Magnetic storms and magnetotail currents

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Abstract. The magnetospheric magnetic field is highly time-dependent and may have explosive changes (magnetospheric substorms and geomagnetic storms) accompanied by significant energy input into the magnetosphere. However, the existing stationary magnetospheric models can not simulate the magnetosphere for disturbed conditions associated with the most interesting magnetospheric physics events (intensive auroras, particle injection in the inner magnetosphere, and precipitations at the high latitudes, etc.). We propose a method for constructing a nonstationary model of the magnetospheric magnetic field, which enables us to describe the magnetosphere during the disturbances. The dynamic changes of the magnetosphere will be represented as a sequence of quasistationary states. The relative contributions to the $D_{st}$ index by various sources of magnetospheric magnetic field are considered using a dynamic model of the Earth's magnetosphere. The calculated magnetic field is obtained by using the solar wind and geomagnetic activity empirical data of the magnetic storm of March 23–24, 1969 and the magnetic disturbance of July 24–26, 1986. The main emphasis is on the current system of the magnetospheric tail, the variations of which enable a description of the fast changes of $D_{st}$.

1. Introduction

When the $D_{st}$ index of the geomagnetic field during geomagnetic storm is analyzed, it is apparent that in addition to an observed smooth variation of $D_{st}$ with a characteristic time of $\approx 10$ hours, as a rule, rapid variations with a characteristic time of $\approx 1$ hour are also detected. However, opinions about the cause of these variations are rather contradictory at present [Feldstein, 1992; Grafe and Bisk, 1966; Tinsley and Akasofu, 1982; Pisarsky et al., 1986; Grafe, 1988; Gonzales et al., 1990]. Measurements of the spectrum of energies (1–300 KeV/q) in the ring current region ($L \sim 3–6$) show that the main mechanism of losses is a charge exchange with the exosphere neutrals (see e.g., the AMPTE data by Kistler et al. [1989]). Fok et al. [1993] describe the influence of the Coulomb collisions with plasmaspheric ions on the ring current ions lifetime. Another ring current loss process is pitch angle diffusion driven by ion-cyclotron resonance [Ether and Carovillano, 1971]. The typical time of change of ring current ions flux determined by these loss processes is about 10 hours [see e.g., Fok et al., 1993; Gonzales et al., 1994], and it is possible to explain smooth variations of $D_{st}$ index by these processes. However, it is not possible to explain rapid (about 1 hour) changes in $D_{st}$ index during the recovery phase by similar intensity variation of the ring current particles. While an increase of the $D_{st}$ absolute value can be due to particle injection, a similar rapid decrease of disturbance can hardly be associated with an abrupt drop of intensity resulting from particle losses due to the precipitation or charge exchange. This fact makes it reasonable to raise again the question of possible sources of $D_{st}$ index, other than the ring current particles. A current system of the magnetospheric tail [Alexeev et al., 1975] and currents at the magnetopause [Alexeev, 1978] are the most likely candidates. Therefore following Maltsev [1991], we shall deal with the influence of tail current system on the $D_{st}$ index geomagnetic field.

2. Model

Relative contributions to the $D_{st}$ index by various sources of magnetic field (the ring current, currents on the magnetopause, and the current system of the magnetospheric tail) may be estimated using a dynamic magnetospheric model. This approach is valid if we neglect transition processes with
characteristic time less than the Alfvén wave propagation time along magnetospheric field lines (that is, about 10 min). IICrC variations of the magnetospheric field with time scale more than 1 hour will be described. These time variations will be characterized by modification of the magnetosphere parameters. To calculate a modeled magnetospheric field, we use a modified magnetospheric model [Alexeev, 1978]:

\[
\mathbf{B}_m = \mathbf{B}_d(\psi) + \mathbf{B}_{sd}(\psi, R_1) + \mathbf{B}_t(\psi, R_1, R_2; \Phi_\infty) + \mathbf{B}_r(\psi, b_r) + \mathbf{B}_{sr}(\psi, R_1, b_r). \tag{1}
\]

Here \( \mathbf{B}_d \) is the dipole field; \( \mathbf{B}_{sd} \) is the field of currents on the magnetopause screening the dipole field; \( \mathbf{B}_t \) is the field of the magnetospheric tail current system (crosstalk currents and closure magnetopause currents); \( \mathbf{B}_r \) is the field of ring current calculated in terms of the model similar to the Tyaganenko one [Tyaganenko and Usmanov, 1982], but the ring current terminates at a fixed distance, and beyond this distance, \( \mathbf{B}_r \) is proportional to the dipole field; \( \mathbf{B}_{sr} \) is the field of currents on the magnetopause screening the ring current field. In the total field \( \mathbf{B}_m \) (equation (1)) the interplanetary magnetic field penetrating into the magnetosphere is not presented, as its value is rather small [see Alexeev, 1986].

The dynamic model depends on five time-dependent input parameters: \( \psi \) (dipole tilt angle); \( R_1 \) (magnetopause subsolar distance); \( R_2 \) (the distance to the earthward edge of the current sheet in the magnetospheric tail); \( \Phi_\infty \) (the tail lobe magnetic flux which defines the intensity of the magnetospheric tail current); and \( b_r \) (the ring current magnetic field intensity at the Earth’s equator).

We will test model calculations by comparison with observational values of the Dst index. The Dst index presents a symmetric part of the magnetic field disturbance at the Earth’s equator. Latitudinal component of the magnetic field of the region 1 field-aligned currents has opposite signs on the dayside and nightside in the equatorial plane. We will not study an asymmetric part of magnetic disturbance hence the subject of the field-aligned currents will not be included in our consideration. For the same reason the asymmetric magnetic field of the partial ring current, of the middle-latitude ionospheric currents, etc. will be omitted too. A more detail discussion of this topic is included in section 5.

Although our model current systems cannot be claimed as a unique set of currents for describing the observations, they represent a best fit solution which is consistent with general knowledge of the behavior of magnetospheric currents.

3. Calculations

Let us calculate the magnetospheric magnetic field using empirical data of the solar wind density and velocity and the auroral and geomagnetic activity (AL index, Dst, and the latitudinal location of the westward electrojet maximum at midnight). To compare the obtained model results with the onground measurements, we calculate

\[
\Delta \mathbf{B}(t) = \mathbf{B}_m(t) - \mathbf{B}_d = \mathbf{B}_{sd} + \mathbf{B}_t + \mathbf{B}_r + \mathbf{B}_{sr}. \tag{2}
\]

The input parameters of the dynamic model are obtained from the empirical data.

3.1. Geomagnetic Dipole Tilt Angle

The geomagnetic dipole tilt angle \( \psi \) is obtained from

\[
\sin \psi = -\sin \beta \cos \alpha_1 + \cos \beta \sin \alpha_1 \cos \varphi_m \tag{3}
\]

where \( \alpha_1 = 11.43^\circ \) is the angle between the Earth’s axis and the geodipole moment, \( \beta \) is the declination of the Sun (\( \sin \beta = \sin \alpha_2 \cos \varphi_{se} \)), \( \alpha_2 = 23.5^\circ \) is the angle between the Earth’s axis and the normal to the ecliptic plane, \( \varphi_{se} = 0.9856263(172 - I_{day}) \) is the angle between the Sun-Earth line and the projection of the Earth’s axis on the ecliptic plane, \( I_{day} \) is the day’s number, and \( \varphi_m = UT 15^\circ - 69.76^\circ \) is the angle between the noon-midnight and north magnetic pole meridians, UT is the universal time in hours.

The tilt angle \( \psi \) is the single model parameter which has explicit time dependence. For calculation of other parameters it is necessary to construct more or less complex sub-models. Model parameters are determined from observational data.

3.2. Magnetopause Subsolar Distance

The distance from the Earth to subsolar point at the magnetopause \( R_1 \) is the main parameter which determines the scale of the magnetosphere. This value is usually calculated from the balance between dynamic and magnetic pressures using data of the solar wind velocity \( v \) and density \( n \)

\[
R_1 = 100/(nv^2)^{1/6} \tag{4}
\]

\( R_1 \) is in \( R_E \); \( n \) is in \( \text{cm}^{-3} \); and \( v \) is in \( \text{km/s} \).

According to Aubry et al. [1970], Fairfield [1971], and Kupper and Feldstein [1973] the subsolar distance depends not only on the dynamic pressure of solar wind but also on the interplanetary magnetic field (IMF) \( H_z \) component. An enhancement of the southward component of IMF results in the decreasing of subsolar distance. The subsolar distance \( R_1 \) was calculated by us based on the result of Roeiolf and Sibeck [1993].

3.3. Distance to the Earthward Edge of the Current Sheet

The geotail current system consists of the dawn-dusk directed neutral sheet currents as well as of the magnetopause closure currents [Alexeev et al., 1975]. The magnetic field of these currents depends on two spatial parameters: the subsolar distance \( R_1 \) and the distance to the earthward edge of the current sheet in the magnetospheric tail \( R_2 \). The value of \( R_2 \) will be calculated as

\[
R_2 = 1/\cos^2 \varphi_k, \tag{5}
\]

where \( R_2 \) is in \( R_E \) and \( \varphi_k \) is the latitude of the maximum of the midnight auroral electrojet.

Two assumptions are used in (5). First of all, use is made of the dipolar relation between the equatorial distance to the held line and the latitude of its intersection with the Earth’s
surface. We suppose that magnetic field lines are quasi-dipolar type earthward of the inner edge of the geotail current sheet [Pullkinen, 1991]. Second, we suppose that the inner edge of the tail current sheet is mapped to the electrojet maximum. As one can see in section 4.2 and in Figure 6, there is a good agreement between the values of $\varphi_b$ obtained from the observation data (European Incoherent Scatter (EISCAT) magnetometer chain data) and calculated latitude of the equatorward auroral oval boundary.

3.4. Tail Lobe Magnetic Flux

We will define the intensity of the magnetospheric tail current by the value of the tail lobe magnetic flux $\Phi_\infty$. The magnetic flux in the geotail lobe approaches a constant as one moves away from the Earth. As was discussed by Rostoker and Skone [1993], the increasing area of the lobe cross section is balanced by an appropriate decrease in the tail lobe field magnitude. The tail lobe flux $\Phi_\infty$ is calculated as

$$\Phi_\infty = \lim_{x \to -\infty} \int_S B_\parallel dS,$$

where $B_\parallel$ is the tail magnetic field and $S$ is the tail lobe cross section. For the paraboloid model [Alexeev et al., 1975; Alexeev, 1978], $\Phi_\infty$ will be defined by $R_1$, $R_2$ and $b_t$, where $b_t$ is the strength of the tail current magnetic field at the earthward edge of the tail current sheet. The value $b_t$ is proportional to the maximum magnitude of the tail current density. We have (see Appendix):

$$\Phi_\infty = b_t \frac{\pi R_1^2}{2} \sqrt{\frac{2R_0}{R_1} + 1}.$$  

For description of the disturbed tail current system, we will calculate $\Phi_\infty$ as sum

$$\Phi_\infty = \Phi_0 + \Phi_s,$$

where $\Phi_0$ is the undisturbed (quiet) tail lobe magnetic flux and $\Phi_s$ is the disturbed time-dependent lobe magnetic flux, which is associated with enhancement of tail current system during disturbances.

For values characteristic of an undisturbed magnetosphere, $R_1 = 10 R_E$, $R_2 = 5 R_E$, $b_t = 40$ nT, we obtain from (7) the quiet magnetic flux through the tail lobe.

$$\Phi_0 = 3.7 \times 10^8 \text{ Wb} \quad \text{[Stern and Alexeev, 1988].}$$

From (7) we can thus determine adiabatic change of $b_{10}$ by the known $R_1$ and $R_2$, where $b_{10}$ is the field strength near the earthward edge of the quiet tail current

$$b_{10} = \frac{2\Phi_0}{\pi R_1^2} \sqrt{R_1/(2R_2 + R_1)}.$$  

Using $R_1$ and $R_2$ calculated from (4) and (5), we find that $b_{10}$ varies in the range of 40–70 nT during the disturbance under consideration.

During disturbed times when substorm activity occurs, the tail lobe flux includes an additional term. This term is defined by (7) with $b_t = b_{ts}$, where $b_{ts}$ is an enhancement of the field strength near the earthward edge of the tail current sheet. This value is calculated from the $AL$ index:

$$b_{ts} = -k(\text{AL}).$$

It is assumed in (10) that the additional disturbed tail current is proportional to the westward electrojet intensity. This fact was recognized by Lui et al. [1992] based on AMPTE/CCE data [see Lui et al., 1992, Figure 12e]. Lui et al. [1992] found that the amount of tail current buildup prior to dipolarization was related to the subsequent strength of the substorm westward electrojet.

The numerical coefficient $k$ in (10) was calculated by Alexeev et al. [1992] from the fact that the westward electrojet is the ionospheric part of the substorm current wedge. The ratio of the area of the ionospheric cross section of the substorms current wedge to the area of the tail cross section of the same current loop gave us $k \approx 1/7$ for $R = 6 R_E$. A similar relation was obtained by Lopez and von Rosenwinge [1993] from statistical analysis of the correlation between field perturbation $\delta H$ directly below the westward electrojet and $B_p$ (deviation from the dipole field at the earthward boundary of the tail current sheet) during substorm:

$$\delta H = 7.2B_p - 188.$$  

Here $(-\delta H)$ is the same as the $AL$ index because $\delta H$ is the perturbation of the $H$ component at Poste de la Baleine which was the reporting station during the cases studied [Lopez and von Rosenwinge, 1993].

The formula (10) was supported by the results of Kaufmann [1987]. He used the observations of tail-like magnetic field patterns in the geosynchronous region during disturbances. To explain the field value $b_t \approx 180$ nT [Kaufmann, 1987], it is necessary to use the value of $k \approx 1/7$.

It is clear to us that (10) does not take into account the total dynamics of the cross-tail currents. Perturbation of the current system can complex features with several different time scales and space scales. However, our study is concentrated on the main question about the strength of the tail current contribution to the magnetic field on the Earth’s surface. A more precise equation instead of (10) which includes more parameters will lead us to a more complex model and will make our results less explicit. For this reason we started from the simple relation (10).

A similar modification of the geomagnetic tail field $b_t$ was proposed by Pullkinen et al. [1991]. The increased level of the tail flux during the magnetospheric substorm was modeled by the transformation of $b_t$ into $(1 + f)b_t$, where $f$ is the constant determined from empirical data.

3.5. Ring Current Intensity

The Hessel-Parker-Scoppe relation

$$b_r = -\frac{2}{3} \frac{\varepsilon_r}{\varepsilon_d}$$

associates the ring current field in the Earth’s center $b_r$ with the total ring current particles energy $\varepsilon_r$ [Akasofu and Chapman, 1972]. Here $B_0$ is the dipole field at the Earth’s equa-
tor, and $\varepsilon_d = \frac{1}{2}B_0 M$ is the dipole field energy ($M$ is the geodipole magnetic moment). According to this relation, one need not use a specific geometry of the ring current when considering the $Dst$ index. We will use the ring current field model with fixed spatial parameters (the geocentric distances to the ring current maximum and to the ring current outer boundary).

The magnitude of the ring current magnetic field $b_r$ depends on three parameters: $t_0$ is the moment of injection, $\tau_0$ represents the characteristic decay time of the ring current, and $b_{r0}$ is the magnetic field corresponding to the current maximum during the disturbance. Before the moment $t_0$, $b_r$ (and $\varepsilon_r$ as one can see from (12)) is assumed to be zero. After $t_0$, $b_r$ is described by the formula

$$b_r = \frac{1}{\tau_0} b_{r0} (t - t_0) \exp \left\{ \frac{(t - t_0 - \tau_0)}{\tau_0} \right\}.$$ (13)

This relation describes the usual time dependence of the energy $\varepsilon_r(t)$ (see review of Gonzalez et al. [1994]). It represents both the single-particle injection into the ring current occurring at the moment $t_0$ and the decay of the ring current with the characteristic time $\tau_0$. The $b_{r0}$, $t_0$, and $\tau_0$ should be chosen in each disturbance proceeding from the observed $Dst$ index profile by best fitting of it.

4. Results

All parameters of the model are determined from empirical data (solar wind parameters, $AL$, $Dst$, and the auroral electrojet maximum latitude). At each moment they represent an instantaneous state of the magnetosphere. The dynamics of the magnetosphere can be presented as a sequence of the instantaneous states.

Let us calculate the magnetic field on the Earth’s surface using independent data of the magnetospheric disturbances of March 23–24, 1969 and July 24–26, 1986.

4.1. Magnetic Storm of March 23–24, 1969

Figure 1a shows King’s catalogue data of the solar wind parameters in the interval March 23–24, 1969. These data allow calculation of the time dependence of the geocentric distance $R_1$ to the subsolar point based on [Roelof and Sibeck, 1993] results. The $AL$ index shown in Figure 1b was determined by data of auroral and subauroral observations, taking into account expansion of the auroral electrojet during the magnetic storm [Sumaruk et al., 1989]. The midnight location of westward electrojet maximum $\varphi_{bk}$ (Figure 1c) is determined by using magnetometer chains data. This allows us to calculate the distance to the geotail current sheet ward edge $R_0$.

In Figure 1d the $Dst$ index is presented. It was constructed using the data of the 11 low-latitude stations for a magnetic storm of March 23–24, 1969 [Sumaruk et al., 1989]. As one can see from Figure 1d, the $Dst$ index profile has two minima. We explore two representations. The first corresponds to a single injection of particles where the ring current intensity was defined by formula (13). Using the minimum of the rms deviation of $\Delta B$ (see (2)) calculated on the Earth’s equator from the $Dst$ index (see Figure 1d), the injection beginning was chosen at $t_0 = 1800$ UT on March 23, the characteristic decay time was set to be $\tau_0 = 0700$ UT, and the maximum intensity of the ring current was chosen to be $b_{r0} = -200$ nT.

The second representation utilizes double injections. Since the profile of the $Dst$ index had two distinct humps, formula (13) was used together with a version of two injections

$$b_r = b_{r1} \frac{t - t_1}{\tau_1} \exp \left\{ \frac{\tau_1}{\tau_1} t_1 - \frac{t}{\tau_1} \right\}, \quad t_2 > t > t_1$$ (14a)

$$b_r = \sum_{i=1}^{2} b_{ri} \frac{t - t_i}{\tau_i} \exp \left\{ \frac{\tau_i}{\tau_i} t_i - \frac{t}{\tau_i} \right\}, \quad t > t_2$$ (14b)

Here sets $(b_{r1}, t_1, \tau_1)$ and $(b_{r2}, t_2, \tau_2)$ are determined similar to $(b_{r0}, t_0, \tau_0)$ in (13).

In (14), use was made of the values $t_1 = 1800$ UT on March 23, $t_2 = 0700$ UT on March 24, $\tau_1 = 0700$ UT, $\tau_2 = 0500$ UT, $b_{r1} = -180$ nT, and $b_{r2} = -70$ nT. As in the first case, $b_r$ at the moment before $t_1$ was assumed to be zero. From $t_1$ until $t_2$, $b_r$ was determined by the (14a), and at the moment later $t_2$, $b_r$ was determined by the (14b).
An examination of our results shows that modeling calculations reproduce on-ground measurements with an accuracy of tens of nanoteslas. Comparison of the $D_{st}$ index, $\Delta B$, and $B_t$ time dependences shows that rapid changes of the $D_{st}$ index are strongly correlated with the rapid changes of $B_t$. This agreement indicates that rapid variations of the $D_{st}$ index are strongly influenced by spatial changes of the magnetospheric shape and by changes in the tail current system intensity (time dependence of the tail lobe magnetic flux).

Variations of the distance $R_1$ to the subsolar point (Figure 2a) reflect the effect of the solar wind dynamic parameters on the magnetospheric dimensions. Variations of $R_2$ (Figure 2a) are in a good accord with the idea that the earthward edge of the geotail current sheet moves closer to the Earth as the activity ensues and moves downtail during the recovery phase. The calculated field magnitude at the inner edge of the tail current sheet ($b_i < 140 \text{ nT}$) agrees with available data [Kaufmann, 1987; Lu et al., 1992; Lopez and von Rosenvinge, 1993] during strong disturbances.

This analysis demonstrates that the magnetospheric tail current system makes a prominent contribution to the $D_{st}$ index and is responsible for the fast changes of the $D_{st}$ index.


Figure 4 presents 1-hour values of solar wind and geomagnetic data during the period under consideration (solar

Thus it is possible to calculate (see sections 3.1–3.5) the time dependence of $R_1$, $R_2$, $\Phi_{\infty}$, and $b_i$ for the interval under consideration (see Figures 2a, 2b, and 2c) and then to calculate the time dependence of the model field at the Earth’s equator.

Figure 3a compares model calculations for the case of a single injection with the values of the $D_{st}$ index. The dotted curve shows the field of the tail current system, the field of the ring current and of the magnetopause screening currents is depicted by the dashed curve, the solid curve presents a total modeled field of the magnetospheric sources ($\Delta B$), and the thick solid curve is for measured values of the $D_{st}$ index. The modeled fields of the last four terms in formula (1) were calculated at the Earth's equator and were multiplied by a factor of 1.5 because of the effect of interterrestrial induced currents preventing the external field penetration into the Earth [Akasofu and Chapman, 1972].

Figure 3b shows similar curves for the case of two injections. A comparison of Figures 3a and 3b shows that both “one-hump” and “two-hump” models give a good agreement with the observed values of the $D_{st}$ index.

Figure 3. (a) The comparison of the $D_{st}$ index (heavy solid line) and the modeled $\Delta B$ (solid line) for the magnetic storm of March 23–24, 1969 for the case of (a) one injection into the ring current and (b) two injections. The line marked by triangles is the contribution of geotail current system ($B_t$) to $D_{st}$, and the line marked by asterisks is the field of the ring current and Chapman-Ferraro currents ($B_a$).
Figure 4. (a) Solar wind density (dashed line), in \( \text{cm}^{-3} \) (right scale), and velocity (solid line), in 100 km/s (left scale); (b) AL index, in nanoteslas; (c) latitude of the westward electrojet maximum, in degrees; (d) Dst index, in nanoteslas; and (e) \( B_z \) component of IMF, in nanoteslas, for the magnetic disturbance of July 24–26, 1986.

In Figure 4d, the injection beginning was chosen at \( t_1 = 2200 \text{ UT} \) on July 24, the characteristic decay time was set to be \( \tau_2 = 1100 \text{ UT} \), and the maximum intensity of the ring current was taken as \( b_0 = -45 \text{ nT} \).

In Figure 5 the modeled field is compared with the Dst index. As in Figure 3, the dotted curve shows the field of the tail current system; the dashed curve depicts the sum of the magnetic fields of the magnetopause screening currents and of the ring current, the solid curve presents the total modeled field of magnetospheric sources; and the thick solid curve represents measured values of the Dst index. The minimum of the Dst index near 2400 UT on July 24 is well described by the extremum of \( b_t \), due to westward electrojet enhancement (see AL index in Figure 4c).

For independent checking of the model result we will study the auroral oval dynamic during this case. Approximating the polar cap by a circle with the center near the magnetic pole, we can express its magnetic flux as

\[
\Phi_{pc} = 2 b_0 \pi R_E^2 \sin^2 \theta_{pc},
\]

where \( b_0 \) is the magnetic field at the Earth's equator and \( \theta_{pc} \) is the colatitude of the polar cap boundary. The polar cap flux \( \Phi_{pc} \) is equal to the tail lobe flux \( \Phi_{sw} \). Using (7) we can estimate the polar cap scale:

\[
\sin^2 \theta_{pc} = \frac{1}{4} \frac{b_0 R_E^2}{b_t R_E} \sqrt{\frac{2 R_2}{R_1}} + 1.
\]

Then we use the experimental data about the width of the nightside auroral oval and about location of the center of its equatorward boundary [see e.g., Starkov and Feldstein, 1967; Iijima and Potempska, 1976; Holzworth and Meng, 1984]. From these data and from the calculated radius of the polar cap the midnight latitudes of the auroral oval boundaries were determined.

In Figure 6 the latitudes of equatorward and poleward boundaries of the modeled auroral oval at 2400 magnetic local time and the westward electrojet maximum measured by EISCAT chain stations are presented. EISCAT data are in good accordance with the values of the equatorward boundary of the auroral oval, calculated by the magnetic flux variations through the geomagnetic tail.

Figure 5. The comparison of the Dst index and the modeled \( \Delta B \) for the magnetic disturbances of July 24–26, 1986. Notations are the same as in the Figure 3.
5. Discussion

The main finding of our paper concerns the contribution of the magnetic field of the cross-tail current to the Dst index during magnetic storms. We find that this contribution may be equal to or even more than the perturbation produced by the ring current. In checking this conclusion we will discuss several topics.

5.1. Verification of our Results

Two storms were studied in detail. One of them (March 23–24, 1969) has a large Dst index, with a maximum of |ΔDst| ≈ 200 nT, and another one has a small Dst index. In each disturbance only three input parameters (t0) is the moment of injection beginning, τ0 represents the characteristic decay time of the ring current, and Bτ0 is the magnetic field corresponding to the current maximum during the disturbance) were chosen from the observed Dst index profile by best fitting. The other input model parameters were defined from independent experimental data. The hourly averaged strength of the magnetic field during about 48 hours was calculated. As a result, residual rms deviation of the model calculations from observational data is ≈25 nT. The 10% accuracy is evidence of a good agreement between model calculations and observations.

![Figure 7a](image1)

**Figure 7a.** The input power ε, in 10^{11} W, into the magnetosphere for the interval of July 24–26, 1986:

![Figure 7b](image2)

**Figure 7b.** The energy input E(t) into the magnetosphere (dotted line), the energy stored in the geomagnetic tail (dashed line), the sum of them (solid line), and the total energy E(t) (see (17)) transported into the magnetosphere (thick solid line) are presented. The substorm energy changes are well described by the sum of the ionospheric Joule heating and geotail energy storage.
5.2. A Contribution from the Partial Ring Current

Fast (~1 hour) variations of the Dst index strongly support our conclusion of significant contribution of the tail current to the magnetic field variations. These variations can not be explained by variations of the symmetric ring current particle flux. However, partial ring current may have a similar timescale, and it is another possible cause of the Dst index fast variations [Takahashi et al., 1991]. At first sight the partial ring current is very similar to the near-Earth cross-tail current. Both currents occupy the same region of the magnetosphere, at the distance of ~4–6 RE in the nightside. However, they have different closure currents. The first (the partial ring current) is connected by field-aligned currents to the ionospheric currents, and the second (the cross-tail current) is closed by Chapman Ferraro currents at the magnetopause. For this reason, the field of the total loop of the partial ring current has strong local time dependence at the Earth’s equator, in contrast to the field of the cross-tail current system which is approximately independent of the longitude. It is easy to estimate from the Biot-Savart’s law, that the longitudinal average of the partial ring loop’s field is ~20% of the amplitude of its asymmetric perturbation. The ratio of these terms (symmetric to the asymmetric) is roughly proportional to the ratio of the distance to the ionospheric part of the current loop RE to the distance to the magnetospheric (equatorial) part of it Rpr. This ratio is about RE/Rpr = 0.2, here Rpr ~ 5 RE is the distance to the partial ring current.

We may estimate the contribution of the partial ring current to the Dst index during the storm of March 23–24, 1969, based on the measurements of the equatorial field asymmetry. These results were obtained by Feldstein et al. [1990] from the data of 11 magnetic low-latitude observatories. During the maximum of the main phase the asymmetric strength is ~100 nT and the maximal contribution from partial ring current to Dst index is ~20 nT. (It is about the accuracy of the model, see section 5.1.)

![Figure 8](image)

Figure 8. The x component of the tail magnetic field strength near to the current sheet, in nanoteslas (left scale), and the tail current density, in milliamperes per meter (right scale), are shown at the maximum of Dst during the March 24, 1969 storm. Both depend on the distance to the Earth r, as 1/r. They are equal to zero closer than 3.5 RE to the Earth.

5.3. Unexpected Great Strength of Cross-Tail Current Field at the Earth’s Equator

As one can see from Figure 3, sometimes the cross-tail current field may be as large as ~140 nT, in contrast to popular opinion that this value is about 20 nT [see e.g., Tsyganenko and Sibeck, 1994].

During the magnetic storm interval, the tail current strength increases. As shown in Figure 8, for the maximum of Dst (~0900 UT) in the March 24, 1969 storm the tail current density was about 300 mA/m at the inner edge of the current sheet (~3.5 RE). This current density corresponds to the tail magnetic field strength of about 170 nT. In Figure 8 the model dependence of the tail field strength (as well as of the current density) on the distance along the Earth-Sun line is shown for moment of maximum of Dst. In Figure 8 only values of the x component of the tail field near to the equatorial plane are shown. It is zero closer to the Earth than to the inner edge of the current sheet.

The current increasing is one reason for the great strength of the cross-tail field, and the other reason is the peculiarity of the model three-dimensional current system connected with the tail currents. Our model of the tail currents is shown in Figure 9 [Alexeev et al., 1975]. The closure currents are placed on the magnetopause starting from the subsolar point. The cross-tail currents together with the their magnetopause closure currents form the current loops which lie close to the equatorial plane. In the nearest to the Earth region of the magnetosphere their magnetic field structure is like the ring current’s structure.

The cross-tail currents magnetic field lines connect northern and southern tail lobes through the inner magnetosphere equatorial cross section (from the dayside magnetopause to the inner edge of the geotail current sheet). For simple estimation of the average cross-tail current field at the Earth’s equator one can use the ratio of the tail lobe magnetic flux to the area of the inner magnetosphere equatorial cross sec-
tion. During magnetic storms this area is reduced by about 2 times in comparison with the quiet conditions. This occurs because during magnetic storms the magnetoopause is located closer to the Earth and the inner edge of the tail current sheet moves earthward. As one can see from Figure 2a, \( R_1 \approx 8 R_E \) and \( R_2 \approx 4 R_E \) during the studied case (average values \( R_1 = 10 R_E \) and \( R_2 = 6 R_E \)).

On the other hand, the tail lobe magnetic flux may increase because of the solar wind pressure enhancement. The tail lobe magnetic field is balanced by the thermal pressure of the solar wind plasma. During the studied case (March 24, 1969) the solar wind plasma density increases by \( \sim 4 \) times. The tail lobe magnetic field strength must increase twice as \( B_l \sim \sqrt{\rho} \). At the same time the lobe magnetic flux increases during magnetic storm. Owing to the rise of the tail lobe field strength and decrease of the equatorial section area, the cross-tail current field strength at geomagnetic equator increases by about 4 times in comparison with its quiet value. Taking into account the effect of interterrestrial induced currents preventing the external field penetration into the Earth [Akasofu and Chapman, 1972] (see section 4.1), we obtain the values of \( B_t \approx 120 \) nT, closed to our model results.

5.4. Auroral Oval Size Modification Occurs During Magnetic Storms

There is numerous observational evidence [after Akasofu and Chapman, 1962; Feldstein and Starkov, 1968] that the nightside auroral oval latitude decreases with the \( Dst \) index increase. The hourly average location of the auroral oval's equatorward boundary moves to low latitude during magnetic storms. Auroral oval expansion is independent support of our conclusion about the key role of the cross-tail currents in the magnetospheric dynamics during magnetic storm. As was demonstrated by model calculations, the ring current may modify the polar cap and polar oval sizes only insignificantly. To the contrary, the cross tail current directly controls the polar cap and auroral oval locations. This fact strongly supports our conclusion about the cross-tail current's contribution to the \( Dst \) index.

6. Conclusion

The magnetic field during magnetospheric disturbances is investigated using the dynamic model of the magnetosphere. The magnetic field changes with a characteristic time of about 1 hour are described as the corresponding variations of the parameters of large-scale current systems in the magnetosphere. The latter can be obtained using measured parameters of the solar wind (density and velocity) and of geomagnetic activity (the \( AL \) index, \( Dst \), and the midnight latitude of an auroral electrojet maximum). The dynamic model enables us to describe the dynamics of the magnetospheric field during magnetic storm and high levels of auroral activity.

It was shown by model calculations of the ring current and tail current magnetic field during magnetic disturbances that the tail current magnetic field at Earth surface has approximately the same magnitude as the ring current magnetic field. As Figures 3 and 5 show, the conformity between the calculated and observed magnetic fields is rather good, especially during the recovery phase. It is important to note that the more rapid variations, that appear during the recovery phase, are caused by the tail current.

The fact that the tail current magnetic field supplies an important contribution to the \( Dst \) index is strongly supported by this investigation. In spite of the fact that measurements in a limited volume (at the Earth's surface) do not allow us to distinguish between two sources of the \( Dst \) index (ring current and geotail current), the time dependence of the disturbance and of the polar cap size suggests that our estimation of the tail current term in the \( Dst \) index is valid. As one can see, the polar cap size strongly related to \( \Phi_\infty \) (see section 3.4), but the value of ring current does not influence the polar cap area. The good correspondence between model calculations of the auroral oval boundaries and EISCAT magnetometer chain measurements (see Figure 6) supports our conclusion.

Appendix

For calculating the magnetic flux (6) by using a paraboloid magnetospheric model, it is useful to deal with an orthogonal parabolic coordinate system \((\alpha, \beta, \varphi)\). In terms of these coordinates the usual solar magnetospheric Cartesian coordinates are given by

\[
\begin{align*}
x &= R_1 (\varphi^2 - \alpha^2 + 1)/2, \\
y &= R_1 \alpha \beta \sin \varphi, \\
z &= R_1 \alpha \beta \cos \varphi.
\end{align*}
\]

(A1)

Here the constant \( \alpha \) surfaces are confocal paraboloids of revolution that open toward the Sun (positive \( x \)), and the constant \( \beta \) surfaces are paraboloids with the same focus that open on the night side. The coordinate \( \varphi \) measures the angle around the Sun-Earth line, so the \( \varphi = 0 \) is the north and \( \varphi = \pi/2 \) lies on the dusk side. The Earth is at the origin of solar-magnetospheric (SMG) coordinates and at \( \alpha = 1 \) and \( \beta = 0 \) in parabolic coordinates. The magnetopause is the \( \beta = 1 \) surface. The subsolar point on the magnetopause corresponds to \( \alpha = 0 \) and \( \beta = 1 \) or \((R_1, 0, 0)\) in SMG coordinates.

\[
\Phi_\infty = R_1^2 \lim_\alpha \lim_\varphi \int_0^1 \alpha_0 \beta \sqrt{\alpha^2 + \beta^2} d\beta \int_{-\pi/2}^{\pi/2} B_{\alpha \beta}(\alpha, \beta, \varphi) d\varphi.
\]

(A2)

For calculation of \( \Phi_\infty \) we may take into account only the main term of the tail current field which decreases on the nightside more slowly. This term is [see Alexeev et al., 1975]

\[
B_{\alpha \beta} = b_t \frac{\alpha_0}{\alpha} \frac{1}{\sqrt{\alpha^2 + \beta^2}}.
\]

(A3)

The constant \( b_t \) is the tail current magnetic field strength at the earthward edge of the geotail current sheet, \( \alpha_0 \) is determined by the distance to the earthward edge of the geotail current sheet.
\[ R_2 = R_1 \left(\alpha_e^2 - 1\right)^{1/2}. \]  
(A4)

The other terms in the total field (1) decrease faster than the geotail field moving in antisunward direction. If the main term of \( D_t \) is proportional to \( \sqrt{R_t^2 / |x|} \), the other terms are proportional to \( \exp(-|x| / R_t) \) [see Alexeev, 1978]. If we calculate (A2) using (A3), we will have:

\[ \Phi_{\infty} = b_l \frac{\pi R_l^2}{2} \sqrt{\frac{2R_2}{R_1} + 1}. \]  
(A5)

Acknowledgments. The authors thank Lasse Hakkinen, Finnish Meteorological Institute, Department of Geophysics, Helsinki Finland, for EISCAT magnetometer chain data.

This work was supported in part by the Deutsche Forschungsgemeinschaft with the project MASRAEL. YIF acknowledges the Russian Basic Research Foundation (RBRF) grant 93-05-8722, and the International Science Foundation (ISF) grant M6P000. Work at MSU was supported by RBRF grant 95-05-14057, and by ISF grants NCM000 and NCM300.

The Editor thanks WD Gonzales and Gordon Rostoker and a third referee for their assistance in evaluating this paper.

References


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(Received June 7, 1993; revised November 2, 1995; accepted November 7, 1995.)