Ionospheric positive storm phase on 18 December 2019 observed by the Kharkiv incoherent scatter radar

S. V. Katsko, L. Ya. Emelyanov, V. V. Kolodyazhnyi*, I. F. Domnin
Institute of Ionosphere, Kharkiv, Ukraine, 16, Kyrpychova str., Kharkiv, Ukraine, 61001,
Vyacheslav.Kolodyazhnyi@infiz.khpi.edu.ua

Abstract

The aim of the work is experimental studies of variations in ionospheric plasma parameters over Ukraine during the very moderate magnetic storm on December 18, 2019 ($K_p = 4$). The ionosphere response over Kharkiv to the magnetic storm on December 18, 2019 was analyzed. It was established that a very moderate magnetic storm caused noticeable changes in ionospheric plasma parameters in the entire range of studied altitudes. An increase in the N_mF2 (up to by a factor of 2.8) were accompanied by a chain of changes in the variations of the main parameters of the ionospheric plasma. The mechanisms are considered to explain generation of the positive storm.

1 Introduction

In general, the study of the effects of weak magnetic disturbances has received less attention than that of strong ones. But even with weak storms, the state of the ionosphere and plasmasphere, which interact with each other, is very sensitive. Of particular interest is the occurrence of positive ionospheric disturbances in mid-latitudes, because usually the mechanism of their formation is complex and it is the result of the interaction of several generation mechanisms at once [1–6].

In this study, we present observations of a positive ionospheric storm at the mid-latitudes during the daytime in order to understand due to which mechanisms the increase in electron density could be generated.

2 Geophysical conditions

Fig. 1 presents solar-geophysical conditions during December 16–19, 2019: interplanetary magnetic field (IMF) B_z component, the solar wind velocity V_{sw} and dynamic pressure $p_{sw,}$ the zonal component of magnetospheric electric field E_y and geomagnetic activity indices (D_{st}, K_p, AE). Here and below, the time is UT. The magnetic storm arose as a result of the interaction of the magnetosphere with high-speed solar wind flowing from the coronal hole on the Sun. On 18 December at about 02:30, solar wind pressure on the Earth increased rapidly, p_{sw} reached almost 5.3 nPa. After that V_{sw} gradually increased and around 12:00 and exceeded 500 km/s. Sharp changes in the direction and values of the B_z component were observed after a rapid decline in p_{sw}. At 02:00, the B_z value was +2.8 nT, at 03:00 it decreased to +1.1 nT, at 04:00 it increased again to +4.2 nT and at 05:00 it once again decreased to +0.7 nT. At 07:00, B_z component reached its maximum of +5.1 nT, and at 11:00, it reached its minimum of –5.3 nT.

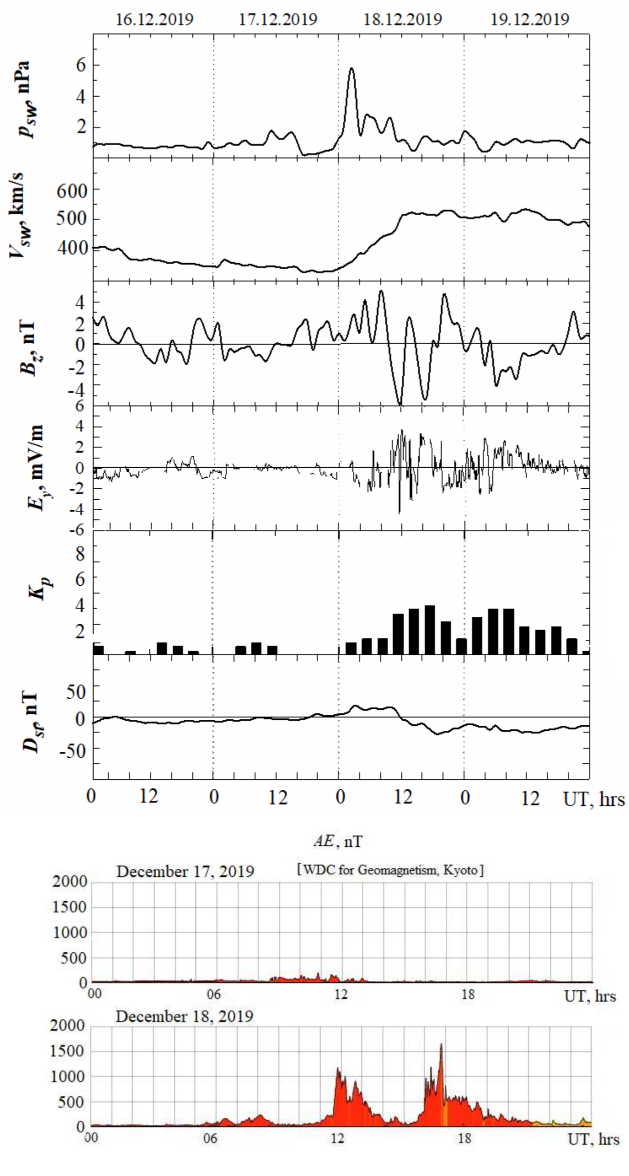

Figure 1. Variations of solar wind pressure $p_{sw,}$ and velocity V_{sw}, IMF B_z component, the zonal component of electric field E_y, K_p, D_{st} and AE indices.

The first increase in the K_p index to 3+ occurred at 09:00–12:00, and in the next three-hour period it increased to 4–. From 15:00 to 16:00, the B_z component value was –4.7 nT. The K_p index was 4 until 18:00. The first significant increase in the AE index by more than 1100 nT was around 11:50 after the B_z component, turning southward, reached its minimum of –5.3 nT at 11:00. After the second minimum B_z was –4.7 nT at 15:00–16:00, the AE index reached almost 1700 nT at about 16:50. The magnetic storm began at around 11:00, the negative deviation of the D_{st} index was insignificant (–28 nT) at 19:00, when the next significant maximum of the IMF B_z component (+4.6 nT) was recorded.

3 Methods and instruments

Observations of the ionosphere were carried out with incoherent scatter (IS) radar located near Kharkiv at the Ionospheric Observatory of Institute of Ionosphere of the National Academy of Sciences and the Ministry of Education and Science of Ukraine. This radar is the only one at the mid-latitudes of Europe, which allows simultaneous measuring the main parameters of the ionosphere with high accuracy in a wide range of altitudes [7, 8]. Its main parameters are as follows: the operating frequency is about 158 MHz, the diameter of a vertically directed antenna of the Cassegrain type is 100 m, its effective aperture is about 3700 m^2 (the beam width of the antenna pattern is about 1.3°), the polarization is circular, and the repetition frequency of the sounding pulse signal is 24.4 Hz. In December 2019, the radar operated in the mode of radiation of a two-frequency composite radio pulse signal with a pulse power of 2 MW with elements of 130 and 660 μs duration, which provides an altitude resolution of 20 and 100 km in the altitude ranges 100–400 km and 200–1500 km, respectively. The noise temperature of the receiver is 120 K and the receiver bandwidth is 11–19 kHz.

The method of data processing of the IS radar is described in [9, 10]. The measurement errors of ionospheric parameters are 1–10%, and drift velocities are 1–30 m/s at a signal-to-noise ratio of more than 0.1.

4 Experimental data

4.1 Fluctuations in N_mF2 and h_mF2

Fig. 2 shows plots of N_mF2 observed by ionosonde station in Kharkiv. The data N_mF2 of December 16, 2019, was selected as the magnetically quiet period, when K_p index did not exceed 1.

As can be seen from Fig. 2, the magnetic storm on December 18, 2019, caused a positive ionospheric storm over Kharkiv with a duration of about 5 hours. The magnetic storm beginning was accompanied by an increase in N_mF2 (about 12:00 it increased from $3.44 \cdot 10^{11}$ m^{-3} to $4.46 \cdot 10^{11}$ m^{-3}). During 14:30–14:45, N_mF2 achieved an increase by a factor of 2.8 (from $0.82 \cdot 10^{11}$ m^{-3} to $2.3 \cdot 10^{11}$ m^{-3}). In the time interval 16:30–19:00, N_mF2 continued to significantly exceeded the magnetic quiet data, the increase in density values reached by a factor of 1.6–1.8.

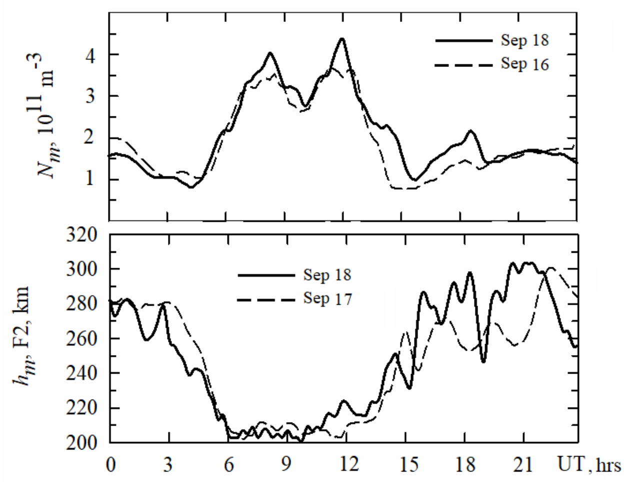

Figure 2. Variations in the peak F2 layer electron density N_mF2 and F2 peak height h_mF2 during the quiet (17 September) and enhanced (18 September) magnetic activity.

The F2 peak height data (h_mF2) on December 18, obtained by the IS radar, were compared with the data obtained on December 17, 2019. It can be seen that the maximum increase in N_mF2 by a factor of 2.8 in the time interval 14:30–14:45 was accompanied by a decrease in h_mF2 from 264 to 235 km at 15:00, followed by an increase to 280–285 km. During subsequent increases of N_mF2 by a factor of 1.6 in the interval 16:30–17:00, the height values for December 17 and 18 were close. Then, h_mF2 began to gradually increase until 19:00. At 18:45, while N_mF2 increased by a factor of 1.8, the h_mF2 decreased slightly. Further, when the N_mF2 values began to approach the values characteristic of magnetically quiet conditions, the h_mF2 values, on the contrary, were significantly greater on average by 40–45 km in the interval 20:15–21:15.

4.2 Diurnal variations in N_e, T_e, T_i and V_z

Fig. 3 illustrates the diurnal variation of electron density N_e, electron temperature T_e, ion temperature T_i, and ionospheric plasma vertical drift velocity V_z at altitudes 300 and 400 km. It can be seen that at altitude of 300 km, the beginning of the magnetic storm was accompanied by a decrease in N_e. During the ionospheric storm on December 18 at altitudes of 300 and 400 km the N_e values exceeded ones for December 17. The maximum increase in N_e was observed at 300 km, which was accompanied by a decrease in temperature T_e. The decrease in T_e is directly the result from enhancement in N_e as the electron cooling rate is proportional to the square of N_e [11].

On December 18 at 300 km altitude the T_i values was less than on December 17 since the beginning of the magnetic storm. The increase in h_mF2 on 18 December after 17:00

was also accompanied by a decrease in temperature values: the changes in T_e and T_i values during the h_mF2 increase from 252 to 298 km at 18:15 were quite noticeable at 300 and 400 km altitudes.

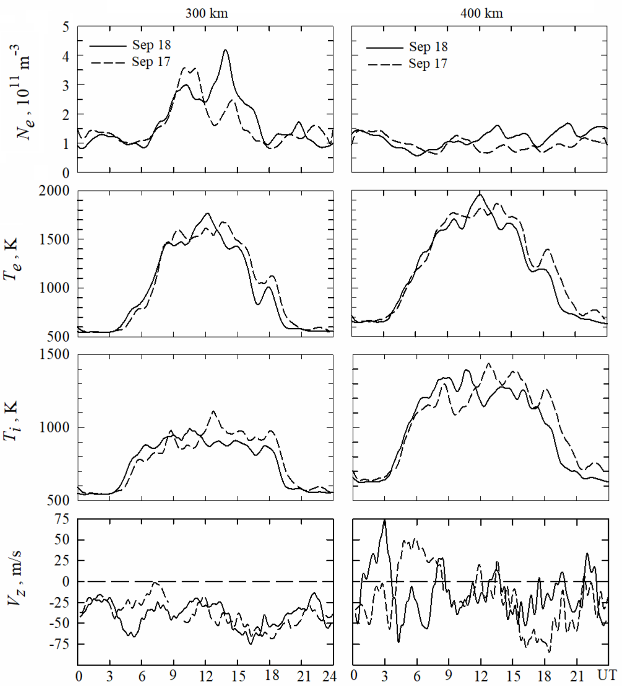

Figure 3. Diurnal variations of electron density, electron and ion temperatures and vertical drift velocity at 300 and 400 km altitudes.

The geomagnetic storm affected the variations in the vertical component of the ionospheric plasma drift velocity V_z (Fig. 3). At 11:45, the plasma drift velocity at the altitudes of the outer ionosphere temporarily deviated towards positive values after changing the zonal component of electric field E_y from +4 to −4 mV/m, i.e., the velocity of the downward (V_z<0) plasma motion decreased. A similar effect was observed at 12:30 and 19:20 with a temporary change in the direction of plasma motion to upward. At 12:00 on December 18, 20 min after a sharp change in the *AE* index, the velocity of the descending plasma motion began to decrease at altitudes of 200–360 km compared to the velocity values on December 17, followed by a recovery of V_z at 13:40. At 300 km altitude, the maximum V_z reduction was 27 km at 13:10. After a significant change in E_y from −2 to +2.4 mV/m during interval 14:45−15:15, fluctuations appeared in the variations of V_z at altitudes of 360−420 km with a quasi-period of 1 h 50 min. They lasted approximately until 19:15 (see Fig. 3). This effect was absent on 17 December. On December 18, a significant weakening of the effect of the evening extremum in V_z variations was observed, which usually manifests itself in winter as a temporary increase in the velocity of the downward plasma motion [12]. On the magnetically quiet day of December 17, this effect was observed approximately from 15:00 to 21:00. The maximum differences in velocity variations on December 17 and 18 were observed at approximately 18:20. They increased with height. At 400 km altitude, the decrease in the velocity modulus was about 70 m/s.

5 Discussion

In winter, in the midlatitude ionosphere during the daytime, the zone of reduced ratio [O]/[N2] is "closed" in high latitudes, because the normal circulation prevents the penetration of heated gas into the midlatitudes. At the same time, the normal circulation is weakened by the storm-induced countercurrent circulation, and therefore the downward plasma drift becomes weaker. This leads to new equilibrium conditions in the maximum of the F2 layer, and its height h_mF2 increases and, accordingly, the electron density increases. This is the reason for the dominance of the positive phase in these conditions. This generation mechanism of a positive ionospheric storm is in good agreement with the obtained results. The increase in N_mF2 after 12:00 on 18 December was accompanied by slightly higher h_mF2 values compared to 17 December. At that time, a noticeable increase in N_e at 300 km altitude was observed, and V_z slightly decreased. Around 14:00, the T_e values at 300 km were lower. A similar generation mechanism of the positive phase of the storm was also described by other scientists [1]. After the maximum increase in N_mF2 around 14:30–14:45, a sharp decline in N_mF2 was observed, the mechanisms of negative ionospheric storm generation began to dominate. It was accompanied by a rapid decrease in h_mF2. During this period, the N_e began to decrease rapidly in the entire range of studied heights, and the modulus of the downward ($V_z < 0$) motion velocity at the indicated heights remained almost unchanged.

Further, the generation mechanisms of positive ionospheric storms began to prevail again: after 15:00, the h_mF2 began to increase and at 15:45 it increased from 242 to 282 km, then the values of N_mF2 also increased. After 16:00, the values of T_e began to decrease compared to the previous day, the N_e and the modulus of the V_z of the downward motion of the plasma began to increase at altitudes greater than 300 km. The same positive storm formation mechanism was also observed around 18:00, except that the modulus of the velocity of the downward movement of the plasma was smaller than on December 17.

As can be seen from Fig. 1, the beginning of the positive phase was also preceded by an increase in the auroral index *AE*, which is consistent with the mechanism of traveling atmospheric/ionospheric disturbances (TAD/TID), the propagation of which causes the ionospheric layer to rise due to amplification of the meridional wind. The formation of the positive phase due to the meridional wind directed towards the equator is effective just in the daytime, when ion formation processes predominate. On December 18, 2019, the penetration of the electric field took place: the E_y component abruptly changed its direction and magnitude. Therefore, the mechanism of penetration of the electric field could also take place in the formation of a positive phase at the middle latitudes. This is confirmed by the fact that after sharp changes in the electric field E_y from positive values to negative ones, the vertical plasma drift velocity changed towards positive values (decrease in the downward velocity of the plasma), which was accompanied by an increase h_mF2 and the rise of the F2 layer to the region of lower recombination.

6 Conclusions

It is shown that a very moderate magnetic storm on December 18, 2019 ($K_p = 4$) was accompanied by a positive ionospheric disturbance over Ukraine with a significant increase in N_mF2 up to by a factor of 2.8. Notable changes were observed in all parameters of the ionospheric plasma. Temporal variations of the h_mF2 changed significantly due to the action of the generation mechanisms of effects in the disturbed ionosphere, and its values were mostly increased compared to the day before. Before the onset of the ionospheric storm, the values of the T_e were higher than under magnetic quiet conditions, but with the development of the ionospheric disturbance, the temperature was lower. During the storm, the velocity of the downward plasma motion decreased compared to a magnetically quiet day.

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7 References

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