

EVIDENCE OF THE MAJOR MAGNETOTAIL CURRENT CONTRIBUTION TO *DST*

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Abstract. Magnetic field of the magnetotail current is curl-free in the dayside magnetosphere and can be found from the solution of the Neumann boundary problem. The dayside magnetopause and plane $x = 0$ separating the dayside and nightside regions of the magnetosphere were chosen as the boundaries. At the magnetopause the normal magnetic component is equal to zero. In the plane $x = 0$ we took the normal component $B_x(y, z)$ from the database of Fairfield *et al.* [1994] processed by Ostapenko and Maltsev [2000]. The symmetrical ring current yields zero normal the component on the plane $x = 0$ so that $B_x(x = 0, y, z)$ is produced by the magnetotail and magnetopause currents. The effect of the magnetopause current can be excluded with the use of the Mead [1964] model. The calculations show that the tail current yields about 90% of contribution to *Dst*.

1. Introduction

The main manifestation of the magnetic storm is a global depression of the geomagnetic field H component. The H component perturbation (*Dst* variation) is caused by three electric currents: the ring current, cross-tail current, and current in the magnetopause. Each of these currents is related to a different population of charged particles. The ring current is carried by the trapped particles of the radiation belts. The carriers of the cross-tail current are particles temporarily trapped in the plasma sheet. The currents on the magnetopause arise due to solar wind particles reflecting from the magnetosphere. The cross-tail current is partially related to the magnetopause current to provide the closure of the current system. There is no direct relation between the ring and cross-tail currents, although a distinct boundary between them is not found either.

Different physics of the three currents responsible for the *Dst* variations prompts investigators to estimate the relative contribution of these three sources. For decades the ring current was considered to be the main cause of the storm time depression. This opinion was based on several observations of the trapped particle density enhancement during a number of storms [Frank, 1967; Smith and Hoffman, 1973; Hamilton *et al.*, 1986; Lui *et al.*, 1987], though for some storms a depletion of the energetic particle density was reported [Korth and Friedel, 1997]. De Michelis *et al.* [1999] found statistically that the plasma pressure in the ring current region does not practically depend on geomagnetic activity measured by *AE* index. In any case, the dominant role of the ring current seems disputable until the contribution of the cross-tail current, which can also lead to a geomagnetic depression, is evaluated.

Indirect indications of the important role of the cross-tail current can be obtained from the observed equatorward expansion of all the regions usually considered to be high-latitude ones. Both the auroral oval [Akasofu and Chapman, 1972] and auroral electrojets [Khorosheva, 1987; Feldstein *et al.*, 1997] shift equatorwards during storms. The ring current enhancement can explain only 25% of the shift [Siscoe, 1979;

Schultz, 1997]. The other 75% are evidently caused by the cross-tail current. When Maltsev *et al.* [1996] and Alexeev *et al.* [1996] estimated the cross-tail current intensity which is necessary to provide the observed shift of the auroral oval they found that the contribution of the cross-tail current together with the closure currents in the magnetopause to the storm time depression exceeds the contribution of the ring current. Another indirect evidence of the large contribution of the cross-tail current is a close relation of the *Dst* growth rate to the southward IMF [Burton *et al.*, 1975]. Arykov and Maltsev [1996] explained this relationship theoretically, having supposed that *Dst* variation is caused by the cross-tail current.

Turner *et al.* [2000] estimated the contribution of the cross-tail current from the Tsyganenko [1989, 1996] models with the use of the Biot-Savart-Laplace law. They found that the cross-tail current yields only 25% to the *Dst* variation.

In this paper we try to estimate the contribution of the magnetotail current by another method. We solve the Neumann problem for the dayside magnetosphere with the boundary conditions obtained from observations.

2. Neumann boundary problem

Firstly we stress out the crucial role of the magnetic field measurements near the $x = 0$ plane for the present study. The plane $x = 0$ divides the dayside and nightside regions of the magnetosphere. Everywhere further the x axis is assumed to be directed sunward, and z axis northward. The point $x = 0, y = 0, z = 0$ is located at the Earth center. It is these measurements that permit to separate the effects of various electric currents. Figure 1 shows schematically the effects of the ring (the left) and cross-tail (the right) currents. One can see that the symmetric ring current produces zero magnetic component normal to the $x = 0$ plane. So the observed normal component on this boundary provides us with an information about the cross-tail current.

The external magnetic field in the magnetosphere can be presented as the sum

$$\mathbf{B}^{ext} = \mathbf{B}^{rc} + \mathbf{B}^{ct} + \mathbf{B}^{mp} \quad (1)$$

where $\mathbf{B}^c$, $\mathbf{B}^{ct}$, and $\mathbf{B}^{mp}$ are the fields of the ring, cross-tail, and magnetopause currents, respectively. In the most part of the dayside magnetosphere the cross-tail current is absent, hence we have in this region

$$\text{curl}(\mathbf{B}^{ct} + \mathbf{B}^{mp}) = 0 \quad (2)$$

and

$$\mathbf{B}^{ct} + \mathbf{B}^{mp} = -\nabla U \quad (3)$$

where U is the scalar magnetic potential of the cross-tail and magnetopause currents. It satisfies the Laplace equation

$$\Delta U = 0. \quad (4)$$

On the dayside magnetopause the normal derivative of the potential is equal to zero:

$$\left. \frac{\partial U}{\partial n} \right|_{\mathbf{r}=\mathbf{r}_{mp}} = 0. \quad (5)$$

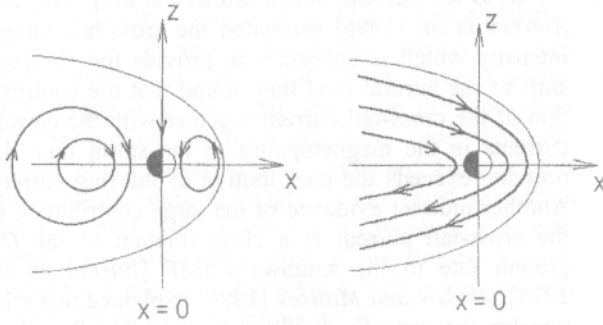


Figure 1. Schematic shape of magnetic field lines of the ring current (the left) and magnetotail current (the right) in the noon-midnight meridian plane.

The plane $x = 0$ were chosen as the second boundary, for the normal magnetic field component produced by the ring current is zero here. As a result we have

$$\left. \frac{\partial U}{\partial n} \right|_{x=0} = -B_x^{obs}(y, z) \quad (6)$$

where B_x^{obs} is the observed magnetic field in the $x = 0$ plane. Equation (4) with boundary conditions (5) and (6) presents the boundary problem of Neumann which has a single solution. The region considered is schematically shown in Figure 2.

In order to obtain B_x^{obs} we utilized the results of the paper by Ostapenko and Maltsev [2000] who had processed the database by Fairfield *et al.* [1994] and built the contours $B_x(x = 0, y, z) = \text{const}$ under three levels of Dst conditions. Figure 3 results from subtraction of the left panel of their Figure 5 ($Dst > 0$, the averaged $Dst = 7$ nT, $B_z \text{ IMF} = 1.2$ nT, the solar wind dynamic pressure $P = 2.4$ nPa) from the right panel ($Dst < -50$ nT, the averaged $Dst = -74$ nT, $B_z \text{ IMF} = -2.2$ nT, $P = 3.4$ nPa). Thus the contours $B_x^{obs} = \text{const}$ in Figure 3 present the differential response in the magnetic field to the Dst variation equal to -81 nT.

Strictly speaking, the procedure of Figure 3 construction is not quite consistent with boundary condi-

tion (5) on the dayside magnetopause because the magnetopause is statistically closer to the Earth during storms due to both the compression caused by the dynamic pressure enhancement [Mead, 1964] and erosion related to the IMF southward component [Aubry *et al.*, 1970]. Nevertheless the discrepancy in the magnetopause location is not very large so that condition (5) in the first approximation holds valid.

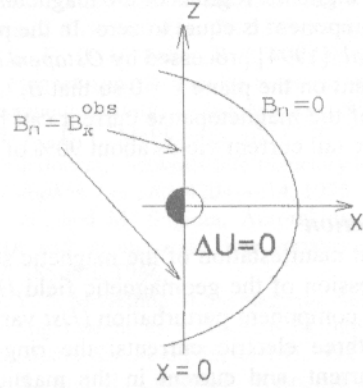


Figure 2. The dayside magnetosphere where the Neumann problem is solved.

We assume the dayside magnetopause to be a sphere of the radius $r_0 = 15 R_E$ (R_E is the Earth radius) with the center at the point $x = x_0 = -6 R_E$, $y = 0$, $z = 0$. The solution of equation (5) can be presented as a series of spherical harmonics:

$$U = \sum_i \sum_j a_{ij} R_i(r) Y_{ij}(\theta, \varphi). \quad (7)$$

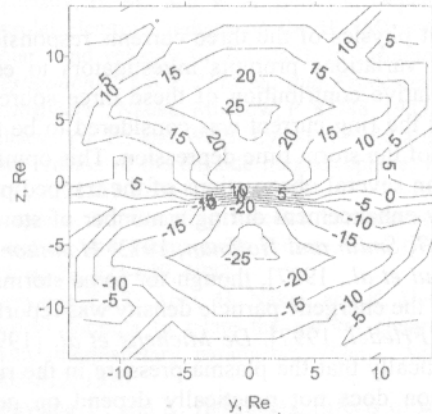


Figure 3. Contours $B_x^{obs} = \text{const}$ in the plane $x = 0$ corresponding to $\delta Dst = -81$ nT.

We restrict ourselves by the first three pairs of the harmonics dependent at the distance:

$$R_1(r) = r + r_0^3 / 2r^2,$$

$$R_2(r) = r^2 + 2r_0^5 / 3r^3,$$

$$R_3(r) = r^3 + 3r_0^7 / 4r^4,$$

where $r = [(x - x_0)^2 + y^2 + z^2]^{1/2}$ is the distance from the center of the sphere. Here the condition (5) is satisfied. The requirement of the north-south and dawn-dusk symmetry preserves only odd values of j :

$$\begin{aligned}
Y_{11}(\theta, \varphi) &= \sin \theta \sin \varphi, \\
Y_{21}(\theta, \varphi) &= \cos \theta \sin \theta \sin \varphi, \\
Y_{31}(\theta, \varphi) &= (1 - 5 \cos^2 \theta) \sin \theta \sin \varphi, \\
Y_{33}(\theta, \varphi) &= \sin^3 \theta \sin 3\varphi,
\end{aligned}$$

where $\theta = \arccos [(x - x_0)/r]$ is the polar angle, $\varphi = \text{Arctan}(z/y)$ is the azimuthal angle. The coefficients a_{ij} were fitted to boundary condition (6) by the least squares technique. We obtained

$$\begin{aligned}
a_{11} &= -13.03, \quad a_{21} = 0.258, \\
a_{31} &= 0.00062, \quad a_{33} = -0.00103,
\end{aligned} \quad (8)$$

providing the magnetic field is expressed in nT and distance in R_E .

Combining (3), (7), and (8) we computed $B_x = -\partial U/\partial x$ in the plane $x = 0$ and $B_z = -\partial U/\partial z$ in the plane $z = 0$. The results are shown in Figure 4. It is seen from the left panel that the computed field does not differ strongly from the observed one shown in Figure 3. The right panel of Figure 4 yields the following disturbance in the Earth center

$$B_z^{ct} + B_z^{mp} = -\frac{\partial U}{\partial z} \Big|_{x=0, y=0, z=0} \approx -53 \text{ nT} \quad (9)$$

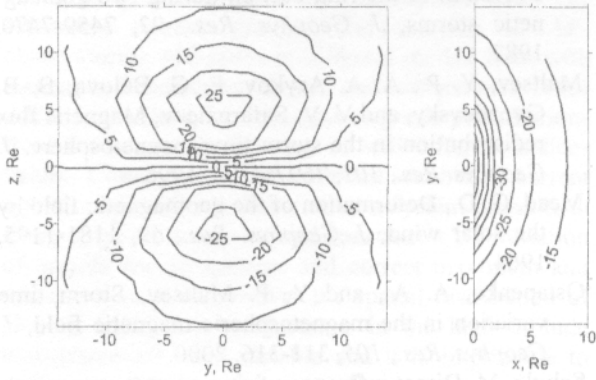


Figure 4. Model distribution of contours $B_x = \text{const}$ in the plane $x = 0$ (the left) and $B_z = \text{const}$ in the plane $z = 0$ (the right).

The effect of the magnetopause currents associated with the solar wind pressure can be estimated from the Mead [1964] model

$$B_z^{mp} = B_{z0}^{mp} \frac{\sqrt{P_2 - \sqrt{P_1}}}{\sqrt{P_0}} \quad (10)$$

where P_0 is the average solar wind dynamic pressure, B_{z0}^{mp} is the magnetopause current effect under the average pressure, P_1 and P_2 are the pressures under quiet conditions ($Dst > 0$) and storms ($Dst < -50$ nT), respectively. Assuming $B_{z0}^{mp} = 25$ nT, $P_0 = 2.3$ nPa, $P_1 = 2.4$ nPa, and $P_2 = 3.4$ nPa, we obtain $B_z^{mp} \approx 5$ nT.

Subtracting $B_z^{mp} \approx 5$ nT from expression (10) we get

$$B_z^{ct} \approx -58 \text{ nT}. \quad (11)$$

Diamagnetic effect of the magnetotail currents flowing partly to the dayside magnetosphere somewhat weakens the magnetic disturbance inside the current region, i.e. on the flanks of the magnetosphere. The disturbance in the inner magnetosphere including the Earth will be stronger the one given by (11). However expression (11) gives sufficiently large contribution to the *Dst*. Remember that Figures 3 and 4 as well as expression (11) are related to the variation $\delta Dst = Dst_2 - Dst_1 = -81$ nT. Currents induced inside the Earth increase the ground magnetic disturbance in the low latitudes so that the following perturbation is observed

$$H^{ct} = kB_z^{ct} \quad (12)$$

where the coefficient k depends on the electrical conductivity inside the Earth. Supposing $k = 1.26$ [Langel and Estes, 1985] we find from (12) $H^{ct} = -73$ nT which yields $\sim 90\%$ of contribution to *Dst* variation.

3. Discussion

It is interesting to compare our results with those predicted by the Tsyganenko [1996] model (T96). The cross-tail current in the T96 model is not explicitly parameterized by the *Dst* index. The dependence of this current on the *Dst* manifests indirectly, through the statistical dependence of the *Dst* on the IMF southward component. Figure 5 is obtained by the same procedure as Figure 3, i.e. by subtraction of the T96 model fields under $Dst = 7$ nT, $B_z \text{ IMF} = 1.2$ nT, $P = 2.4$ nPa from those under $Dst = -74$ nT, $B_z \text{ IMF} = -2.2$ nT, and $P = 3.4$ nPa.

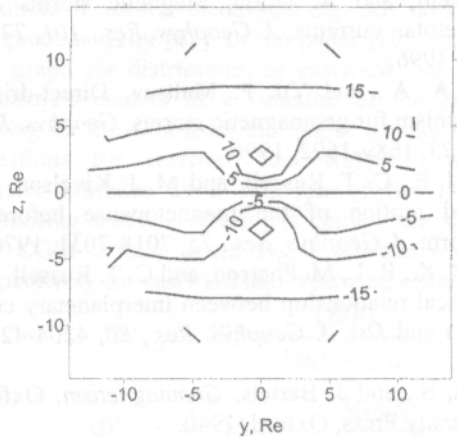


Figure 5. Contours $B_x = \text{const}$ in the plane $x = 0$ from the T96 model.

We solved the Neumann problem described in the previous section but into boundary condition (6) we substituted the field shown in Figure 5 instead of the observed field B_x^{obs} . The results of the computations are shown in Figure 6. Instead of (9) we obtained at the Earth center $B_z^{ct} + B_z^{mp} \approx -45$ nT. Correspondingly we have $B_z^{ct} \approx -50$ nT, $H^{ct} \approx -63$ nT, and $H^{ct}/\delta Dst \approx 78\%$. The latter value appeared to be by a factor 3 larger than 25% as estimated by Turner *et al.* [2000]. Note that Turner *et al.* [2000] only took into consid-

eration a far part of the cross-tail current located at $x < -6 R_E$ only. Neither the current flowing near the flanks of the magnetosphere at $x > -6 R_E$ nor the closure current on the magnetopause were considered. Meanwhile those currents can yield a large contribution to the ground-observed disturbance.

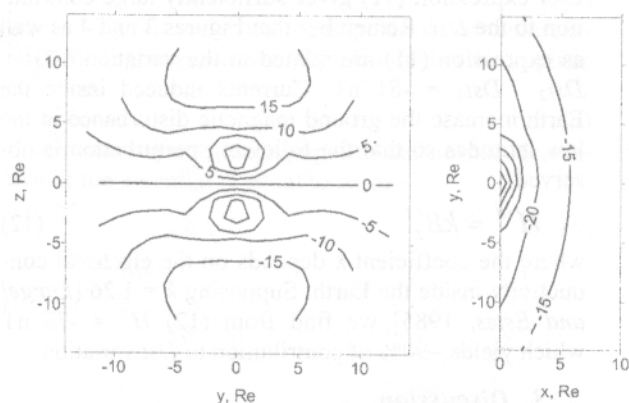


Figure 6. The same as in Figure 4 but for the T96 model.

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