

INSTRUMENTS AND METHODS

Ionospheric effects were observed using two instruments: an incoherent scatter radar of the Ionospheric Observatory of the Institute of Ionosphere (Kharkiv) and a digital ionosonde of the Radiophysical Observatory of the V.N. Karazin Kharkiv National University (RPO KNU).

The incoherent scatter method has the most complete diagnostic capabilities in the study of ionospheric and thermospheric effects of geospace storms and makes it possible to simultaneously measure the main parameters of the ionosphere with high accuracy and over a wide range of heights. The Kharkiv

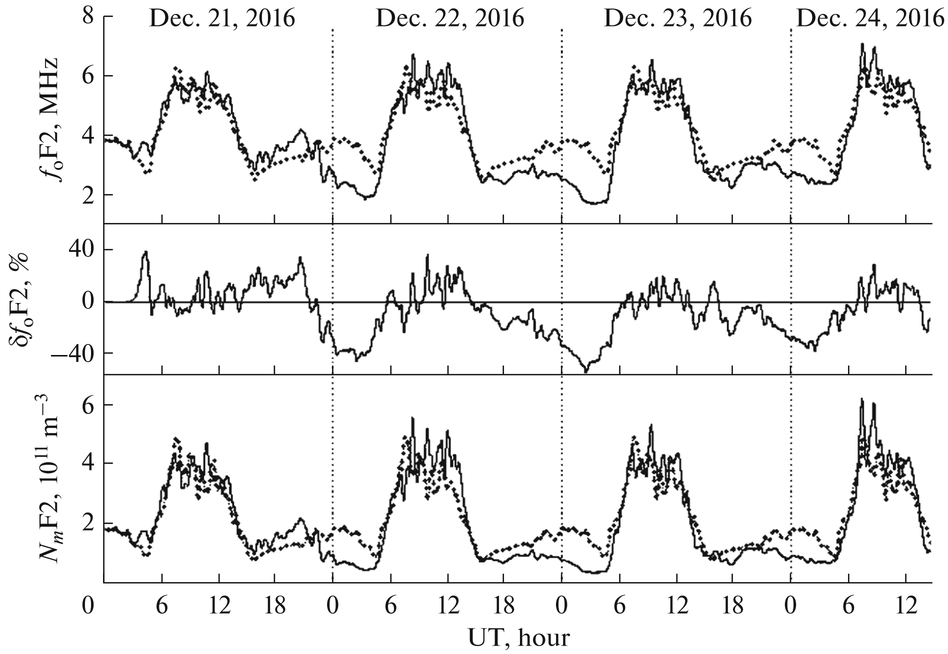

Fig. 2. Temporal variations of the critical frequency f_oF2 (top panel) during the measurement period on Dec. 21–24, 2016 (line), and, under magnetically quiet conditions (dotted line), its relative deviation δf_oF2 (middle panel) and the electron density N_mF2 at the F2 layer peak (bottom panel, the line and dots in corresponding periods).

Incoherent Scatter (IS) radar of the Institute of Ionosphere is the only source of data on variations of a number of basic ionospheric parameters in mid-latitude Europe. Pulse power of the two-channel transmitter reaches 3.6 MW (average power, 100 kW), gain of the parabolic antenna is 12 700 (antenna diameter is 100 m, its effective area is approximately 3700 m^2, and the beamwidth is approximately 1°). The relative error of determination of the ionospheric parameters usually does not exceed 10%. During the measurement period from 20:00 UT on December 21 to 24:00 UT on December 23, the radar operated in the radiation mode using a 2-MW two-frequency multicomponent radio pulse signal with two elements with a duration of 130 and 660 μs, which provides 20 and 100 km height resolution in the 100–400 km and 200–1500 km height ranges, respectively.

The ionosonde of the RPO KNU uses vertical broadband rhombic Aizenberg antennas for emission and reception of radio waves. The antennas are suspended at a height of 18 m, and their horizontal size is 50 m. Sounding radio pulses with a duration of 100 μs, a repetition frequency of 125 Hz, a carrier frequency in the range of 1–16 MHz, and a peak pulse power of up to 1.5 kW are radiated by a broadband radio-frequency power amplifier of the Brig-2 transmitter. The ionospheric parameters were measured using the vertical sounding method from 13:00 UT on December 19 to 13:45 UT on December 24, 2016.

EXPERIMENTAL RESULTS

Variations of the Critical Frequency of the F2 Layer

Figure 2 shows temporal variations in the critical frequency f_oF2 obtained using the ionosonde during December 21–24, 2016, and its relative deviation δf_oF2. In the analysis of the diurnal variation of the critical frequency f_oF2, the averaged values of f_oF2 for December 19–20, 2016 (dotted curve), when the geomagnetic index K_p did not exceed 2, were selected as reference data. The reference data for f_oF2 (as well as the electron density N_mF2 at the F2 layer peak) are characterized by a postmidnight maximum in winter.

The relative deviation of the critical frequency is determined by the following formula:

$$\delta f_oF2 = \frac{f_oF2 - \langle f_oF2 \rangle}{\langle f_oF2 \rangle} \times 100\%,$$

where f_oF2 is the value of the critical frequency measured during the experiment, $\langle f_oF2 \rangle$ are the averaged values of the critical frequency during undisturbed conditions.

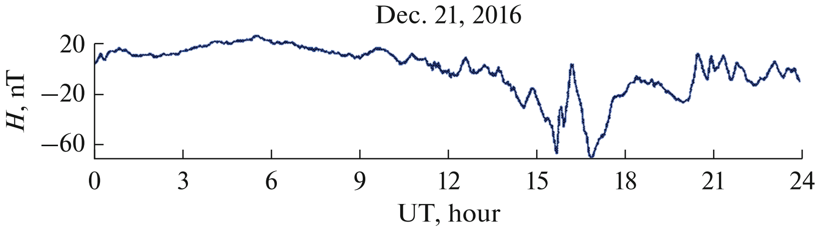

Fig. 3. One-minute variations of the *H*-component of the geomagnetic field on Dec. 21, 2016.

Magnetic disturbance over Ukraine occurred at approximately 16:00 UT on December 21, 2016, according to data of the variations of the *H*-component of the geomagnetic field (Fig. 3) by observations of the magnetic observatory Kyiv (coordinates: 50.72° N, 30.3° E) [http://ottawa.intermagnet.org]. At that time, f_oF2 frequency values began to increase (see Fig. 2), and, in the time interval 16:00–21:00 UT, when the 3-h K_p values reached 6 and 4, respectively, the f_oF2 values were 10–30% higher than under quiet conditions. The maximum frequency increase from 3.1 to 4.2 MHz (1.35-fold increase) was observed around 20:45 UT. Since f_oF2 data represent variations in the electron density N_mF2 at the F2 layer peak, this corresponded to a 1.8-fold increase in N_mF2 (see Fig. 2).

After the main phase of the magnetic storm that ended at 21:00 UT on December 21, 2016, it was followed by a rapid decrease in f_oF2 over Kharkiv, which marked the onset of the negative ionospheric disturbance. After midnight on December 22, 2016, when the K_p index again increased to 4.7, the relative deviation δf_oF2 exceeded –30% and reached its extreme value of –45.8% around 02:30 UT. Accordingly, the N_mF2 density decreased by a factor of 3.4. In winter, the nighttime ionosphere (in particular, the N_mF2 density) is usually controlled to the greatest extent by plasma fluxes from the plasmasphere.

Since the Earth's magnetic field disturbances were observed until the end of the measurements, the solar wind velocity remained high, approximately 650–700 km/s, this was the reason for the subsequent noticeable change in the diurnal variation of the critical frequency f_oF2 during the measurements.

On December 22, 2016, between 12:00–14:00 UT, f_oF2 values were higher than on December 20, 2016: δf_oF2 was 15–20%, while N_mF2 density increased 1.4–1.6-fold. After 21:00 UT, when $K_p = 4$, a rapid decrease in f_oF2 followed. The maximum relative deviation $\delta f_o\text{F2} = -54.6\%$ was at 02:30 UT on December 23, and N_mF2 at the same time decreased 4.9-fold.

From the obtained results, it can be seen that f_oF2 values varied markedly after 13:30 UT on December 23, 2016, and there was a significant decrease in f_oF2 after 22:00 UT, when the K_p index changed from 4 to 3.7. The negative ionospheric disturbance during this period was weaker than during the preceding periods. The extreme value of δf_oF2 was –37.9% at 02:30 UT on December 24, 2016, and the electron density decreased 2.6-fold accordingly.

Variations of the Ionospheric F2 Peak Height

For the analysis of the incoherent scatter radar data, December 22, 2010, was selected as the reference day. This day is closest in both ionosphere observation time and solar activity level (solar radio emission flux $F_{10.7}$ on December 22, 2010, and December 22, 2016, was 78 and 75, respectively) [ftp://ftp.swpc.noaa.gov/pub/indices/old_indices/]. On the reference day, the ionosphere was in quiet geomagnetic conditions: the K_p index was 0–0.3, while the K_p index did not exceed 1 on the previous and subsequent days (December 21 and 23, 2010).

The values of the height of the F2 layer peak h_mF2 (see Fig. 4) obtained with the incoherent scatter radar during the 2016 experiment correlate well with the 2010 data. Noticeable differences were observed only at the beginning of radar measurements, at the end of the main phase of the magnetic storm on December 21, 2016, and at night time on December 22, 2016, when a negative ionospheric disturbance was observed over Kharkiv. For example, at 21:00 UT on December 21, 2016, the height of the layer peak decreased from 316 km to 264 km. Further, from midnight to 03:00 UT on December 22, 2016, the h_mF2 height values were higher than the values of the reference day and increased by 20–28 km.

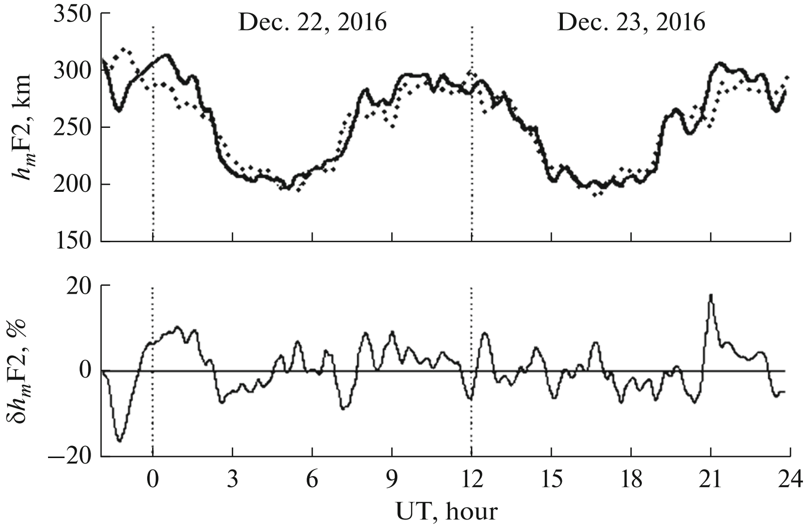

Fig. 4. Temporal variations of the F2 peak height h_mF2 (top panel) on Dec. 21–23, 2016 (line), and on the reference day of Dec. 22, 2010 (dots) as well as its relative deviation δh_mF2 (bottom panel).

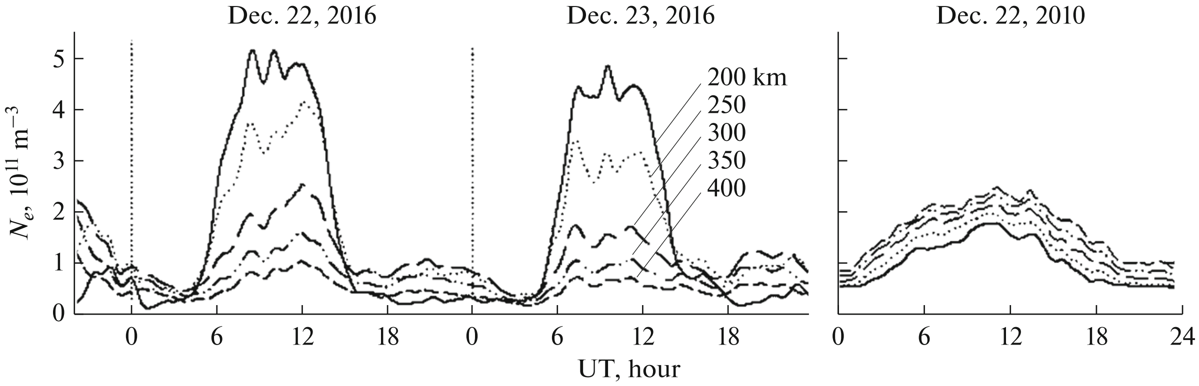

Fig. 5. Temporal variations of N_e electron densities at fixed heights of 200–400 km on Dec. 21–23, 2016, and on the reference day of Dec. 22, 2010.

Electron Density Variations

Figure 5 shows the height profiles of the density N_e at successive times (after 15 min) obtained with the IS radar. The $N_e(h)$ profiles deformed during the measurement period compared to the N_e data in undisturbed conditions. Significant changes in density values were observed at heights of 200–250 km on December 22, 2016, where the height of the F2 layer peak was located during the daytime. For example, the density increased to ~4.8×10^{11} m^{-3} at the height of 200 km and to 3.7×10^{11} m^{-3} at 250 km in the time interval 10:00–12:00 UT, while, in the undisturbed ionosphere, N_e values reached 1.6×10^{11} m^{-3} and 1.9×10^{11} m^{-3}, respectively. At heights of 300–400 km at the same time, the values of electron density decreased. At heights of 350 and 400 km, the decrease was more pronounced, to 1.5×10^{11} m^{-3} (from 2.3×10^{11} m^{-3} on December 22, 2010) and 0.9×10^{11} m^{-3} (from 2.4×10^{11} m^{-3} in December 2010), respectively. In general, the $N_e(h)$ profile on December 22, 2016, during the ionospheric disturbance was characterized by a later increase and an earlier decrease and, respectively, a prolonged decrease in the evening and nighttime hours. After 18:00 UT, the highest density of electrons was observed at the height of 300 km, which was close to the height of the h_mF2 peak at that time.

Similar N_e variations were observed on December 23, 2016, only the density values were slightly lower. A rapid increase in N_e began after 04:00 UT, and N_e values reached $(4.2–4.7) \times 10^{11}$ m^{-3} around 07:00 UT at the height of 200 km. After 18:00 UT at a height of 300 km, the electron density was higher and was approximately 1.2×10^{11} m^{-3} (until 22:00 UT).

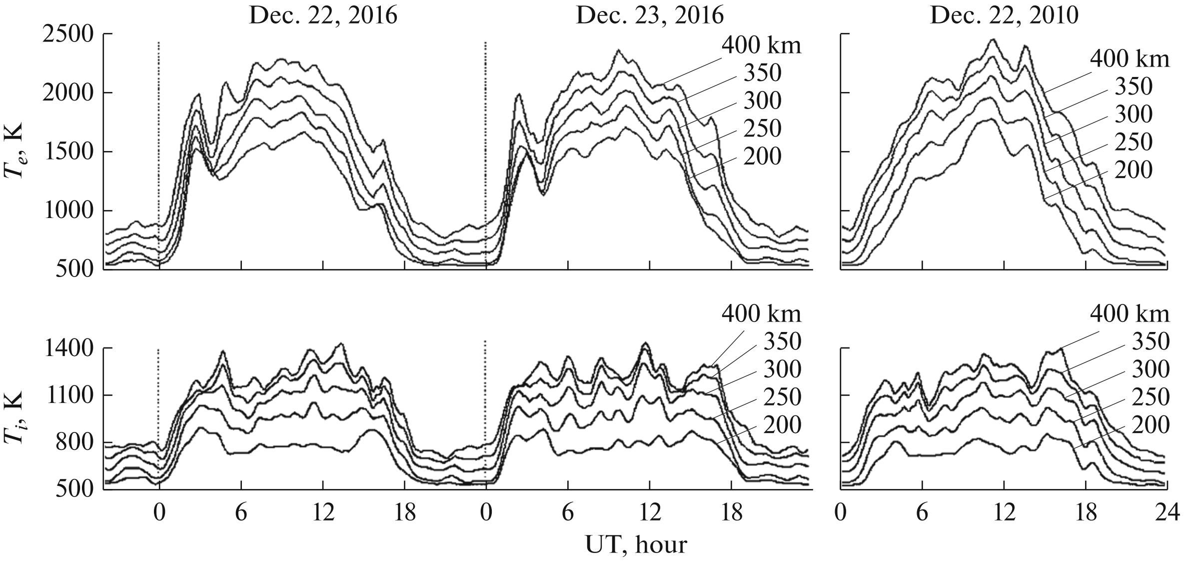

Fig. 6. Temporal variations of electron T_e and ion T_i temperatures on Dec. 21–23, 2016, and on Dec. 22, 2010, at fixed heights.

Variations of Electron and Ion Temperatures

Comparing the obtained temperatures of the T_e electrons and T_i ions with those of the reference day, it can be seen (Fig. 6) in general that the diurnal temperature variations changed, and the extreme decreases in the N_mF2 electron density at the F2 layer peak were accompanied by a marked increase in electron temperatures over the entire 200–400 km height range studied. For example, on December 22, 2016, at 02:30 UT, T_e increased at the height of 200 km from 671 to 1475 K, from 852 to 1574 K at 250 km, from 1041 to 1662 K at 300 km, from 1173 to 1772 K at 350 km, and from 1266 to 1906 K at 400 km. The increase in the temperature T_i was not as significant: 829 K (667 K under magnetically quiet conditions) at 200 km, 966 K (817 K) at 250 km, 1043 K (954 K) at 300 km, 1087 K (1045 K) at 350 km, and 1158 K (1093 K) at 400 km. During the increase in the N_mF2 density around noon, the T_e electron temperatures were slightly lower than the 2010 values: less by 100–250 K at the height of 200–300 km and by 200–400 K at 350–400 km. The ion temperature T_i changed little: it was a few tens of kelvin higher than the values of the reference day after 13:00 UT, and it increased by 100–200 K from heights of 300 km and higher after 13:45 UT.

On December 23, 2016, the behavior of temperatures was similar. At 02:30 UT, when the 4.9-fold decrease in N_mF2 was accompanied by plasma heating, the T_e and T_i values were approximately the same as those of December 22, 2016, at 02:30 UT. The near-afternoon increase in N_mF2 was also accompanied by a decrease in T_e and an increase in T_i compared to the reference day.

Variations in the Vertical Component of the Ionospheric Plasma Drift Velocity

Figure 7 shows the results of observations of the vertical component of the ionospheric plasma drift velocity V_z on December 21–23, 2016. The sunrise and sunset at the corresponding heights are indicated by arrows: bold arrows for the Kharkiv radar (49°36′ N, 36°18′ E) and thin arrows for the magnetically conjugate region (36°30′ S, 52°12′ E).

The bottom panel of Fig. 7 shows darkened sections of the height–time diagram, where the signal-to-noise ratio is $q < 0.1$, and, as a consequence, the statistical error of velocity determination in these sections is such that it does not allow us to consider the obtained data reliable. Such conditions are typical for the winter period with low solar activity. Standard deviation of velocity during the period under study was from 1 to 6 m/s at the heights of 198–253 km and from 4 to 10 m/s at the heights of 308–418 km during the day and up to 30 m/s in the morning.

Figure 7 shows that variations V_z obtained in 2010 and 2016 are quite similar. For example, an increase in the absolute value of the downward plasma velocity ($V_z < 0$) at 253 km and higher in the period from

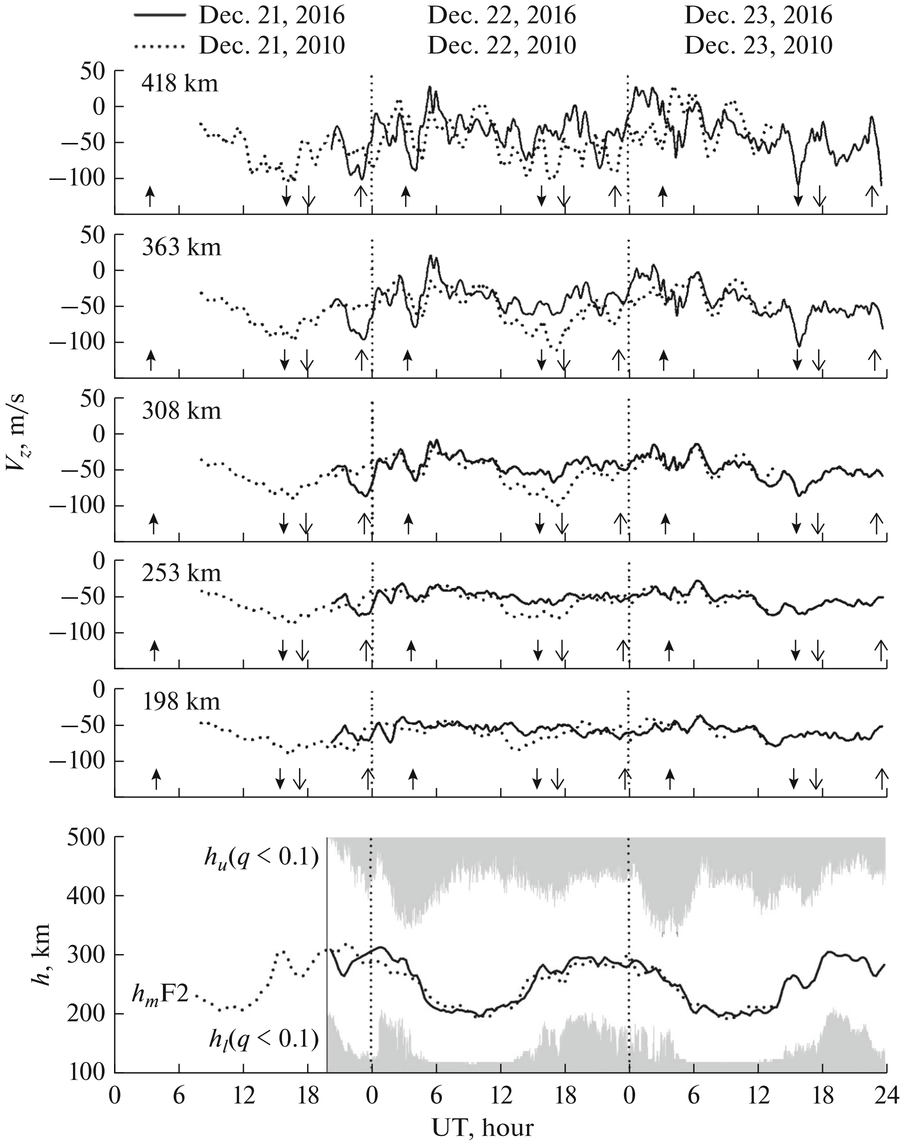

Fig. 7. Temporal variations of the vertical component of the ionospheric plasma velocity V_z for a series of ionospheric heights and F2 peak height h_mF2 during the measurement period on Dec. 21–23, 2016 (lines), and on the reference days of Dec. 21–23, 2010 (dots).

02:30 to 04:00 UT and then its decrease to 05:30 UT were observed on December 22 in both experiments. These variations are caused by ionospheric restructuring associated with the morning solar terminator in the magnetically conjugate region and, to a greater extent, in Kharkiv. However, in 2016 there are also differences caused by the magnetic storm.

In the variations V_z from 21:30 UT on December 21, 2016, to 02:30 UT on December 22, 2016, there were oscillations that were absent in 2010. The most intense, observed with the IS radar, oscillation of V_z began at 21:30 UT on December 21, 2016 (i.e., approximately 7 h after the start of the magnetic storm). Its quasiperiod was approximately 3 h, and the maximum oscillation of the downward plasma flux toward increase in velocity (relative to the mean V_z value before the oscillation started and after it ended) observed at 23:15 UT was 17, 25, 43, and 59 m/s at heights of 198, 253, 308, and 363 km, respectively. The amplitude of the velocity deviation relative to the value of V_z on December 21, 2010, at 23:15 UT had values close to those given above: 14, 26, 40, and 50 m/s at the same heights, respectively.

A similar oscillation was observed in the variations of the F2 peak height h_mF2 on December 21, 2016, from 20:15 to 24:45 UT with an extremum (minimum) at 21:30 UT (see Fig. 7). From 23:00 UT on December 21, 2016, the h_mF2 height continued to rise and it was greater relative to h_mF2 in 2010 from that point until 04:00 on December 22. The maximum difference was observed at approximately 01:00 UT and was 25 km.

The second recorded V_z oscillation with an extremum (velocity modulus maximum) at approximately 01:45 UT on December 21, 2016, had a quasiperiod of 2 h and amplitudes of 26, 20, 18, 25, and 37 m/s at heights of 198, 253, 308, 363, and 418 km respectively, whereas no such oscillation was observed in 2010.

On December 22, 2016, there was hardly any evening minimum (increase in the velocity modulus of the downward plasma flux ($V_z < 0$) in the evening), while it was observed at all presented heights from 12:00 to 19:30 UT on December 22, 2010 (see Fig. 7), and is also usually observed in winter for many years. Obviously, this is a consequence of the influence of the magnetic storm. It should be noted that, in the absence of geomagnetic disturbances, the increase in the velocity modulus in the evening is usually more pronounced in winter than in summer [16].

Therefore, we can state that the geospace storm affected the diurnal variations of the vertical component of the ionospheric plasma velocity V_z and the height of the ionization peak during the main phase of the storm.

RESULTS AND DISCUSSION

According to the results of observations over Kharkiv, it is evident that a moderate magnetic storm on December 21, 2016, caused an intense ionospheric disturbance with sign-variable phases [3]. Prolonged magnetospheric disturbance was accompanied by correspondingly noticeable changes in the ionospheric plasma until the end of measurements.

The state of ionospheric plasma during the storm depends on a large number of factors. In addition, the explanation of interaction processes in the global magnetosphere–ionosphere–atmosphere system is complicated by insufficient predictability of induced effects, despite significant statistical data on storms accumulated to date.

According to the authors of [8], a prolonged decrease in the N_mF2 density and total electron content during the main phase of a storm, especially at middle latitudes, is considered the main sign of a storm in the F2-layer of the ionosphere. Before such a negative phase, a positive phase is usually observed. It may appear during the main phase at low latitudes and in winter at middle latitudes, which is confirmed by statistics and analysis of a large number of observations [1, 2, 9, 10, 14]. This feature of the ionospheric storm (increase of f_oF2 during the main phase) is consistent with observations made on December 21–24, 2016. Decrease of f_oF2 followed the end of the main phase of the magnetic storm, after which a negative ionospheric disturbance was observed that lasted approximately 6 h. Unfortunately, it is impossible to estimate the behavior of h_mF2 before the start of the magnetic storm and its main phase using the IS radar data due to lack of data at that time as well as explain the mechanisms of the positive phase over Kharkiv during the main phase of the storm. For example, one of the causes of positive disturbances is the rise of the F2 layer (to the region of lower recombination) due to intensification of meridional winds directed toward the equator [10]. This mechanism is effective in the daytime, when ion-formation processes dominate. For this purpose, it is necessary to analyze data on f_oF2 and h_mF2 of other nearby ionospheric stations. The other mechanism is related to changes in the composition of the neutral atmosphere due to the deposition of light gas components at low and middle latitudes as a result of heating of the thermosphere during a magnetic storm. The role of the second mechanism is more significant at night. In both cases, the influence of the solar wind occurs along the following channel: boundary layer of the magnetotail–plasma layer–longitudinal currents–Joule heating–changes in the thermospheric circulation and neutral composition [10]. The high-latitude heating of the thermosphere during the magnetic storm and the precipitation of soft particles with energies $E \leq 1$ keV into the daytime cusp region (energy is absorbed at the heights of the F region of 200–300 km, heats it, and causes meridional circulation, which contributes to the transport of atomic-oxygen-rich gas toward the equator) could also be the reason for the f_oF2 frequency increase [2]. However, since there were no data from the GUVI instrument onboard the TIMED satellite over Ukraine, it was also impossible to verify the implementation of the latter mechanism.

Note that the first negative phase (from December 21 to 22, 2016) was accompanied by a slight rise of the F2 layer (up to ~300 km) and a rapid heating of plasma (a sharp increase in the temperature of the electrons T_e). The ionospheric plasma transport velocity (vertical component) decreased rapidly at 308 km (see Fig. 7) by approximately 50 m/s at this time. A decrease in the downward plasma flux velocity and an increase in temperature could be the cause of the rise of the F2 layer.

According to the ionosonde data, it can be seen that negative ionospheric disturbances were observed in the next few days, December 22–24, 2016, in the evening and at the night time over Kharkiv with a relative deviation δf_{o}F2 up to –50% and –30%, which corresponds to a decrease in the density N_mF2 by more than 4.5 times in the first case and by 2.5 times in the second one. In winter at middle latitudes, the negative phase at night is explained by the fact that the directions (toward the equator) of the background circulation (induced by solar heating) and storm-induced circulation coincided. Therefore, air with a reduced $[\mathrm{O}]/[\mathrm{N}_2]$ ratio spreads to much lower latitudes than in the daytime. The thermospheric composition (decreasing $[\mathrm{O}]/[\mathrm{N}_2]$) changes during geomagnetic disturbances as a result of heating of the lower thermosphere at heights of 100–140 km in the auroral region, the source of which is the Joule current dissipation and absorption of precipitating particles. Heating leads to a decrease in the $[\mathrm{O}]/[\mathrm{N}_2]$ ratio throughout the high-latitude thermosphere and induces its own circulation, which, at the heights of the F2 layer, tends to carry the air toward the equator to lower latitudes. A heated gas with a reduced $[\mathrm{O}]/[\mathrm{N}_2]$ ratio has a higher temperature in the thermosphere. A decrease in temperature leads to an increase in the linear recombination coefficient at the heights of the F region. Therefore, the negative phase is formed in the heated thermospheric gas due to a decrease in $[\mathrm{O}]/[\mathrm{N}_2]$ and an increase in temperature [15]. As seen in Figs. 2 and 6, the maximum reductions in N_mF2 on December 22 and 23, 2016, were accompanied by a sharp increase in T_e and, to a lesser extent, T_i temperatures. The role of $[\mathrm{O}]/[\mathrm{N}_2]$, as mentioned above, is currently not known. As for the height of the F2 layer peak (see Fig. 4), it hardly changed during the second and third negative phases compared to the reference data; the differences were insignificant. The variations of the vertical component V_z on December 22, 2016, after 19:00 UT began to gradually recover to the values characteristic of undisturbed conditions.

The moderate geomagnetic storm on December 21, 2016, caused a two-phase ionospheric storm (with a change of phases from positive to negative) over Kharkiv. Until the end of measurements at the Radiophysical Observatory, a long disturbance in the magnetosphere was accompanied by strong (according to the classification given in [7]) negative ionospheric disturbances. Significant changes during disturbances were manifested in diurnal variations of critical frequencies (and, accordingly, electron densities at the F2 layer peak) and plasma temperatures.

In conclusion, we present the values of the indices describing the strength of the ionospheric storm.

Positive ionospheric storm index [7]

$$I_{\text{PIS}} = 10\log\frac{N_{e\max}}{N_{e0}}$$

for $N_{e\max}/N_{e0} \approx 1.8$ is 2.6. Such a positive ionospheric storm, according to the classification from [7], refers to moderate storms. For them, $I_{\text{PIS}} = 2.3–3.1$.

Negative ionospheric storm index

$$I_{\text{NIS}} = 10\log\frac{N_{e0}}{N_{e\min}}$$

for $N_{e0}/N_{e\min} \approx 4.9$ is 6.9. According to the classification from [7], such a negative ionospheric storm belongs to very strong ones. For such storms, $I_{\text{NIS}} = 6.0–9.9$.

For $N_{e0}/N_{e\min} = 3.4$ and $N_{e0}/N_{e\min} = 2.6$, we have $I_{\text{NIS}} \approx 5.3$ (strong ionospheric storm) and $I_{\text{NIS}} \approx 4.1$ (strong ionospheric storm).

Therefore, a moderate magnetic storm was accompanied by a moderate positive ionospheric storm and also a very strong and two strong negative ionospheric storms.

CONCLUSIONS

(1) The moderate geomagnetic storm on December 21, 2016, caused a two-phase ionospheric storm over Ukraine with the first positive phase and the second negative phase. The maximum increase in the density N_mF2 was 1.8 times and decrease was 3.4 times. The negative phase was accompanied by a slight rise of the F2 layer (by 20–28 km), which could be due to a decrease in the vertical component of the motion velocity and an increase in plasma temperature (the electron temperature increased by 600–800 K, while the ion temperature only by 100–160 K).

(2) Subsequent disturbances in the magnetosphere on December 22–24, 2016, caused strong negative disturbances (with a maximum decrease of N_mF2 by 4.9 and 2.6 times, respectively), whose effects were manifested in variations of electron and ion temperatures. The F2 layer height variations were similar to those characteristic of magnetically undisturbed conditions.

(3) The geospace storm during its main phase influenced daily variations of the vertical component of the ionospheric plasma velocity V_z. Two oscillations of V_z variations were detected toward the increase in the velocity modulus of the downward plasma flux with quasiperiods of 3 and 2 h and a maximum deviation at 23:15 UT on December 21, 2016, increasing with height from 14 to 50 m/s at heights of 200–400 km, and a maximum deviation at 01:45 UT on December 22, 2016, of 26, 20, 18, 25, and 37 m/s at the heights of 198, 253, 308, 363, and 418 km, respectively.

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