On thermospheric-ionospheric perturbations under conditions of quiet and perturbed ionosphere

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The main mechanisms of ionospheric storms are thoroughly studied, but ionospheric perturbations often are unsatisfactorily predicted, maybe because of insufficient allowance for the ionospheric background. In particular, according to data on the electron concentration N_e in the maximum of the $F2$ region and the total electron content, it has been shown that the amplitude of the positive phase for similar atmospheric storms can differ by about 1.5 times. Such a difference can be caused by changes in thermospheric conditions that are not reflected by known activity indices. For further investigation of the ionosphere, we used the data of an incoherent scattering radar of the Institute of Ionosphere (Kharkiv, Ukraine) for the altitude range from 200 to 1000 km in very quiet periods ending by geomagnetic perturbations (K_p = 4–5). Stable periodic perturbations of the electron concentration N_e were found in the entire altitude range. These perturbations can be associated with the tidal mode $m = 6$. The wave amplitude is ~ 15%, and the phase varies with altitude. The beginning of a storm leads to amplitude doubling with the phase unchanged. The presence of perturbations in the ionosphere under very quiet conditions may be an extra factor complicating the ionospheric reaction to a magnetic storm.

Introduction

Main peculiarities in the behavior of the ionosphere during magnetic storms (MS) are studied rather comprehensively by now.[1–5] Basic components of perturbations and their most probable sources are established. Theoretical calculations with the use of current ionospheric models allow one to reconstruct the main global and large-scale regularities of ionospheric storms,[1,3] but peculiarities of particular ionospheric storms in a given region are often reconstructed unsatisfactorily.[6] Ionospheric prediction under distorted conditions turns out to be unsatisfactory as well. In recent years, these problems have been solved using the results of combined global measurements, including satellite composition and drift measurements mostly in the periods of strong MS.

At the same time, attention should be paid to the fact that significant deviations of ionospheric parameters from their median values are also possible under other conditions. Consequently, it may be useful to analyze in a more detail quiet conditions in the ionosphere, first of all, those prior to the ionospheric storms. The aim of this paper is to study peculiarities in the behavior of the mid-latitude ionosphere at transition from very quiet to magneto-disturbed conditions.

1. Methods and instruments

To solve this problem, we used the data of an incoherent scattering (IS) radar of the Institute of Ionosphere (Ukrainian National Academy of Sciences and the Ministry of Education and Science). The radar was located near Kharkiv and had the following coordinates[7]:

– geographic: 49.6°N, 36.3°E;
– geomagnetic: 45.4°N, 117.7°E;
– geomagnetic field inclination: 66°.

The IS radar has the world's largest zenith two-mirror parabolic antenna of 100-m diameter and is designed for ionospheric investigations in the altitude range from 200 to 1500 km. The operating frequency of the radar is 150 MHz. The pulsed power of the radio transmitter is about 2 MW. The pulse duration can be widely varied from about 40 μs to 1 ms. The noise temperature of the system is about 300 K.

The radar parameters were chosen from the condition of obtaining the maximum number of ionospheric characteristics in as wide as possible altitude range. To solve some problems arising in the ionospheric investigations, several operating modes of the system were used. These modes differ by the sensing pulse parameters (pulse duration, repetition frequency, and the gap between pulses).

Among the radar findings, for this investigation we used the electron concentration N_e, the ion T_i and electron T_e temperatures, and the speed of vertical plasma drift V_d. These parameters were determined with the step of 10 km (Ref. 8).

Two periods: June 24–27 of 1997 and February 9–11 of 1999 were analyzed. The beginning of both periods fell on very quiet conditions characterized by a low level of geomagnetic activity on the considered and previous days, the absence of solar flares and intersections of boundaries of the interplanetary magnetic field. Each period ended with a weak MS: on June 27 of 1997 the geomagnetic index $K_{p\,\max} = 5_-$ and on February 11 of 1999 $K_{p\,\max} = 4\supseteq$. A more detailed information about the analyzed periods is tabulated below.

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Geophysical conditions during the observation time

Indices			First period (June 1997)				Second period (February 1999)		
			24	25	26	27	9	10	11
Level of solar and geomagnetic activity	W		9	19	15	12	41	60	78
	$F_{10.7}$		72	74	74	74	126	148	159
	A_p		4	7	4	17	3	6	20
	ΣK_p		7_+	15_0	8_+	22_+	6_0	11_+	27_+
Local sunrise and sunset time	Sunrise	OS	3:47	3:47	3:48	3:49	7:17	7:15	7:13
		MCP	6:01	6:01	6:02	6:03	4:33	4:35	4:37
	Sunset	OS	20:10	20:10	20:11	20:12	17:04	17:06	17:08
		MCP	16:00	16:00	16:01	16:02	18:06	18:04	18:02

Note. OS stands for the observation site; MCP stands for the magnetoconjugate point.

2. Results and discussion

In spite of the absence of external perturbation sources, variations of all indices during both of the quiet periods all over the considered altitude range are indicative of the presence of marked quasi-wave processes in the ionosphere. The prevalent oscillation period T is about 4 h in summer and 2–4 h in winter. The oscillation amplitude increases with height. The amplitude in terms of N_e at the altitudes higher than or about 400 km is 15–20% and in some waves up to 40%. At high altitudes the relative amplitude remains almost unchanged, but the absolute amplitude values decrease. Both in summer and winter, the first quasiwave increase of N_e begins after sunrise. Since in summer the sunrise time significantly depends on the altitude, perturbation at high altitudes begins almost 2 h before that at lower altitudes; phase mismatch with height holds in the following oscillations as well (Fig. 1). In winter the difference in the sunrise time for the considered altitudes is small, and, correspondingly, N_e oscillations at all altitudes are almost in-phase. In neighboring quiet days, the wave front structure holds almost without changes.

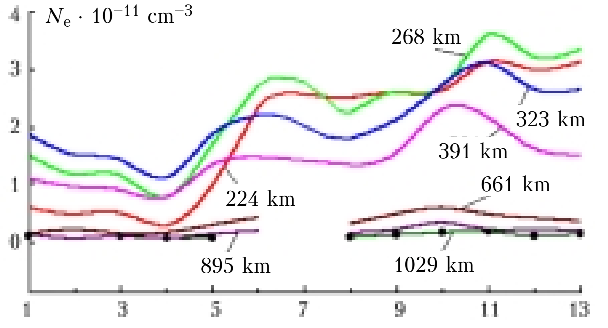

Fig. 1. Tidal waves in N_e at different altitudes under very quiet conditions (June 25 of 1997).

Daytime variations of the vertical drift speed V_d are 10–15 m/s and occur synchronously with N_e variations (as N_e increases, the drift is directed upward). Nighttime variations of V_d can be even larger (up to ± 40 m/s), but they have almost no effect on N_e variations, since at night the smoothing effect of viscosity leads to the upward and downward homogeneous shift of the $F2$ region without a marked change in the altitude profile of N_e. Variations of the temperature T_e are less marked (in summer) or less regular (in winter).

Close relation between the sunrise and the beginning of perturbations with the pronounced altitude peculiarities, as well as the wave field stability, suggests that the observed waves are standing tidal high-order thermospheric modes with $m = 6$. The marked shift between the beginnings of perturbation at different altitudes with an advance at high altitudes suggests also that the source of waves is located in the thermosphere in summer. In winter, we cannot exclude the presence of a source in the lower atmospheric layers as well. Theoretical calculations and analysis of observations usually include only the modes of no higher than the second order.[9–11] If in the first case this can be connected with a cumbersome analytical description of high-order modes, then in the second case this is likely caused by insufficient attention paid to the state of the ionosphere in very quiet periods. It is obvious that in the presence of even minor additional perturbation sources, e.g., those connected with substorms, solution of the problem about the nature of such oscillations becomes far more complicated. A certain role also belongs to the fact that the wave structure becomes most obvious at the altitudes higher than the maximum of $F2$ region. Investigation of the wave structure by the ground-based vertical sensing systems is very difficult.

The transition to the distorted conditions is accompanied by a marked reconfiguration of the wave structure occurring under quiet conditions. However, it is not yet destroyed. Thus, on February 11 the amplitude of the first and third waves in N_e decreased somewhat with respect to its value at the sunrise, while the amplitude of the second wave increased more than twice. It can be assumed (for more reliable assumptions we need longer observation periods) that reconfiguration of the wave field of perturbation occurs at transition to the distorted conditions with prevalence of lower tidal modes. The second thermospheric tidal mode $m = 2$ likely prevails under distorted conditions.

The largest increase of N_e occurred at the altitudes above the maximum of $F2$ region, and this fact agrees well with typical peculiarities of variation of the electron concentration after the MS beginning. At the same time, quantitative variations of N_e cannot be called typical. Figure 2*a* depicts diurnal variations of N_e on

February 10 and 11 at the altitude $h = 294$ km corresponding to the maximum increase of N_e. It is interesting that N_e kept high value for a long time. The N_e values exceeded the undistorted values for almost entire daytime roughly by 50%, and the maximum value was almost doubled. Such a significant N_e growth is rarely observed even in the periods of strong MS, and therefore it deserves analysis that is more detailed.

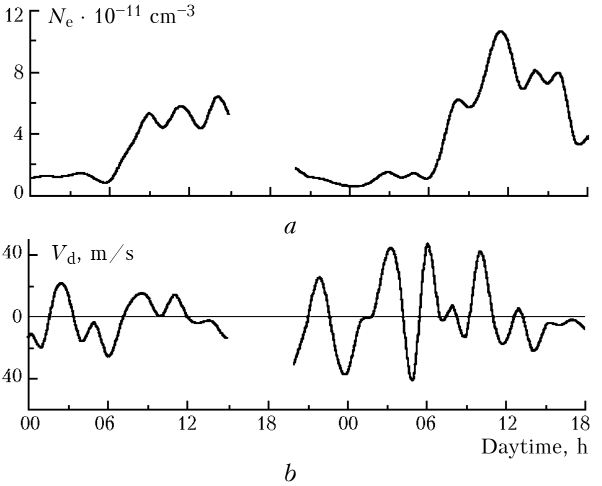

Fig. 2. Diurnal behavior of N_e and V_d at the altitude $h = 294$ km at transition from very quiet to distorted conditions (February 10–11 of 1999).

As known, the positive phase of ionospheric storms is formed due to the meridional component of the neutral wind velocity in the southern direction caused by the Joule heating of the auroral atmosphere at dissipation of high-latitude electric currents.[1–5,9] The momentum is transferred from horizontally moving neutral particles to ions through the wind entrainment mechanism, and this leads to upward displacement of ions along the lines of force of the magnetic field. In daytime the upward plasma drift is accompanied by a marked deformation of the altitude profile and a marked increase of N_e at high altitudes. The decrease in the loss rate with the altitude also favors for the keeping of N_e. The following enrichment of the high- and mid-latitude thermosphere with heavier components, first of all with N_2 and O_2, leads to a decrease in N_e proportionally to the decrease in the ratio $[O]/([N_2]+[O_2])$. As a result, negative phase of the ionospheric storm alternates the positive phase within several hours after the MS beginning.

The positive phase of ionospheric perturbation is most pronounced over the North America (see, for example, Ref. 12). This is likely connected with the maximum southward shift of the auroral oval because the Earth's magnetic and geographic poles are not in the same location. It is also known that the positive phase is most often recorded in the case that the MS beginning occurs in daytime hours.[12] If MS begins at night, the positive phase is usually absent and the ionospheric storm begins from the negative phase.

In recent years, the long-lived positive phase of ionospheric storms is considered as an independent phenomenon. Two its basic mechanisms are discussed: changes in the neutral composition[2,13] (some authors[14] believe that variations in the concentration of atomic oxygen are most important in variation of the ratio $[O]/[N_2]$) and effects of thermospheric winds similar to those causing the appearance of positive phase in evening hours, but of larger-scale.[3]

In our case on February 10, the MS beginning falls on pre midnight hours. The main MS phase began after midnight. Thus, the decrease of N_e, rather than increase, should be expected. To explain the significant deviation of the N_e behavior from the expected one, we should take into account that the types of ionospheric responses were studied for a rather strong MS. Thus, in Ref. 12 magnetic storms with $A_p > 30$ were sampled for analysis. Besides, MS in our case began after a long period of very quiet conditions in the Earth's magnetic field. In the absence of an auroral heating source, the system of thermospheric winds is formed due to heating by solar radiation, which favors the increase in the speed of the thermospheric wind directed northward in the daytime hours.

Thus, the considered magnetic storm was weak, and the auroral heating source was able only to decrease the background wind without changing its direction. The decrease of the background wind turned out to be sufficient for the $F2$ region to move upwards, thus providing for the beginning of the positive phase. At the same time, for an efficient diffusion of heavy particles to the mid-latitudes to occur, alternation of the wind direction is needed. Since such a turn is unlikely for the considered MS in daytime hours (according to calculations from Ref. 15, at $K_p = 4_o$ the resulting wind velocity in the daytime hours is still directed northward), alternation of the positive phase of the ionospheric storm by the negative one was not observed.

The preceding very quiet conditions could also contribute to the increase of the amplitude of the positive phase through a more pronounced altitude stratification of the main ionospheric components, so the effect of the upward shift of the $F2$ region after beginning of the MS could prove more pronounced. It is also possible that the winter ionosphere under quiet conditions is richer with oxygen atoms (due to the transequatorial transport from the summer hemisphere to the winter one), because in the absence of auroral heating, which manifests itself simultaneously in both hemispheres, the temperature gradient between the hemispheres should increase.

Thus, the peculiarities of the state of the ionosphere and thermosphere before the beginning of perturbation can markedly affect the development of ionospheric perturbation. In particular, they can contribute considerably to formation of the conditions favorable for the long-lived positive phase. Such conditions can lead to significant ionospheric perturbations comparable, in the amplitude, with the effects of very strong MS even in the periods of weak and moderate MS.

The background thermospheric winds and the stable wave structure formed under quiet conditions could affect, in a certain way, the development of ionospheric perturbation.

The marked effects of the active MS include also the marked increase of fluctuations of the vertical drift speed V_d. Figure 2*b* shows variations of V_d at the same altitude as N_e. However, the maximum effect of V_d increase was observed at the altitudes below the maximum of the *F*2 region. The beginning of MS here was accompanied by an increase of fluctuations up to ± 60 m/s, that is, at least by 1.5 times as compared with the amplitude of fluctuations in the preceding night. The beginning of the main MS phase has led to their further increase. The V_d phase difference in the altitude range of 223–341 km was ~ 0.5 h with the advance at high altitudes; the oscillation period was ~ 2 h.

Thus, these oscillations can be thought manifestation of the acoustic-gravity waves generated by an auroral source.[1,2,9] Important factors are their pronounced character in spite of a weak MS, as well as fast beginning – yet before the beginning of the main phase, during which the main part of energy is released. Taking into account the storm conditions, it is needed to determine peculiarities of amplitude variations of the vertical component of the plasma drift velocity V_d.

Conclusion

Our analysis of the ionospheric conditions characterized by the transition from very quiet to distorted conditions allows us to state that under certain conditions even weak and moderate MS can lead to such changes in the ionosphere that are usually observed in the periods of strong perturbations. One of such conditions can be long periods of very quiet days likely forming some peculiarities in the system of thermospheric winds, including transequatorial transport, as well as stable quasiwave structure with tidal modes of high orders. Correspondingly, the approach involving analysis of conditions and peculiarities of transition from quiet to perturbed conditions may prove fruitful not only from the viewpoint of studying ionospheric perturbations (in such an approach, many perturbations show themselves just as they are and are undistorted by overlap of several perturbations), but also from the viewpoint of looking for the causes of significant variations of ionospheric parameters, many of which remain beyond the investigators' field of view because of the preferable analysis of a narrow class of events.

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