A Model for the Distant Tail Field: ISEE 3 Revisited

T. I. PULKKINEN¹, D. N. BAKER², C. J. OWEN^{3,4}, and J. A. SLAVIN³

¹*Finnish Meteorological Institute, FIN-00101 Helsinki, Finland*

²*LASP, University of Colorado, Boulder, CO 80309, USA*

³*NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA*

⁴*now at: Astronomy Unit, Queen Mary and Westfield College, London E1 4NS, UK*

(Received November 8, 1995; Revised March 11, 1996; Accepted March 29, 1996)

We construct a simple model for the distant ($R > 40 R_E$) magnetotail using data from the ISEE 3 magnetic field instrument. The data are divided into plasma sheet and lobe categories using the plasma measurements. We present the average behavior of the field in various projections, and show that a relatively simple mathematical model can be used to describe the distant tail magnetic field. The model results are in good accordance with previously published GEOTAIL observations.

1. Introduction

The large-scale magnetotail structure with the plasma/current sheet at the tail center enveloped by the relatively empty tail lobes has been shown to persist to large radial distances (Tsurutani *et al.*, 1984; Slavin *et al.*, 1985). Although the distant magnetotail probably does not play an active role in magnetospheric substorm events, its structure is an important factor for global plasma transport within the magnetosphere as well as for the intercoupling between the solar wind and the magnetosphere.

Global MHD simulations giving full magnetospheric dynamics as a function of the solar wind driving (e.g., Raeder, 1994; Fedder and Lyon, 1995) have revealed a complex picture of the distant magnetotail: IMF B_Y causes substantial twisting of the tail, and during northward IMF the tail lobes close almost completely. These models are in agreement with the previous ISEE 3 measurements, which indicated that the position and shape of the tail can vary quite significantly (e.g., Fairfield, 1979; Tsurutani *et al.*, 1984; Sibeck *et al.*, 1985), and that the tail may even disappear at large distances during very long periods of strongly northward interplanetary magnetic field (Fairfield *et al.*, 1993).

The near-Earth magnetic field configuration has received considerable attention during the past years. Models by Tsyganenko (1987; 1989; 1995) and Hilmer and Voigt (1995) describe the average inner magnetosphere magnetic field with a high degree of accuracy (see, e.g., recent reviews by Jordan, 1994; Tsyganenko, 1990). However, data-based models for the distant tail magnetic field have not been included in these approaches. Slavin *et al.* (1984; 1985; 1987) and Tsurutani *et al.* (1986) discuss in detail the statistical properties of the tail magnetic field configuration both during quiet periods and during substorm times, but these results have not been utilized for modeling purposes.

The global configuration of the open magnetosphere can be qualitatively described by the reconnection–convection picture (Dungey, 1961). This picture predicts that tailward of the distant neutral line, the magnetic field at the current sheet is southward, and the $\mathbf{v} \times \mathbf{B}$ electric field is in the direction to support tailward plasma flow. Furthermore, reconnection at this distant neutral line would cause plasma jetting both Earthward and tailward giving rise to the global convection pattern in the plasma sheet and tailward flow tailward of the neutral line. However, the observations have revealed a much more complex pattern, in which a flow reversal region can

be found at about $X = -100 R_E$ distance (Slavin *et al.*, 1985), but where B_Z at the current sheet tailward of that distance is northward for significant periods of time (Slavin *et al.*, 1987). Whether this is due to current sheet filamentation (which would give rise to many such northward field regions) or due to some other processes active in the tail is not yet clear (see also Nishida *et al.*, 1995).

In this paper we discuss the ISEE 3 magnetic field observations from the point of view of building a simple, quantitative model for the distant tail field. In Section 2 we describe the data set and the dependence of the field values of various parameters. Section 3 describes a procedure to deduce the current sheet thickness using energetic particle observations, and Section 4 addresses the magnetopause location. In Section 5 we present a model that gives a reasonable representation of the data averaged over all activity conditions.

2. Magnetic Field Observations

ISEE 3 distant geotail measurements were made during six orbits with nightside apogees from 80 to 240 R_E (Slavin *et al.*, 1985). The 1-min averaged magnetic field measurements were available from the entire period (Frandsen *et al.*, 1978). Here we concentrate on observations made in the region tailward of $X = -40 R_E$, an arbitrarily set boundary between the "inner magnetotail" and the "distant magnetotail". Furthermore, the magnetospheric region indicator developed by Zwickl *et al.* (1984) is used to divide the data set into "lobe data points" and "plasma sheet data points". All solar wind or magnetosheath observations were excluded from the data set used in this study. We present all data and modeling results in an aberrated GSM (geocentric solar magnetospheric) coordinate system, where the 4.5° aberration of the magnetotail in the X - Y plane has been taken into account.

The top two panels of Fig. 1 show the regions where observations were made, respectively, for the "lobe" and "plasma sheet" data points projected to the GSM X - Z plane. It is immediately clear that both data sets effectively outline the satellite orbit: Only in the region 50–100 R_E the lobe observations are at higher Z values; in the more distant tail there is virtually no difference due to large-amplitude flapping of the tail. For magnetic field modeling, the most important variable is the distance of the measurement point from the cross-tail current sheet center. In the inner tail, the GSM Z coordinate gives a good indication of that distance; in the distant tail field it is apparent that such connection cannot be made.

The bottom panels of Fig. 1 show the magnetic field magnitude in both the plasma sheet and the lobe as a function of radial distance. The solid lines give simple fits of the form $B = a + b/X$ to the data. Although the variability is quite large, it is evident that the lobe field decreases from about 17 nT to below 10 nT; being relatively constant tailward of about $X = -100 R_E$. The field magnitude within the plasma sheet varies from very small values (at current sheet crossings) to values close to the lobe field intensity (at the plasma sheet boundary). In the plasma sheet, the mean total field magnitude is a much weaker function of downtail distance than that of the lobes.

The Y variation of the magnetic field is an important question in terms of complexity of a field model. The top four panels of Fig. 2 show the B_X and B_Y components as a function of Y , averaged over all X and Z values for both the lobe (upper panels) and the plasma sheet (lower panels). The northern hemisphere ($B_X > 0$) points are denoted with crosses, and the southern hemisphere points ($B_X < 0$) are denoted with open circles; the averages have been computed for 5- R_E bins in the Y direction. The vertical bars indicate the standard deviation in the observations. It is evident that both in the lobe and in the plasma sheet B_X is relatively constant as a function of Y . For both regions, B_Y is very small, and there is a slight hint of flaring of the tail: B_Y in the northern hemisphere is positive for negative Y and negative for positive Y ; the reverse is true for the southern hemisphere. However, the effect is small enough

Fig. 1. Top panels: locations of magnetic field measurements reduced to the aberrated GSM X - Z plane. The lobe field observations and the plasma sheet observations are shown separately. Observations from other regions have been excluded from the data set. Bottom panels: Total field intensity measurements reduced to the aberrated GSM X - Z plane and a polynomial fit to the data. The division into plasma sheet and lobe points is as in the top panels.

Fig. 2. Dependence of the magnetic field components on the Y coordinate. Top panels: Plasma sheet and lobe observations averaged over all X and Z values. The northern ($B_x > 0$) and southern ($B_x < 0$) hemisphere measurements are shown separately. Bottom: similar to the top panels, but now for each 40- R_E bin in X direction separately.

that a two-dimensional model considering only B_X and B_Z with no variations in the Y direction seems justified.

The lower panels of Fig. 2 confirm that the result discussed above is true for all radial distances tailward of $X = -40 R_E$. The data were divided into 5 bins corresponding to X ranges $-40 > X > -80$, $-80 > X > -120$, $-120 > X > -160$, $-160 > X > -200$, and $-200 > X > -240$ (all in R_E). These panels show curves similar to the upper panels, but for each $40 R_E$ bin separately. Note that due to incomplete coverage, the entire range of Y values is not covered in all bins.

Yet another way to look at the relative importance of the field components is to plot them against the total field intensity. The right hand panel of Fig. 3 shows that, with a few exceptions probably associated with magnetic activity, B_X accounts for almost all of the total field intensity in the lobes. On the other hand, the corresponding figure for the plasma sheet observations (left) indicates that although B_X is still often the largest component, the other components are also significant. From the plots for B_Y and B_Z (not shown) one can deduce that the average B_Z is slightly positive, but that B_Y is small and the measurements are evenly distributed around zero (see also Siscoe *et al.*, 1984).

Fig. 3. Plasma sheet B_Z (left) and lobe B_X (right) as a function of the total field intensity.

In a simple picture of a tail-like field, the magnetic field is created as a combination of the cross-tail current and its closure currents along the magnetopause. Thus, the field intensity is smaller near the current sheets, but is constant within the curl-free tail lobes. The left panels of Fig. 4 show the plasma sheet B_X and B_Z dependence of $|Z|$, averaged over all X and Y values. B_X shows basically no variation as a function of Z . It is notable that the field at $Z = 0$ does not go to zero, which again points out that the current sheet center cannot be localized by using the Z coordinate. B_Z within the plasma sheet is larger near $Z = 0$ and decreases slightly towards larger Z values. There is no notable variation in B_Y as a function of Z (not shown). The lobe field B_X (Fig. 4, third panel) shows a slight maximum near $Z = 10 R_E$, but the variability is large. B_Z in the lobe is close to zero for all Z values. The heavy dashed lines are the values given by the model developed in this paper, these will be discussed in a later section.

Fig. 4. Variability of the magnetic field in the Z direction. The plasma sheet B_X (left), B_Z (middle), and lobe B_X (right) as a function of $|Z|$. The solid lines denote model values derived in Section 5.

Fig. 5. Top: Plasma sheet B_z as a function of X . The averages ($20-R_E$ bins) and variances are shown with the heavy lines. Middle: Plasma sheet B_z at current sheet crossings ($|B_x| < 0.5 R_E$). The averages ($20-R_E$ bins) and variances are shown with the heavy lines. Bottom: A quasi-three-dimensional view of the B_z at the plasma sheet. The vertical bars indicate the average B_z , the scale is given in the lower left corner.

The average B_Z at the tail current sheet is an interesting question that bears significance also to the global topology of the field. The top panel of Fig. 5 shows the measured B_Z values within the plasma sheet and the averages ($20-R_E$ bins in the X direction, averaged over all Y). The averages decrease as a function of increasing radial distance, and reach a local minimum close to the flow reversal region at $X \approx -100 R_E$. Tailward of that, the average B_Z is small but slightly positive, reaching values very close to zero tailward of $\sim 200 R_E$. Note that the variability is quite large, and that negative B_Z values are frequently observed at all radial distances. Slavin *et al.* (1987) found that the probability for negative B_Z increases substantially with increasing magnetic activity: in a subset of observations covering only the magnetically active periods, the B_Z averages were negative tailward of $\sim 100 R_E$. The middle panel concentrates on B_Z values exactly at the current sheet crossings ($|B_X| < 0.5$ nT). The averaged results are virtually the same for both data sets, suggesting that the current sheet structure is relatively homogeneous. Because B_Z is generally small in this region, there could also be coupling between B_Z and other field components due to tail flapping and twisting. Whereas in individual cases this has to be analyzed in detail, we have here assumed that any such effects average out in the relatively large data set.

The bottom panel shows the B_Z distribution in the X - Y plane in a quasi-three dimensional representation. The data were divided into $20 R_E$ by $5 R_E$ bins in the X - Y plane. The thick vertical bars indicate the averaged B_Z values within each bin (the scale is given in the lower left corner). B_Z is slightly larger in the flanks than near the tail center; also the only four bins where the average was negative (marked with circles instead of crosses) were all near the central part of the tail (see also Slavin *et al.*, 1985).

3. Current sheet thickness evaluation

The thickness and structure of the cross-tail current sheet are important parameters for magnetic field models that cannot be obtained from magnetic field measurements alone. When the spacecraft position cannot be taken to indicate the distance to the current sheet center, the plasma measurements have to be employed in order to deduce the current sheet thickness as the spacecraft traverses the field reversal region.

Pulkkinen *et al.* (1993) analyzed 33 events, where ISEE 3 crossed within relatively short time period (~ 15 min) from lobe to lobe. The velocity of the current sheet was estimated for each event separately using the method developed by Murphy *et al.* (1987) and the energetic particle anisotropy spectrometer (EPAS) on ISEE 3 (Balogh *et al.*, 1978). For each event, the current sheet thickness was estimated using two methods: First, the current sheet thickness was determined from $\lambda = U \cdot \Delta t$, where U is the current sheet velocity relative to the satellite deduced from the energetic ion measurements, and Δt is the time for depressed magnetic field magnitude during the current sheet crossings estimated using 3-s averaged magnetic field measurements. Secondly, the current sheet thickness was estimated using a Harris sheet model for the magnetic field, $B = B_0 \tanh[U \cdot (t - t_0)/\lambda]$, where B_0 is the field magnitude in the lobes and t_0 is the time of the current sheet crossing. By determining U and measuring $B(t)$, B_0 , and t_0 , λ could be obtained. These analyses yielded a distribution with a mean of $2.45 R_E$, the smallest thicknesses obtained being only a fraction of R_E , and the largest being as large as $10 R_E$ (see Fig. 6). The plasma flow was tailward in all but 3 of the 33 events, indicating that the satellite was tailward of the flow reversal region during the current sheet crossings. All the crossings in that study are included in the present data set for field modeling.

Fig. 6. Current sheet thickness observations (from Pulkkinen *et al.*, 1993).

Fig. 7. Magnetopause crossings from Sibeck *et al.* (1991). The solid line indicates a linear approximation of the model by Sibeck *et al.* (1991) for the pressure range 1.47–2.60 nPa.

4. Magnetopause location

At large radial distances, the magnetopause can be approximated by a cylindrical surface with a radius independent of distance from the Earth (Fairfield, 1993). However, earthward of about $X = -100 R_E$, the magnetopause flaring (increasing tail radius as a function of distance from the Earth) can be an effect important for magnetotail models.

Sibeck *et al.* (1991) assembled a data set of 1821 magnetopause crossings using data from various satellites. Figure 7 is a reproduction of their figure, it gives the magnetopause location in X - R coordinates where $R^2 = Y^2 + Z^2$ in aberrated coordinates. Sibeck *et al.* (1991) modeled the magnetopause location with an ellipsoid of the form $R^2 + AX^2 + BX + C = 0$, where the coefficients A , B , and C were determined through a minimizing procedure for different subsets of the data. They produced two sets of models: One employed data binning according to IMF, and in the other model the data was binned in different ranges of the solar wind dynamic pressure. The solid line in Fig. 7 shows a linear approximation of their magnetopause model, which corresponds to the dynamic pressure range 1.47–2.60 nPa (the intermediate bin of their five bins). For this model the coefficients are $A = 0.14$, $B = 18.2$, and $C = -217.2$. The linear approximation shown in Fig. 7 and the actual model curve coincide at $X = -40 R_E$ and at $X = -10 R_E$.

5. Tail field model

Guided by the observations, we represent the distant tail magnetic field with three current sheets, one at the tail center and two at the magnetopause (Fig. 8). The current sheets were assumed to consist of infinitely long (in the Y direction) wires, and the total field was integrated over the desired range of X values. The finite thickness of the current sheet as well as the current sheet intensity variations along the tail axis were introduced in the integral (see Tsyganenko, 1987).

The magnetic field produced by a current sheet at the plane $Z = 0$ can be given in integral form as

$$\begin{aligned} B_X(X, Z) &= \int_{X_f}^{X_n} \frac{\mu_0}{2\pi} K(x) \frac{Z}{(x-X)^2 + Z^2 + D^2} dx \\ B_Z(X, Z) &= \int_{X_f}^{X_n} \frac{\mu_0}{2\pi} K(x) \frac{x-X}{(x-X)^2 + Z^2 + D^2} dx \end{aligned} \quad (1)$$

$$K(x) = K_0 + \frac{K_1}{x - X_1}$$

where X and Z are the (aberrated) GSM coordinates. The radial profile of the current is given by $K(X)$, whose form was suggested by the field fits in Fig. 1. The model contains six free parameters: The current sheet thickness (D), the current sheet extent in X (X_n , X_f), and the current intensity radial profile (K_0 , K_1 , X_1). The current sheet thickness was chosen to be the average value ($2.45 R_E$) found in the detailed analysis of the current sheet crossings and $X_n = -10 R_E$ was chosen as the inner boundary. The other parameters were retained as free parameters and were evaluated through a least squares fit to the data.

The return currents along the magnetopause were modeled by two current sheets, whose distance from the equatorial plane varied linearly. Between $X = -10$ and $X = -40 R_E$ the linear fit to the Sibeck *et al.* (1991) shown in Fig. 7 was used. Tailward of $X = -100 R_E$ the tail radius was taken to be constant. Between $X = -40 R_E$ and $X = -100 R_E$ the tail radius was taken to increase linearly such that the magnetopause forms a continuous surface (see the schematic drawing in Fig. 8). Mathematically, the magnetopause distance from the equatorial plane can be

Fig. 8. A schematic of the distant tail field model.

expressed as

$$R_T(X) = R_T + k(X - X_{T2}), \quad (2)$$

where

$$\begin{aligned} R_T &= R_{T3}, & X_{T3} > X > X_F \\ &R_{T2}, & X_{T2} > X > X_{T3} \\ &R_{T2}, & X_n > X > X_{T2} \end{aligned} \quad (3)$$

and

$$\begin{aligned} k &= 0, & X_{T3} > X > X_F \\ &\frac{R_{T3} - R_{T2}}{X_{T3} - X_{T2}}, & X_{T2} > X > X_{T3} \\ &\frac{R_{T2} - R_{T1}}{X_{T2} - X_{T1}}, & X_n > X > X_{T2}. \end{aligned} \quad (4)$$

$$(5)$$

As indicated above, we chose $X_{T1} = -10 R_E$ and $X_{T2} = -40 R_E$, then the Sibeck *et al.* (1991) model then gives $R_{T1} = 19.6 R_E$ and $R_{T2} = 26.9 R_E$. X_{T3} was chosen to be $-100 R_E$, and R_{T3} was left as a free parameter to be evaluated through the data fitting procedure. The two current sheets above and below the equatorial plane were assumed to be symmetric.

The contribution to the magnetic field from the return currents along the magnetopause is functionally similar to that given in Eq. (1) for the equatorial cross-tail current sheet when Z is replaced by $Z \pm R_T(X)$. Because the current along the magnetopause flows in the opposite direction as the cross-tail current sheet, and because half of the current closes through each of the boundaries (northern and southern hemisphere), the field contributions from the magnetopause current sheets have a negative sign and a factor 1/2 different from the cross-tail current sheet. Thus, the total magnetic field is given by

$$B_X(X, Z) = \int_{X_f}^{X_n} \frac{\mu_0}{2\pi} K(x) \left(\frac{Z}{(x - X)^2 + Z^2 + D^2} \right) \quad (6)$$

$$\begin{aligned}
B_Z(X, Z) = & \int_{X_f}^{X_n} \frac{\mu_0}{2\pi} K(x) \left(\frac{x - X}{(x - X)^2 + Z^2 + D^2} \right. \\
& \left. - \frac{\frac{1}{2}(Z + R_T(x))}{(x - X)^2 + (Z + R_T(x))^2 + D^2} - \frac{\frac{1}{2}(Z - R_T(x))}{(x - X)^2 + (Z - R_T(x))^2 + D^2} \right) dx \\
& - \frac{\frac{1}{2}(x - X)}{(x - X)^2 + (Z + R_T(x))^2 + D^2} - \frac{\frac{1}{2}(x - X)}{(x - X)^2 + (Z - R_T(x))^2 + D^2} \right) dx.
\end{aligned} \quad (7)$$

These equations were integrated analytically to give the magnetic field components at each point (X, Z) in the distant magnetotail.

The model field value depends on the distance from the Earth (X) and on the distance of the point from the current sheets (Z). As the Z value was not known for the observations, it was necessary to reduce the data set further. Using the fact that the field values were only weakly dependent on Z , we reduced the lobe measurements to $Z = 15 R_E$ and all plasma

Table 1. Parameter values for Equation 1 that give the best fit to the observed field values.

D	X_n	X_f	K_0	K_1	X_1	R_{T3}
2.45	-10.0	-500.0	11.0	-650.0	-3.0	30.0

Fig. 9. Distant tail field model results (dashed line) and the extension of the Tsyganenko (1989) model field (solid line).

sheet measurements to $Z = 0$ (i.e., all the lobe measurements were assigned a Z coordinate $Z = 15 R_E$, and all the plasma sheet measurements were assigned a Z coordinate equal to zero). Furthermore, the 1-min magnetic field data shown in the previous plots were further averaged to 30-min averages to make the computing time shorter. Then, the optimal model parameters were found by minimizing the least squares error between the model and the measurements. The parameters corresponding to the best fit are given in Table 1. Note that although the model current sheets extend to radial distances not covered by data, the model is valid only in the region $-40 > X > -240 R_E$.

Figure 9 shows the tail field model results as compared with the extension of the Tsyganenko (1989) (T89) model field for $Kp = 3$ to large radial distances. As the data used to create the T89 model has good coverage only to about $40 R_E$ distance, the model is not accurate at larger distances (see also Tsyganenko, 1987). However, because the T89 model is often extended to also the distant magnetotail, we compare the T89 model extension with our results. The averages of the field ($20 R_E$ bins) and the model results are virtually identical. The lobe field in the extended T89 model is lower than that indicated by the tail model, and the lobe field rapidly decreases to very low values. The B_Z agreement between the two models is good—at the current sheet center both models predict a monotonously decreasing field that approaches zero at large radial distances. Thus, the minimum present in the averaged data or the negative B_Z values also observed are not represented by either of the models. The lowest panel shows the current

Fig. 10. A comparison of the distant tail field model (dashed line) and observed current sheet crossing (solid line) on Jan 25, 1983.

Fig. 11. GEOTAIL magnetic field measurements (Yamanoto *et al.*, 1994) and the distant tail field model (dashed line).

integrated over the current sheet thickness (in mA/m). As expected, the radial profile closely resembles that of B_X in each of the respective models.

The comparison of the tail field model with an actual current sheet crossing at $X = -211 R_E$ is shown in Fig. 10. To create this plot, Z has been replaced with $U \cdot (t - t_0)$, where U has been estimated from energetic ion measurements, and t_0 is the time of the B_X reversal. In this case, both the lobe field and the current sheet thickness agree relatively well, although the observed current sheet is thinner than the average value used in the tail model. This is indicated in the difference in the slopes in B_X within the reduced field intensity region. The observed B_Z exhibits large variability, whereas the model B_Z is very close to zero at these large radial distances.

To check the effects of the reduction of data to only two Z values, we have plotted the model results at $X = -140 R_E$ in Fig. 4 showing the Z dependence of the field. The current sheet portion was taken to be the region where $B < B_{lobe}$, or about $Z < 5 R_E$. Thus, the model for $Z < 5 R_E$ is plotted on top of the plasma sheet data, whereas the model at $Z > 5 R_E$ is plotted over the lobe data. Within the plasma sheet, the scatter in B_X is sufficiently large so that the Z dependence present in the model is not apparent in the data, but the values are in agreement. In the lobe, the model gives quite a good representation of B_X , and the model B_Z values are close to zero consistently with the observations.

The GEOTAIL mission has considerably increased the number of observations in the distant tail. Figure 11 from Yamamoto *et al.* (1994) has been modified to include the tail field model results for B_X ($B_Y = 0$). Although the model slightly overestimates the average field intensity inside about $150 R_E$, the good correspondence of the tail field model based on ISEE 3 data and the GEOTAIL data show that there is no significant disagreement between these two data sets.

6. Discussion

The difficulty in building data-based magnetic field models for the distant tail is that the tail at these distances flaps around quite significantly (Fairfield *et al.*, 1993), such that the spatial coordinates of the measurement points cannot be used as input variables. To overcome this problem, we have divided the observations into two data sets, the "plasma sheet" and "lobe" observations, and further reduced these at two different altitudes from the current sheet center. With these gross simplifications, we were able to develop a relatively simple magnetic field model for the distant tail field, which on average reflects the properties of the measurements.

This model does not include a distant tail neutral line, as the model produced a weakly positive B_Z throughout the region where measurements were made, in agreement with the averaged data. The variability in the data is sufficient (the mean is much smaller than the variance) to suspect that at least part of the time the average B_Z could have been negative in the distant part of the tail (especially near the tail center and during magnetically active periods (Slavin *et al.*, 1987)). This is a topic that needs to be further investigated.

An accurate model for the distant tail field is required in studies of the global convection pattern and in studies involving particle entry through the high-latitude magnetopause or particles outflowing from the polar ionospheres. These particles move along the tail with their thermal speed, and convect across the tail lobe with the $\mathbf{E} \times \mathbf{B}$ speed. The low lobe field values in the Tsyganenko models at large radial distances enhance the equatorward drift speed quite significantly so that particles arrive at the equatorial plane much closer to the Earth when using the Tsyganenko model than when using the tail field model developed here. For example, a 1-keV proton launched from $X = -40 R_E$, $Z = 30 R_E$ in a 0.3 mV/m electric field, reaches the equatorial plane at about $X = -80 R_E$ using the T89 ($Kp = 3$) model, whereas using the tail field model the crossing point is at about $X = -170 R_E$. Depending on the particle energy and electric field value, the differences can be even larger than that.

The methods outlined in this paper could be merged with the existing empirical magnetic

field models to get a more realistic representation of the distant tail field and the truly global field configuration. Furthermore, including the large database obtained from the GEOTAIL mission would substantially increase the accuracy of the modeling results.

The use of ISEE 3 magnetometer (P.I. E. J. Smith), plasma analyzer (P.I. S. J. Bame) and energetic particle anisotropy spectrometer (P.I. R. J. Hynds) data sets is gratefully acknowledged.

REFERENCES

- Balogh, A., G. van Dijen, J. van Genechten, J. Henrion, R. J. Hynds, G. Korfmann, T. Iversen, J. van Rooijen, T. Sanderson, G. Stevens, and K.-P. Wenzel, The low-energy proton experiment on ISEE-C, *IEEE Trans. Geosci. Electron.*, **GE-16**, 176, 1978.
- Dungey, J. R., Interplanetary magnetic field and the auroral zones, *Phys. Rev. Lett.*, **6**, 47, 1961.
- Fairfield, D. H., On the average configuration of the geomagnetic tail, *J. Geophys. Res.*, **84**, 1950–1958, 1979.
- Fairfield, D. H., Solar wind control of the distant magnetotail: ISEE 3, *J. Geophys. Res.*, **98**, 21,265–21,276, 1993.
- Fedder, J. A., and J. G. Lyon, The Earth's magnetosphere is 165 R_E long: or self-consistent currents, convection, magnetospheric structure and processes for northward IMF, *J. Geophys. Res.*, **100**, 3623–3635, 1995.
- Frandsen, A. M. A., B. V. Connor, J. V. Amersfoort, and E. J. Smith, The ISEE-C vector helium magnetometer, *IEEE Trans. Geosci. Electron.*, **GE-16**, 195, 1978.
- Hilmer, R. V. and G.-H. Voigt, A magnetospheric magnetic field model with flexible internal current systems driven by independent physical parameters, *J. Geophys. Res.*, **100**, 5613–5626, 1995.
- Jordan, C. E., Empirical models of the magnetospheric magnetic field, *Rev. Geophys.*, **32**, 139–157, 1994.
- Murphy, N., J. A. Slavin, D. N. Baker, and W. J. Hughes, Enhancements of energetic ions associated with travelling compression regions in the deep geomagnetic tail, *J. Geophys. Res.*, **92**, 64–70, 1987.
- Nishida, A., T. Mukai, T. Yamamoto, Y. Saito, S. Kokubun, and K. Maezawa, GEOTAIL observation of magnetospheric convection in the distant tail at 200 R_E in quiet times, *J. Geophys. Res.*, **100**, 23,663–23,666, 1995.
- Pulkkinen, T. I., D. N. Baker, C. J. Owen, J. T. Gosling, and N. Murphy, Thin current sheets in the deep geomagnetic tail, *Geophys. Res. Lett.*, **20**, 2427–2430, 1993.
- Raeder, J., Global MHD simulations of the dynamics of the magnetosphere: Weak and strong solar wind forcing, in *Substorms II*, p. 561, Geophysical Institute, University of Alaska Fairbanks, Fairbanks, Alaska, 1994.
- Sibeck, D. G., G. L. Siscoe, J. A. Slavin, E. J. Smith, B. T. Tsurutani, and R. P. Lepping, The distant magnetotail's response to a strong interplanetary magnetic field B_Y : Twisting, flattening, and field line bending, *J. Geophys. Res.*, **90**, 4011–4019, 1985.
- Sibeck, D. G., R. E. Lopez, and E. C. Roelof, Solar wind control of the magnetopause shape, location, and motion, *J. Geophys. Res.*, **96**, 5489–5495, 1991.
- Siscoe, G. L., D. G. Sibeck, J. A. Slavin, E. J. Smith, B. T. Tsurutani, and D. E. Jones, ISEE 3 magnetic field observations in the magnetotail: Implications for reconnection, in *Magnetic reconnection in space and laboratory plasmas*, edited by E. J. Hones, Jr., p. 240, AGU, Washington, D. C., 1984.
- Slavin, J. A., E. J. Smith, B. T. Tsurutani, D. G. Sibeck, H. J. Singer, D. N. Baker, J. T. Gosling, E. W. Hones, and F. L. Scarf, Substorm associated traveling compression regions in the distant tail: ISEE 3 Geotail observations, *Geophys. Res. Lett.*, **11**, 657–660, 1984.
- Slavin, J. A., E. J. Smith, D. G. Sibeck, D. N. Baker, R. D. Zwickl, and S.-I. Akasofu, An ISEE-3 study of average and substorm conditions in the distant magnetotail, *J. Geophys. Res.*, **90**, 10,875–10,895, 1985.
- Slavin, J. A., P. W. Daly, E. J. Smith, T. R. Sanderson, K.-P. Wenzel, R. P. Lepping, and H. W. Kroehl, Magnetic configuration of the distant plasma sheet: ISEE 3 observations, in: *Magnetotail Physics*, edited by A. T. Y. Lui, p. 59, The Johns Hopkins University Press, Baltimore, 1987.
- Tsurutani, B. T., J. A. Slavin, E. J. Smith, R. Okida, and D. E. Jones, Magnetic structure of the distant geotail from -60 to $-220 R_E$: ISEE3, *Geophys. Res. Lett.*, **11**, 1–4, 1984.
- Tsurutani, B. T., D. E. Jones, R. P. Lepping, E. J. Smith, and D. G. Sibeck, The relationship between the IMF B_Y and the distant tail (150 – $220 R_E$) lobe and plasmashet B_Y fields, *Geophys. Res. Lett.*, **11**, 1082–1085, 1984.
- Tsurutani, B. T., B. E. Goldstein, M. E. Burton, and D. E. Jones, A review of the ISEE-3 geotail magnetic field results, *Planet. Space Sci.*, **34**, 931–960, 1986.
- Tsyganenko, N. A., Global quantitative models of the geomagnetic field in the cislunar magnetosphere for different disturbance levels, *Planet. Space Sci.*, **35**, 1347–1358, 1987.
- Tsyganenko, N. A., Magnetospheric magnetic field model with a warped tail current sheet, *Planet. Space Sci.*, **37**, 5–20, 1989.
- Tsyganenko, N. A., Quantitative models of the magnetospheric magnetic field: Methods and results, *Space Sci. Rev.*, **54**, 75–186, 1990.
- Tsyganenko, N. A., Modeling the Earth's magnetospheric magnetic field confined within a realistic magnetopause,

- J. Geophys. Res.*, **100**, 5599–5612, 1995.
- Yamamoto, T., K. Shiokawa, and S. Kokubun, Magnetic field structures of the magnetotail as observed by GEO-TAIL, *Geophys. Res. Lett.*, **21**, 2875–2878, 1994.
- Zwicky, R. D., D. N. Baker, S. J. Bame, W. C. Feldman, J. T. Gosling, E. W. Hones, Jr., and D. J. McComas, Evolution of the Earth's distant magnetotail: ISEE 3 electron plasma results, *J. Geophys. Res.*, **89**, 11,007–11,012, 1984.