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Dynamics of midlatitude ionospheric trough during storms 1. A qualitative picture

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Abstract. Analysis of sounder measurements made by the Cosmos 900 satellite at altitudes of 430 ± 50 km at nighttime has shown that during storms the midlatitude ionospheric trough can be considered to consist of two troughs. The first, i.e., the main ionospheric trough (MIT), tends to be located near the boundary of diffuse electron injections; the second, i.e., a ring ionospheric trough, is characteristic of the recovery phase of magnetic storms and is likely to be associated with a residual magnetospheric ring current. During this phase both troughs can be detected simultaneously. During the expansion phase of a magnetic storm, changes in the MIT position, on the whole, occur ahead of Dst index variations and lag behind changes in the Kp index with a characteristic delay time τ. The higher the rate of τ increase, the longer Kp becomes. A qualitative interpretation of these relationships is given.

Introduction

During storms, the midlatitude ionospheric trough often has a complicated structure. For instance, it can consist of two relatively narrow troughs of electron concentration. This fact is not reflected in empirical models of variations of invariant latitude of electron concentration minima of the midlatitude trough Φ_t containing dependence of Φ_t on the Kp magnetic activity index (see, for example, *Deminov et al.* [1992]). It is therefore not clear whether the obtained statistical dependencies of Φ_t on Kp refer to one of these electron concentration troughs or to their average value.

The goal of this work is to solve qualitatively this question by using measurements of electron concentration N_e and temperature T_e made by the Cosmos 900 satellite at altitudes of 430 ± 50 km. Measurements of N_e or, to be more precise, of total ion concentration, were carried out by a PL 40A retarding potential analyzer [*Gubskiy et al.,* 1982] and a spherical three-electrode ion trap with a “floating” external grid potential [*Belyashin et al.,* 1982]. Electron temperature was measured by a high-frequency sounder [*Afonin et al.,* 1973]. Measuring limits of N_e and T_e were $10^3 - 10^6$ cm^{-3} and $5 \times (10^2 - 10^4)$, respectively.

Results of Observational Data Analysis

For the analysis, measurements of N_e and T_e obtained at crossing of subauroral latitudes by the satellites at nighttime in local winter and at equinox during 20 storms with $(Kp)_{\max} = 5-8$, $(-Dst)_{\max} = 60-180$ nT were used. The measuring period (March 1978 until September 1979) corresponded to high solar activity.

Figure 1 shows variations in positions of electron concentration maxima for three storms. The time was counted from the beginning of the Kp index growth. As an example, Figure 2 shows examples of variations of N_e and T_e along separate satellite tracks during the storms of July 26–27, 1979, which are denoted by 1, 2, 3, and 4 in Figure 1. It can be seen that a peak in T_e usually corresponds to a trough in N_e in the subauroral region. The position of the peak in T_e for an extremely small trough in N_e in Figure 1 is shown by a cross. Such a situation is realized, for instance, during case 1 for the

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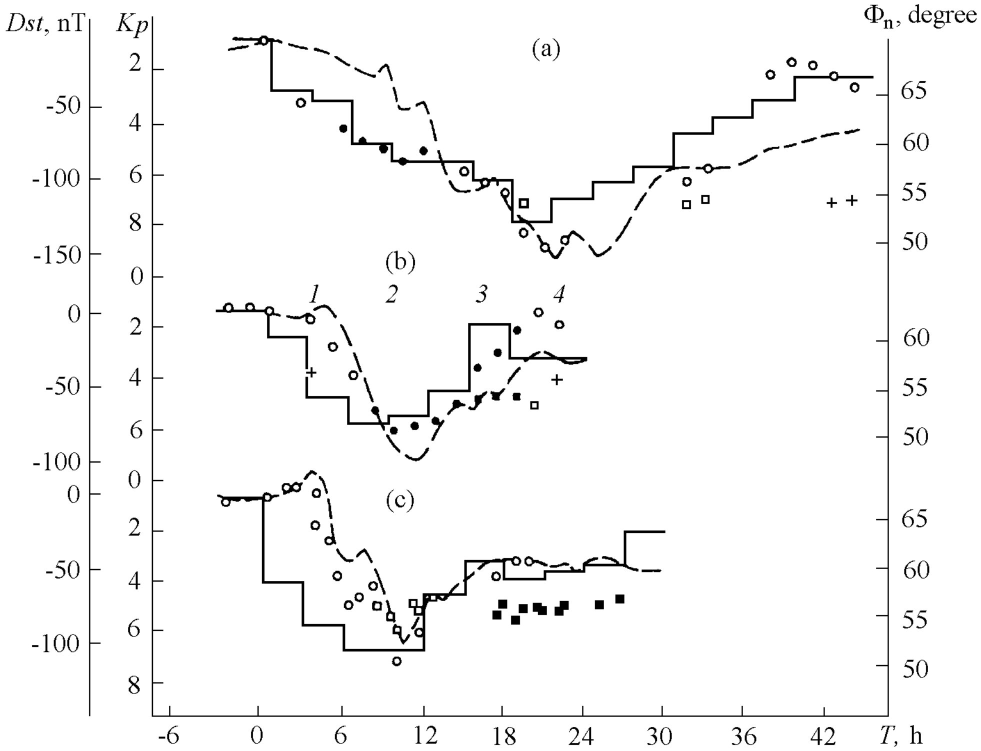

Figure 1. Variations in positions of troughs during three magnetic storms: (a) August 28–30, 1979, 1800–2000 MLT; (b) July 26–27, 1979, 2300–0100 MLT; and (c) March 21–22, 1979, 0300–0500 MLT. The solid lines show variations in the *Kp* index, dashed lines indicate *Dst* variations, circles show the main ionospheric trough; squares denote the ring ionospheric trough, solid circles show a narrow ionization trough, and crosses indicate the T_e peak.

peak in T_e in the vicinity of 55°Φ. For case 2 and especially for case 3, the troughs in N_e are composed of several narrow ionization troughs (shown by solid circles and squares in Figure 1). The trough shown by the circles in Figure 1 will be referred to as the main ionospheric trough (MIT). Its position depends on the current magnetic activity level. The trough that is distinctly separated from the MIT is indicated by a square. It is detected mainly during recovery phases of magnetic storms, and for the majority of intense storms it tends to be located near 55°Φ, irrespective of the current magnetic activity level. We refer to it as an ionospheric trough because of a residual magnetospheric ring current or, for brevity, as a ring ionospheric trough (RIT). Note that the existence of the trough in N_e in the region corresponding to the projection of the ring current position on the ionosphere, where the peak of T_e is located and a midlatitude red arc is often observed, was

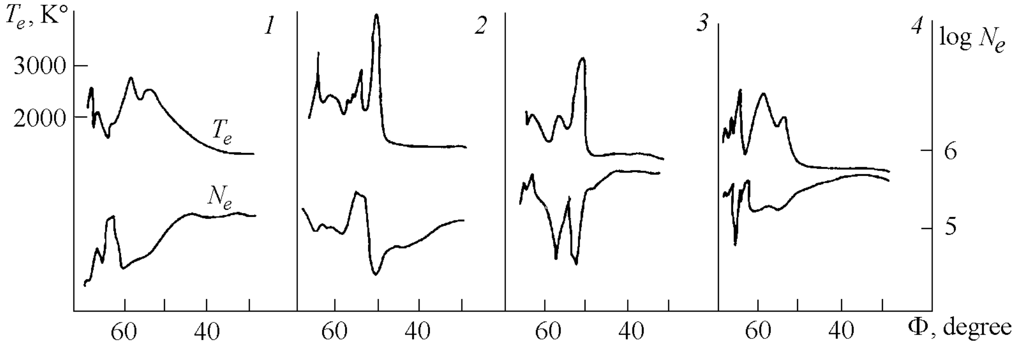

Figure 2. Latitude variations of N_e and T_e during the storm on July 26–27, 1979 for satellite passes indicated by 1, 2, 3, and 4, respectively, in Figure 1.

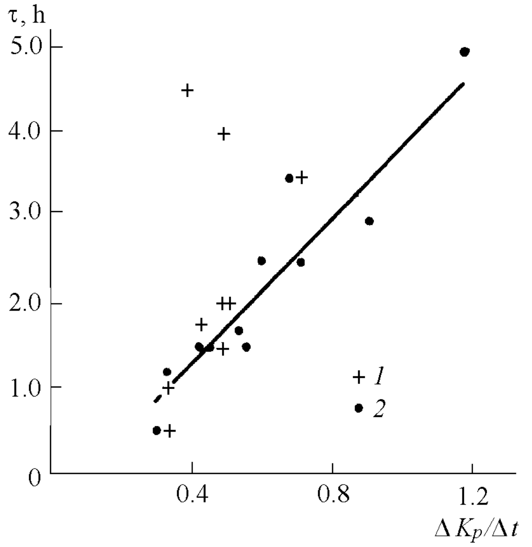

Figure 3. Delay τ in response of a trough to Kp index variations as a function of the perturbation growth rate $\Delta Kp/\Delta t$; 1, evening hours; and 2, near midnight and after midnight hours of local time.

reported by *Norton and Findlay* [1969]. Note also that in the literature the midlatitude ionospheric trough and MIT are often equivalent notions. Here, the midlatitude trough consists of MIT and RIT.

The storms are shown in Figure 1 in the order of the increasing rate of the Kp index variations during the magnetic storm expansion phase. The magnetic local time (MLT) of crossing the subauroral latitudes changes here from evening to morning hours. Such a choice of geophysical conditions allows us to trace basic relationships of MIT and RIT dynamics which have been interred from the analysis of 20 storms. These relationships are as follows.

If the magnetic storm has a pronounced growth phase, i.e., *Dst* increases before the onset of the expansion phase, then MIT hardly changes its position in the beginning of this phase or even shifts somewhat to the pole despite increasing Kp. Then, as a rule, without waiting for the end of the growth phase, the trough moves toward the equator. As a result, the displacement of the MIT to the equator usually lags behind changes in Kp and is ahead of variations in *Dst* until the end of the magnetic storm expansion phase is approached. During such an equatorward displacement the MIT can take the structure of a narrow ionization trough. The MIT structure is most often realized in premidnight hours, consistent with earlier observations [*Gal'perin et al.,* 1990]. The minimum MIT latitude is usually reached at the end of the magnetic storm expansion phase.

During the recovery phase of a magnetic storm, the MIT and RIT can be detected simultaneously. Both troughs shift to the pole during this phase. The MIT displacement to the pole correlates with the magnitude of the Kp index during the preceding 2–3 hours. Displacement of RIT to the pole is much smaller and, on the average, the RIT is located at latitude 55°Φ for the majority of intense storms, which is why the RIT is detected as a trough distinctly separated from the MIT when the MIT is found at latitudes higher than 55°Φ during its displacement. The RIT often has a structure of a narrow ionization trough in the morning and, more rarely, in the near midnight hours. Such a structure is not characteristic of MIT in the morning hours, and therefore the MIT is often unresolveable in the morning sector during the magnetic storm recovery phase. An opposite situation is typical of evening hours, when no RIT is observed at the heights of 430 ± 50 km by satellites.

Thus not in all cases are MIT and RIT simultaneously clearly seen even during the magnetic storm recovery phase. If only one trough is pronounced, it is not necessarily the MIT. The RIT differs from the MIT primarily by the character of the dependence of its position on magnetic activity.

Relationship Between MIT and RIT Position and Kp and DR

Figure 1 shows one more characteristic feature of MIT dynamics during the magnetic storm expansion phase; the greater the rate of Kp index increase, the longer the delay time τ of MIT displacement with respect to Kp, i.e., $\Phi_{\rm t}(t) \sim -Kp(t-\tau)$, where $\tau \sim \Delta Kp/\Delta t$. A correct determination of τ from data of the Cosmos 900 satellite is possible only for storms with a relatively long expansion phase. Therefore from 20 storms, 11 storms were chosen for which the period of Kp growth lasted for not less than 6 hours. For the whole period of Kp growth, the average values of τ and $\Delta Kp/\Delta t$ for each of the selected storms were determined. These values are shown in Figure 3, which also presents a linear fit for near midnight and after midnight hours of magnetic local time, which is given by

$$\tau = -0.4 + 4.5\Delta Kp/\Delta t \tag{1}$$

where τ and t are in hours. It can be seen that the discovered property is stable for near midnight and after midnight hours. The scatter in τ magnitudes for evening hours indicates that at this time there exists an additional reason for the τ increase which was not included into (1).

If storms are not separated into phases, the average value for selected storms is $\bar{\tau} \approx 2.2$ hours. Note that $Kp(t-\tau) \approx \bar{K}p(t-2\tau)$, where $\bar{K}p(t-2\tau)$ is the average Kp for the time interval from $t-2\tau$ to t. Hence on the average, the MIT position correlates with the magnitude of Kp for the preceding 2.2 hours or, what is nearly the same, with the average magnitude of Kp for the preceding interval of 4.4 h.

The ring current field $DR = Dst - \Delta DCF$ is closely connected with the Dst field, where $\Delta DCF \sim \sqrt{P}$ is the current field perturbation at the magnetopause and P is the solar wind pressure [*Nishida*, 1980]. A preliminary analysis showed that for the majority of periods of expansion phases of selected storms the MIT position correlates with the ring current field without a pronounced delay, i.e., $\Phi_{\mathrm{t}} \sim DR(t)$. Therefore the advance in Φ_{t} variations with respect to Dst during the initial period of Φ_{t} displacement equatorward is associated, to a large degree, with an increase in the solar wind pressure.

It was noted earlier that the MIT position, which is denoted by Φ_{t}^*, is nearly independent of the current value of Kp. Nevertheless, a tendency for correlation between Φ_{t}^* and $DR(t)$ during the initial period of the recovery phase of an intense storm for $\Phi_{\mathrm{t}}^* \leq 55°\Phi$ is observed. At a later stage $\Phi_{\mathrm{t}}^* \approx 55°\Phi$.

Thus a qualitative picture of variations in MIT and RIT positions during an intense storm is as follows. During the expansion phase, $\Phi_{\mathrm{t}} \sim DR(t) \sim -Kp(t-\tau)$. In the initial period of the recovery phase, $\Phi_{\mathrm{t}} \sim -Kp\times (t-\tau)$, $\Phi_{\mathrm{t}}^* \sim DR(t)$ for $\Phi_{\mathrm{t}}^* < 55°\Phi$. At a later stage of the recovery phase, $\Phi_{\mathrm{t}} \sim -Kp(t-\tau)$, $\Phi_{\mathrm{t}}^* \approx 55°\Phi$.

Discussion

The correlation relations between the MIT and RIT positions and DR and Kp given above qualitatively reflect the average dependence of Φ_{t} and Φ_{t}^* on magnetic activity level for separate phases of an intense and relatively long storm. Let us discuss possible reasons for such qualitative averaged dependencies with reference to near midnight hours of local time. To this end, we consider the relation between Φ_{t} and Φ_{t}^* and other characteristics of the ionosphere and magnetosphere.

The MIT tends to be contiguous with the equatorial boundary of diffuse electron injections (DIB). On average, both structures change their positions during storms almost simultaneously. This follows from the closeness between statistically average MIT positions in the outer ionosphere and DIB at any level of magnetic activity [*Deminov et al.,* 1992]. In addition, the average delay time $\bar{\tau} = 2.2$ hours for MIT differs only slightly from that for DIB [*Gal'perin et al.,* 1990].

In the quasi-stationary case, for elevated magnetic activity, DIB and, apparently, MIT result from the existence of an Alfvén layer which gives rise to formation of a distinct boundary of high-latitude plasma convection [*Gal'perin et al.,* 1990]. The Alfvén layer is mainly caused by magnetospheric plasma sheet ions with energies of 10–100 keV (see, for example, *Nishida* [1980] and *Blanc and Gaudel* [1985]). These ions are also a source of the magnetospheric ring current [*Hamilton et al.,* 1988]. During magnetic activity growth, the relation between the MIT position and the inner boundary of plasma sheet ions is likely to be preserved. During this period, injection of plasma sheet ions deep into the magnetosphere and an increase in intensities of the auroral electrojet and the ring current occur almost simultaneously after the vertical component of interplanetary magnetic field B_z turns from north to south [*Nishida,* 1980].

The time interval ΔT between the arrival of high-velocity flow of the solar wind plasma and the rotation of B_z from the north to the south in this flow often corresponds to the magnetic storm growth phase. During this phase, the solar wind pressure increase $P \sim N_s V_s^2$ can give rise to a considerable increase of the planetary Kp index for nearly background values of the AE index and slight variations in the DR field and the MIT position. In the relation $\Phi_{\mathrm{t}} \sim -Kp(t-\tau)$, the time τ at the initial stage of storm development is therefore connected with ΔT. An increase in τ with increasing $\Delta Kp/\Delta t$ at this stage apparently indicates that the stronger the perturbation of the solar wind velocity in the high-velocity plasma flow, the greater ΔT. In addition, high magnitudes of V_s after rotation of B_z to the south, i.e., after interval ΔT, provide a quick increase of ring current intensity and maintain high magnitudes of $\Delta Kp/\Delta t$. Condition $\tau \sim \Delta Kp/\Delta t$ is therefore fulfilled on the whole for the entire period of Kp growth.

During the magnetic storm expansion phase, a decrease in the DR field after rotation of B_z from north to south is accompanied and caused, to a high degree, by displacement of the inner boundary of plasma sheet ions toward the Earth [*Hamilton et al.,* 1988]. Since this boundary is connected with MIT, then qualitatively, $\Phi_{\mathrm{t}} \sim DR(t)$. In addition, $\Phi_{\mathrm{t}} \sim -Kp(t-\tau)$, where $\tau \sim \Delta Kp/\Delta t$ by the reasons given above. The relationship between $DR(t)$ and $Kp(t-\tau)$ is also due to the fact that the velocity of outflow of ionospheric ions, some of which are further accelerated and injected to the ring current, to the magnetosphere correlates with Kp [*Cladis and Francis,* 1985; *Yau et al.,* 1985]. This correlation is especially pronounced for O^+ ions [*Yau et al.,* 1985]. Therefore at the end of the intense storm expansion phase, ions of ionospheric origin can comprise up to 80% of the ring current energy density [*Hamilton et al.,* 1988].

The beginning of the magnetic storm recovery phase corresponds to conditions when losses of ring current ions exceed ion injection into the ring current, or when injection stops, for instance, because of B_z rotation to the north. For intense storms, an initial fast and subsequent slow recovery phase with characteristic times of less than 10 and ~ 100 hours, respectively, is often observed. This is apparently due to initial rapid losses of energetic O^+ ions followed by slow losses of H^+ ions with energies of about 100 keV [*Hamilton et al.,* 1988]. The invariant latitude of the ring current energy density maximum Φ_m changes in an almost similar manner, i.e., at first it relatively quickly shifts to the pole to near $55°\Phi$ and then it stabilizes, because this latitude is a typical position of the residual ring current in quiet conditions [*Hamilton et al.,* 1988; *Lui et al.,* 1987]. Relationships between variations in positions of the ring ionospheric trough and Φ_m qualitatively coincide; therefore $\Phi_t^* \approx \Phi_m(t)$ during the magnetic storm recovery phase. At this phase, DIB and MIT displace to the pole with a delay of $\bar{\tau} \approx 2.2$ hours with respect to Kp. The time τ is likely to be associated with the average lifetime of electrons with energies of about 1 keV, the injection of which provides the DIB displacement to the pole [*Gal'perin et al.,* 1990].

The above discussion referred mainly to near midnight hours. It is qualitatively valid for after midnight hours as well. The situation is more complicated for premidnight hours. For instance, it can be seen from Figure 3 that in premidnight hours, the delay time τ during magnetic activity growth often additionally increases, and hence there is no simple relation between τ and $\Delta Kp/\Delta t$. During the expansion phase, this is likely to be due to the polarization jet, i.e., a narrow band of elevated electric field extended in the zonal direction toward the north. It exists in the region of field aligned currents going from the magnetosphere into the ionosphere near DIB but closer to the equator [*Deminov and Shubin,* 1987; *Gal'perin et al.,* 1990]. Therefore for the polarization jet to be formed, it is necessary that the displacement of the inner boundary of plasma sheet ions toward the Earth be ahead of the initial DIB equatorward displacement. However, if the polarization jet is formed, it blocks to a large extent the displacement of DIB and hence of MIT to the equator [*Deminov and Shubin,* 1987], even if displacement of the plasma sheet inner boundary toward the Earth continues. This blocking is apparently one of the reasons for an increase in the delay time of MIT equatorward displacement with respect to magnetic activity growth. The blocking efficiency has a threshold character and strongly depends on background conductivities of the ionosphere in the polarization jet region, which is why there is no simple relation between τ and $\Delta Kp/\Delta t$. Note that the polarization jet ensures deepening of MIT to the structure of a narrow ionization trough. For this reason this trough is detected mainly during premidnight hours in the magnetic storm expansion phase [*Deminov and Shubin,* 1988; *Gal'perin et al.,* 1990].

Conclusions

Analysis of sounder measurements made by the Cosmos 900 satellite at altitudes of 430 ± 50 km for nighttime hours has shown that during storms, the ionospheric trough can be considered to consist of two troughs, i.e., the main ionospheric and ring ionospheric troughs. The MIT is a relatively regular formation and tends to be located near the equatorward boundary of diffuse electron injections during all phases of storms. During the recovery phase, the RIT is distinctly separated from MIT and is likely to be situated near the projection of the energy density maximum of residual ring current on the ionosphere.

Not in all cases are both troughs simultaneously clearly detected even during the storm recovery phase. If one trough is distinctly observed, it is not necessarily MIT. Thus the existing models of the midlatitude trough should be reconsidered using the studies of relationships of MIT and RIT variations.

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