Dependence of the near-Earth magnetotail magnetic field on storm and substorm activities

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Abstract. Equatorial magnetic field data in the near-Earth tail region 3 < R < 23 R\(_e\) have been sampled from the large magnetic field database obtained by ISEE 1 for 1978-1987. The dependence of the field magnitude on storm and substorm activities represented by the Dst and AL indices, respectively, has been examined. The data for declining/quiet phases in terms of the AL index have been used; i.e., the data obtained before and during the periods when the auroral electrojet was rapidly increasing have not been used to avoid the possible influences of substorm expansion onset. The following two features are noted: (1) Magnetic field magnitude does not depend significantly on substorm activity (AL) in the near-Earth magnetotail R < 9 R\(_e\), while it increases with increasing substorm activity in the midmagnetotail R > 9 R\(_e\). The slope of the regression line for the AL index changes in a step-like fashion in the vicinity of R = 9 R\(_e\). (2) Field magnitude decreases with increasing storm activity (Dst) in the region within R < 12 R\(_e\), while it increases beyond R > 12 R\(_e\). In contrast to the regression slope for the auroral electrojet, the slope for the Dst index changes gradually with increasing the distance from the Earth. Considering these points along with the results obtained for the lobe magnetic field, we discuss the changes in the large-scale distribution of the neutral sheet current during the course of major substorms: During the expansion onset of substorms, the neutral sheet current increases in the near-Earth magnetotail and decreases in the midmagnetotail. The neutral sheet current subsequently decreases in both the near-Earth and middistant tail regions during the recovery phase of substorms, where the current reduction is particularly evident near R = 6 R\(_e\). It is also suggested that not only in the near-Earth magnetotail but in the midmagnetotail the cross-tail current is significantly enhanced during intense storms.

1. Introduction

The earthward and tailward magnetic fluxes of the Earth's magnetotail are separated by the neutral sheet region. Magnetic field configuration in the neutral sheet region relates intimately to the distribution of the neutral sheet current, and hence it can be one of the most important indicators to monitor the magnetic field changes in the magnetotail. The magnetic field near the neutral sheet has been surveyed by a number of spacecraft, for example, IMP 6, 7, and 8 at X = -10 - -45 R\(_e\) [Fairfield, 1986].

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AMPE/CCE at R < 8.8 R\(_e\) [Fairfield et al., 1987], ISEE 3 at X = -20 - -240 R\(_e\) [Elcan et al., 1987; Fairfield, 1992], and ISEE 1 and 2 at X = -10 - -22.5 R\(_e\) [Huang and Frank, 1994]. Roskoher and Stone [1991] have merged these observations to derive an empirical formula for the radial dependence of the equatorial B\(_z\) component.

The dependence of the equatorial magnetic field on geomagnetic activity has been one of important issues in the above cited papers. Fairfield et al. [1987] have shown that the average values of the magnetic field magnitude are smaller during disturbed periods than during quiet periods in the region R < 7 R\(_e\) and vice versa in the region R > 7 R\(_e\), consistent with the earlier statistical work by Sugiraka and Furus [1973]. The negative dependence of Dst in the near-Earth region is partly caused by an intensification of the ring current [Fairfield et al., 1987]. Consistent with their results,
Nakai et al. [1997] have demonstrated that the average magnetic field magnitude in the neutral sheet region is greater (or smaller) for $AL > -50$ nT than for $AL < -200$ nT in the region $R < 9 R_E$ (or $R > 9 R_E$). They argued that the large-scale distribution of the cross-tail current, as well as the ring current, is responsible for the behavior of the near-Earth magnetic field. As for the distant tail region, $R = 20 - 240 R_E$, Slight et al. [1987] have found that the average values of the $B_z$ component in the equatorial region for $AL > 100$ nT are greater than those for $AL < 100$ nT except for the region, $R = 20 - 40 R_E$ (see also Fairfield [1992]). It was also shown that the $B_z$ component is negative on average during disturbed periods beyond $R > 100 R_E$, indicating that the distant neutral line exists within $R > 100 R_E$.

The increase and decrease in the magnetic field magnitude in the tail lobe at the expansion onset of substorms has been another key into in substorm modeling [e.g., Cao et al., 1973; Russell and McPherron, 1973]. As will be shown later, the magnitude of the lobe magnetic field also correlates well with storm activity, implying that the lobe-field magnitude varies with a timescale of 5-10 hours, as does the Dist index. These variations should be distinguished from faster transitions associated with substorms. Since intense substorms occur frequently at the main phase of geomagnetic storms, it is reasonably envisaged that these two different types of magnetic field variations can occur simultaneously in the magnetotail. In addition to these effects, the solar wind static and dynamic pressures can significantly influence the tail field configuration as well [Nakai et al., 1959; Fairfield and Jones, 1966]. To understand how the Earth's magnetotail responds to solar wind conditions, we have to identify the differences among these three kinds of magnetic field variations.

Substorm expansion onsets could be identified with an accuracy of $\pm 30$ nT from data of ground-based magnetometers and auroral images. In addition, in the two decades, auroral images from spacecraft have become available in determining the timing of the substorm onsets. Nevertheless, it is still a hard task to sort a large data set according to the substorm phases. Huang and Frank [1994] have identified substorm phases by inspecting the $AL$ and $AU$ indices for 1978-1979 and have examined the distribution of the $B_z$ component in the neutral sheet region. They concluded that substorm-associated variations in the cross-tail current appeared to be more complicated than had been commonly accepted. Some of this complexity originates from the fact that the dipolarization normally begins in a narrow local time sector [e.g., Baker et al., 1995], so that the magnetic field configurations can remain to be tail-like in the region outside the dipolarized region.

However, since the increase westward and eastward auroral electrojets during disturbed periods are connected with magnetotail currents through field-aligned currents, the tail currents should feature different configurations depending on the intensity of ionospheric currents. In the present study, dealing with a data set larger than that of Huang and Frank [1994], we examine the dependence of the equatorial and lobe magnetic fields on geophysical activity represented by the $AL$ and $Dist$ indices. The data analyses are performed for periods when the auroral electrojet was reducing or very weak, aiming to exclude the influence of rapid magnetic field variations during the expansive increase in the auroral electrojet. The results obtained under these criteria are expected to include useful information on storm or substorm associated variations in the large-scale distribution of the neutral sheet current.

Another topic dealt with in this paper is how the solar wind dynamic pressure influences the magnetic field in the magnetotail. It is shown that the influences of the dynamic pressure depend strongly on the distance from the Earth in the equatorial region.

2. Data and Analysis Procedures

The 5-min magnetic field data from ISEE 1, the 5-min $AL$ index, and the 1-hour interplanetary data (National Space Science Data Center Omni Database, edited by J. H. King), as well as the 1-hour Dist index are used in this study. The magnetic field data in the magnetotail have been obtained from the measurements by the University of California, Los Angeles, fluxgate magnetometers on ISEE 1 [Russell, 1978] for 1978-1987. The ISEE 1 satellite had an initial orbit with an apogee of 22.6 $R_E$ and a perigee altitude of 280 km. Our primary interest in this study is confined to the midnight sector, which is defined in this study as $-5 < X < 5 R_E, R > 3 R_E$ in geocentric solar-magnetospheric coordinates.

The equatorial region is defined as $\theta = 45^\circ$ and $-3 < Z_{dist} < 3 R_E$, where $\theta$ and $Z_{dist}$ denote the elevation angle of the magnetic field from the $XY$ plane and the distance from the average position of the neutral sheet, respectively (see Nakai et al. [1997] for the model of the neutral sheet). Figure 1 shows the radial dependence of the magnetic field magnitude in the equatorial region. The dots show the average values of the magnetic field magnitude in each bin with a $1 R_E$ width. The solid lines show the regression curves, represented by $B_\theta = a R^b$, in each of the five segments divided by
Table 1. Regression Coefficients for the Curves, $B_m = a R^3$, Representing the Magnetic Field Magnitude in the Equatorial Region

<table>
<thead>
<tr>
<th>Range, $R_e$</th>
<th>$a$</th>
<th>$b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 ≤ $R_e$ &lt; 6</td>
<td>46803</td>
<td>3.36</td>
</tr>
<tr>
<td>6 ≤ $R_e$ &lt; 9</td>
<td>45347</td>
<td>3.33</td>
</tr>
<tr>
<td>9 ≤ $R_e$ &lt; 12</td>
<td>5692</td>
<td>2.36</td>
</tr>
<tr>
<td>13 ≤ $R_e$ &lt; 15</td>
<td>3820</td>
<td>2.14</td>
</tr>
<tr>
<td>15 ≤ $R_e$ ≤ 23</td>
<td>233.2</td>
<td>1.14</td>
</tr>
</tbody>
</table>

Table 2. Regression Coefficients for the Curves, $B_m = a R^3$, Representing the Magnetic Field Magnitude in the Lobe Region

<table>
<thead>
<tr>
<th>Range, $R_e$</th>
<th>$a$</th>
<th>$b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 ≤ $R_e$ ≤ 8</td>
<td>33440</td>
<td>2.71</td>
</tr>
<tr>
<td>8 ≤ $R_e$ ≤ 11</td>
<td>8726</td>
<td>2.04</td>
</tr>
<tr>
<td>11 ≤ $R_e$ &lt; 14</td>
<td>2565</td>
<td>1.53</td>
</tr>
<tr>
<td>14 ≤ $R_e$ &lt; 17</td>
<td>921.6</td>
<td>1.17</td>
</tr>
<tr>
<td>17 ≤ $R_e$ ≤ 23</td>
<td>497.8</td>
<td>0.95</td>
</tr>
</tbody>
</table>

It is difficult to determine unambiguously the phase of substorm for a long period of time. For instance, the onset time of the substorm expansion phase cannot be precisely identified using the AL index only [Kamide and Akasofu, 1983, Kamide and Kokubun, 1996]. However, the nominal substorm phase determined using the AL index is useful in statistical analyses. The entire periods from 1978 to 1987 are divided into the three phases according to the following criteria as to changes in the auroral electrojet represented by the AL index: (1) the interval during which the auroral electrojet is decreasing or very weak, (2) the interval just before explosive enhancement in the auroral electrojet, and (3) the interval during which the intensity of the auroral electrojet is increasing rapidly. Distinguishing these phases from the traditional substorm phases, they are termed, in this paper, as the declining/quiescent phase, the preonset phase, and the rising phase of the auroral electrojet, respectively.

To perform the classification, two variables for any given time $t$ are introduced, using 5-min AL values:

$$D_l(t) = AL_t^{(+ed)} - AL_t^{(-ed)}$$

$$D_h(t) = AL_t^{(+ed)} - AL_t^{(-ed)}$$

$D_l$ represents the trend in the variations of the AL index at the time $t$, while $D_h$ represents the "future" variation after $t$. After some trials, taking $5t$ and $15t$, respectively, the following criteria have been adopted. The end of the preonset phase is identified when $D_h$ is smaller than $-100$ nT, and the 50-min interval just prior to this is regarded as the preonset phase. The end of the preonset phase should be separated by more than 45 min from the previous one, considering the scale time in the development of the auroral electrojet. During periods with $D_h$ greater than $-30$ nT but not satisfying the criteria for the preonset phase, the AL activity is declining or quiet. These periods are termed as the declining/quiescent phase. The intervals classified into neither the declining phase nor the preonset phase are thought of as the rising phase. Note that in some cases the value of $D_h$ for data points just after the preonset phase can be greater than $-30$ nT. According to the criteria, they are classified as the declining/quiescent phase. However, considering the meaning of the "preonset" phase, such data points are classified as the rising phase. According to these criteria, 5-min periods from 1978 to 1987 have been classified into three groups: 76.9%, 10.0%, and 13.4%, respectively. These are identified as the declining/quiescent, preonset, and rising phase, respectively. The purpose of the present study is to reveal the...
behavior of the magnetic field in the near-Earth and mid-magnetotail during the declining/quiet phase.

3. Results

3.1. Equatorial magnetic field

We define the displacement of the magnetic field magnitude from its average value as $\Delta B_{eq} = B_{eq} - \langle B_{eq} \rangle$. In Figures 3 and 4 the 5-min values of $\Delta B_{eq}$ are plotted as a function of $AL$ for $-40 < AL < -15$ nT and of $Dst$ for $-400 < AL < -150$ nT, respectively, where $\sigma$ denotes the standard deviation of $\Delta B_{eq}$ in each range of $R$. The regression lines are shown by solid lines. It is noticed in Figure 3 that $\Delta B_{eq}$ decreases with decreasing the $AL$ index in the region $R < R_{0}$, while it increases in the region $R > R_{0}$. In Figure 4 $\Delta B_{eq}$ decreases with decreasing the $Dst$ index within $R = R_{0}$. The clear differences between the responses of $\Delta B_{eq}$ to the $AL$ and $Dst$ indices suggest the difference in the tail current configurations during substorm and storm periods. Before discussing this issue in detail, we reexamine the $AL$ and $Dst$ dependence of the equatorial magnetic field, taking the influence of the solar wind dynamic pressure into account.

To eliminate the compression effect of the solar wind pressure on the $Dst$ index, we define $Dst_{0}$ as $\Delta B_{eq}$ in the equatorial region for $-400 < AL < -150$ nT as functions of $Dst$ in the same format as Figure 3.

$$ Dst_{0} = Dst - s P_{sw} + i, $$

where $s = 10.5$ nT/(Pa)$^{0.5}$, $r = 22$ nT [Gonzalez et al., 1994; Valdivia et al., 1996], and $P_{sw}$ denotes the solar wind dynamic pressure. For simplicity, we assume the following linear coupling functions:

$$ \Delta B_{eq} = c_{1} + c_{2} AL + c_{3} P_{sw}, $$

$$ \Delta B_{eq} = c_{4} + c_{5} Dst_{0} + c_{6} P_{sw}, $$

where $c_{ij}$ denotes the regression constant and $c_{ij}$ are the regression coefficients.

The $AL$ and $Dst_{0}$ indices correlate weakly with $P_{sw}$ with correlation coefficients $0.30$ and $0.23$, respectively, for the entire data points concerned in this study, while the internal correlation between the $AL$ and $Dst_{0}$ indices is more evident: $0.03$. Therefore, to examine the effects of the $AL$ and $Dst_{0}$ indices separately, only the data points with $-45 < Dst_{0} < -15$ nT (or $-400 < AL < -150$ nT) are used, when the equation (2) (3) is assumed. It should be noted that combining these two equations into one equation is not appropriate to our purpose because of the high internal correlation between the $AL$ and $Dst_{0}$ indices.

Using the least squares method, the regression equations have been obtained. The resultant values obtained by assuming the equations (2) are shown in Table 3, where $c_{ij}$...
Table 3. Regression Coefficients and Correlation Coefficients for the Equation (2)

<table>
<thead>
<tr>
<th>R, R_E</th>
<th>&lt;ΔB⊙&gt;</th>
<th>AL</th>
<th>c_i</th>
<th>c_i'</th>
<th>&lt;P(E)&gt;</th>
<th>c_i'</th>
<th>c_i</th>
<th>N</th>
<th>c.c.</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-6</td>
<td>-6.7</td>
<td>-144</td>
<td>0.010</td>
<td>0.05</td>
<td>1.55</td>
<td>-27.3</td>
<td>-0.27</td>
<td>37</td>
<td>0.27</td>
</tr>
<tr>
<td>6-9</td>
<td>8.1</td>
<td>-159</td>
<td>0.023</td>
<td>0.26</td>
<td>1.65</td>
<td>-16.5</td>
<td>-0.25</td>
<td>62</td>
<td>0.36</td>
</tr>
<tr>
<td>9-12</td>
<td>1.7</td>
<td>-184</td>
<td>-0.054</td>
<td>-0.36</td>
<td>1.71</td>
<td>12.6</td>
<td>0.54</td>
<td>88</td>
<td>0.78</td>
</tr>
<tr>
<td>12-17</td>
<td>1.8</td>
<td>-265</td>
<td>-0.019</td>
<td>-0.65</td>
<td>1.78</td>
<td>5.6</td>
<td>0.55</td>
<td>41</td>
<td>0.85</td>
</tr>
<tr>
<td>17-23</td>
<td>0.9</td>
<td>-191</td>
<td>-0.004</td>
<td>-0.23</td>
<td>1.57</td>
<td>0.8</td>
<td>0.18</td>
<td>128</td>
<td>0.29</td>
</tr>
</tbody>
</table>

The solar wind dynamic pressure P_E is measured in nPa.

and c_i' denote the partial correlation coefficients of AL and <P(E)> respectively, c_i' and c_i' are equal to c_(0,i) and c_(2,i), respectively. c_i and c_i' denote the standard deviations of AL and <P(E)> respectively. Since the standard deviations of ΔB⊙ differ significantly in different bins of R, partial correlation coefficients are used instead of regression coefficients. The values of c_i' and c_i' are shown by the solid and open circles, respectively, in Figure 5a. The errors in the estimates of c_i' are shown by vertical lines, while the errors for c_i' are the same as those for c_i'. The results for equation (3) are plotted in Figure 5b with the same format as the upper one. It is noted that the correlation coefficients for AL in the range R < 9 R_E are nearly zero or positive, while they are negative in the region beyond R > 9 R_E. The coefficient for ΔB⊙ positive in the near-Earth region decreases gradually with the increasing distance from the Earth and becomes negative at R > 12 R_E. The open squares in Figures 5a and 5b show the correlation coefficients of the assumed coupling functions, (2) and (3), respectively. The values of the correlation coefficients, -0.5 or less, are in general smaller than those for the lobe magnetic field (see Figure 7), reflecting higher variability in the equatorial magnetic field particularly in the near-Earth region [Huang and Frank, 1994].

It is important to question whether the radial dependence of the correlation coefficient for the AL index depends on the range of the ΔB⊙ index or not. The correlation coefficients c_i'

![Figure 5](image)

Figure 5. Partial correlation coefficients of AL, ΔB⊙, and P(E) for ΔB⊙ in the equatorial region. Equation (2) is assumed to be a coupling function. In Figure 5a (Figure 5b), the solid circles show the coefficients for the AL (or ΔB⊙) index. Data points with -40 < ΔB⊙ < -15 nT and -400 < AL < -150 nT are only used in Figures 5a and 5b, respectively. The open circles show the coefficients for the solar wind dynamic pressure. The vertical lines attached to solid circles indicate the estimated errors of the correlation coefficients. The errors for the solar wind dynamic pressure are as great as those for AL or ΔB⊙. The open squares show the correlation coefficients of the coupling functions.

![Figure 6](image)

Figure 6. (a) Partial correlation coefficient of AL for ΔB⊙ in the equatorial region for various ranges of ΔB⊙. (b) Same as Figure 6a except for the coefficients of ΔB⊙ for various ranges of AL.
for the different ranges of $D_{ist}$ are plotted as a function of $R$ in Figure 6a. Unfortunately, the results for $D_{ist} < -45$ nT in the region $R < 17 R_E$ cannot be plotted in the upper panel due to too small data numbers (<20). The coefficient $c_1$ for $D_{ist}$ $\geq -15$ nT depends on the radial distance with the same characteristics as those for $-45 \leq D_{ist} < -11$ nT. The correlation coefficients for $D_{ist}$ for different ranges of $AL$ are also plotted in Figure 6b with the same format as Figure 6a. The radial dependence of $c_1$ seems to differ between the different ranges of $AL$.

In both Figures 5a and 5b the dependence of the equatorial field magnitude on the solar wind dynamic pressure is found to be negative within $R = 9 R_E$ and positive beyond it. The negative dependence is probably due to the edge effect of the neutral sheet current. Furthermore, it is expected that the northward magnetic field induced by the dayside magnetopause current would cancel to some extent the field reduction in the near-Earth equatorial tail region. This is probably responsible for the weak dependence of $R_{ist}$ on the solar wind pressure in the equatorial regions of the near-Earth magnetotail.

3.2. Lobe magnetic field

In the same way as we have treated the equatorial data points in the previous section, the residual values of the magnetic field magnitudes, $\Delta R_{ist}$, have been calculated by subtracting the average field magnitude. Adopting equation (2) (and (3)) for the lobe data set, the partial correlation coefficients of $AL$ (and $D_{ist}$) and $P_W^{1/2}$ for $\Delta R_{ist}$ have been calculated. The results are plotted in Figure 7. The coefficients for both the $AL$ and $D_{ist}$ indices are negative, indicating that the lobe field is intensified in association with high geomagnetic activity. The coefficients for the solar wind dynamic pressure are positive, and the influences in the lobe magnetotail seem to be stronger than those of the $AL$ and $D_{ist}$ indices.

The size of the magnetic field elevation angle, $B/Y_{max}$, is related to the $AL$ and $D_{ist}$ indices by assuming the coupling functions:

$$B/Y_{max} = c_0 + c_1 AL + c_2 P_W^{1/2},$$  \hspace{1cm} (4)

$$B/Y_{max} = c_0 + c_1 D_{ist} + c_2 P_W^{1/2}. \hspace{1cm} (5)$$

Partial correlation coefficients are shown in Figure 8 in the same format as in Figure 7. The correlation between these quantities is low (c.c. = 0.1 - 0.5) probably due to high-frequency flapping motions of the magnetotail. However, a difference between the regression coefficients for $AL$ and $D_{ist}$ is evident in Figure 8; that is, the elevation angle tends to increase with increasing substorm activity in all the ranges of $R$ except in the nearest one, while it tends to decrease with increasing storm activity.

It is also interesting to note that the coefficients for the dynamic pressure decrease from positive to negative as the distance from the Earth increases. Since the elevation angle
is negative on average in the near-Earth lobe region and positive in the midmagnetotail, magnetic field lines in the lobe tend to become more parallel to the tail axis as the solar wind pressure increases. This is consistent with the results of earlier studies [e.g., Fairfield et al., 1999].

4. Discussion

The dependence of the equatorial and lobe magnetic fields on the Al and Dst indices and the solar wind dynamic pressure has been examined using data from ISSEE 1 for 1978-1987. We summarize our main findings in the following way.

In the equatorial region:

1. Magnetic field magnitude does not depend significantly on the intensity of the auroral electrojet in the near-Earth magnetotail R < 9 R_E, while it increases with increasing the electrojet intensity in the midmagnetotail R > 9 R_E. The regression slope for the Al index changes in a step-like fashion in the vicinity of R = 9 R_E.

2. Field magnitude decreases with increasing storm activity in the region within R = 12 - 12 R_E while it increases beyond R > 12 R_E. The regression slope for storm activity changes gradually with increasing distance from the Earth in contrast to that for substorm activity.

3. The field magnitude depends negatively on the solar wind pressure within R = 10 R_E and depends positively beyond R > 10 R_E.

In the lobe region:

4. The field magnitude increases with increasing substorm and/or storm activity.

5. The field magnitude depends positively on the solar wind pressure.

6. The elevation angle of the magnetic field tends to increase with increasing storm activity in the entire range of R except in the nearest range of R.

7. The elevation angle tends to decrease with increasing storm activity in the entire range of R.

8. The elevation angle depends positively (negatively) on the solar wind pressure in the region R < 11 R_E (R > 11 R_E).

4.1. Redistribution of the Neutral Sheet Current During the Declining Phase of Auroral Electrojet

Ostapenko and Mal’tsev [1997] have shown that the Dst index has strong effect on the equatorial magnetic field of the inner magnetosphere, and that the nightside equatorial magnetic field weakens with increasing the solar wind pressure. These points are consistent with our results, points 2 and 3, respectively. On the basis of points 1 and 2, it is inferred that the aforementioned Kp dependence of the equatorial magnetic field magnitude [Fairfield et al., 1987] is attributed to a combined influence of storm activity (in the near-Earth tail region) and substorm activity (in the midmagnetotail).

Our findings provide further information useful to update magnetotail current models for different conditions of geomagnetic activity. Here we discuss what our findings mean with respect to the distribution of the tail current. Points 4 and 7 in our findings above indicate that the dawn-to-dusk currents in the magnetotail are significantly enhanced during intense storms. The correlation coefficient of Dst shown in Figure 3b decreases rather smoothly with an increase in the radial distance and is close to zero near R = 12 R_E (point 2), indicating that the magnetic field induced during geomagnetic storms even in the region beyond R = 12 R_E [Fairfield et al., 1987].

The dependence on the Al index is more distinctive than that on the Dst index. Point 4 implies that the neutral sheet current is enhanced in the entire R range during active periods in terms of the Al index. Point 1, however, indicates that the increase in the tail current does not occur uniformly but is pronounced in the near-Earth tail region, R < 9 R_E. Point 6, i.e., the lobe field elevation angle increases with increasing substorm activity in the region R > 9 R_E, may be accounted for in terms of the following three: (1) The neutral sheet current is weaker for more intense substorms, so that the contribution from the Earth's dipole field becomes relatively larger; (2) the substorm wedge current induces positive Bz inside the current wedge; (3) the radial gradient of the neutral sheet current becomes steeper. The first interpretation is not consistent with the finding that the lobe field magnitude becomes stronger for more intense substorms (point 4), and the second interpretation cannot account for the fact that the elevation angle decreases with increasing substorm activity in the nearest bin of R. Thus the third candidate, indicating the existence of enhanced westward currents in the near-Earth region, is most plausible.

A number of observations have shown that the thin neutral sheet current is formed just prior to the expansion onset of substorms in the "inset" region between the quasi-dipolar and tail-like magnetic field regions, R = 9 - 12 R_E, e.g., Sergeev et al., 1996, references therein]. The magnetic field magnitude in this region is expected to decrease with a thinning in the neutral sheet. Our statistical results, however, indicate that the equatorial magnetic field increases in the interface region with increasing auroral electrojet intensity, implying the existence of a thick neutral sheet. Thus it is inferred that an intense substorm prevents the occurrence of succeeding substorm even during periods of the southward interplanetary magnetic field. This is probably one of the important conditions which determine the characteristic time scale of the substorm occurrence [Horwits, 1985; Borovsky et al., 1993].

4.2. Phase determination

In this study we have defined the three phases on the basis of the development of the auroral electrojet: the declining/quiet, preonset, and rising phases. These classifications have been made with the perspective that data observed during these phases represent the statistical characteristics of the magnetic field configurations in the magnetotail during the traditional substorm phases, the recovery, growth, and expansion phases, respectively. A number of previous papers have attempted to determine the
phases of substorms or the basis of data both from ground and satellites observatories (e.g., Fairfield et al., 1989). It is therefore important to compare our phase determination with that in previous studies. For example, the AL variations on March 25, 1983, November 29, 1984, and January 2, 1986, are shown by solid lines in Figures 9 and 10. The substorm events on these days have been analyzed in detail by Fairfield et al. (1989), Sánchez et al. (1983), and Nakamura et al. (1994), respectively. Dashed and solid arrows indicate pseudobreakups (or initial onsets) and full-scale breakups, respectively, determined by these authors. The preonset phase, the rising phase, and the declining/quiet phase determined by our method are plotted with open circles, solid circles, and crosses, respectively.

It is noticed that time of the pseudobreakup tends to correspond to our preonset phase or late declining phase. Only one pseudobreakup, which occurred at 0614 UT on November 29, 1984, is marked at a rising phase in our classification, reflecting that this event led a small increase in the AL index. It appears that full-scale breakups occur during our rising phase. Exceptionally, however, the 0750 UT onset on March 25, 1983 is marked during the declining phase. Although the AL strength began to increase abruptly at 0705 UT, Fairfield et al. (1989) have not identified the increase as a full-scale onset. Since the AL index was contributed from the morning sector around 0705 UT, Fairfield et al., who examined the data only from the evening-midnight sector, did not recognize the 0705 UT onset. On the other hand, the increase in the auroral electrojet intensity at 0750 UT was covered by the previous enhancement, resulting in a failure to identify this onset in our methodology.

These inspections in Figures 9 and 10 indicate that full-scale onsets are successfully identified by our method. Thus it is most probable that the results of the present analysis represent the magnetic field configurations for the recovery phase of major substorms. However, our method may detect localized small intensifications not necessarily pseudobreakups associated with no remarkable enhancements in the AL index. Further, it should be cautioned that there are two cases in the intervals classified as the rising phase, i.e., the intervals which follow the preonset phase, and those not associated with the preonset phase. The former may be a major enhancement in the auroral electrojet. While the later can be a small and probably localized increase in the auroral electrojet. During intervals just before such small enhancement the magnetic field configurations might become still-like in a localized region in the magnetotail. However, since they do not probably lead to large-scale topological changes in the magnetotail magnetic field (Koskinen et al., 1993), we have not excluded those intervals from our data set for the declining/quiet phase.

It should be noted before concluding this subsection that misidentifications between the declining/quiet phase and the preonset phase might have occurred during our classification process according to the fixing of duration of the preonset phase (30 min). The regression between the tail field magnitude

![Figure 9](image)

**Figure 9.** Variations of the AL index on March 25, 1983. The declining, preonset, and rising phases are shown by plus, open circles, and solid circles. Dashed and solid arrows indicate pseudobreakups (or initial onsets) and full-scale breakups of substorms determined by Fairfield et al. (1989).

![Figure 10](image)

**Figure 10.** Same as Figure 9 except for November 29, 1984, and January 2, 1986. The onset times plotted by arrows have been determined by Sánchez et al. (1993) and Nakamura et al. (1994), respectively.
and substorm activity can be dispersed due to contamination of this kind. Actually, the change from the declining/quiet phase to the premorning phase is not clear but gradual in terms of both ground-based magnetograms and magnetic field measurements. This contamination is expected to occur more often in intense substorms during intense storms. Since periods when $D_{st} < -45$ nT and $AT < 400$ nT are not included in our data set, the influence of this contamination is expected to be minimal in the present study.

4.3. Large Scale Models of the Neutral Sheet Current

The current reconfiguration associated with the expansion onset of substorms has been studied extensively by a number of authors [e.g., Lui, 1978; Ohtani et al., 1992; Nakai and Kamide, 1994]. Most of them have mainly discussed the changes at the expansion onset of substorms, while changes during the recovery phase have been little studied. In this section we discuss the changes in the large-scale magnetic current configurations in the course of major substorms. The discussion is based on the findings in the present study with the assumption that our declining phase data set well reflects the magnetic field configurations in the magnetotail during the recovery phase of major substorms. The results of the present analysis can provide us with some quite useful restrictions in modeling the current distribution particularly for the recovery phase of substorms.

Figures 11a - 11c schematically show three different types of radial profiles of the neutral sheet current. Since the absolute values will not be discussed here, the curves are drawn by focusing on the differences in the current intensity among the three kinds of substorms. Figure 11a is based on the model proposed by Nakai and Kamide [1994, 1995] and the results of the present study. The solid and dashed lines represent approximately the statistical current profiles obtained by Nakai et al. [1991] for disturbed ($AT < -200$ nT) and quiet ($AT > 50$ nT) periods, respectively. In this model the current intensity in the near-Earth region decreases in the mid-magnetotail during the expansion phase of substorms and subsequently decreases during the recovery phase. The current is then the entire range of $X$ concerned here. The current reduction, however, is particularly evident in the near-Earth region. See Nakai et al. [1997] for the model of the substorm current system, which includes the intense westward current in the near-Earth magnetotail.

In Figures 11b and 11c the current intensity is shown to decrease in both the near-Earth and mid-magnetotail regions during the expansion phase of substorms, as suggested by the so-called current disruption model, which hypothesizes that the disruption of the neutral sheet current initiated at the near-Earth region and propagates tailward [e.g., Jacquey et al., 1991; Ohtani et al., 1992]. In Figure 11b the current intensity at the early recovery phase is assumed to be 25% weaker than that of the late recovery phase [Lui, 1978]. The currents weaken during the recovery phase in Figure 11b in the same way as in Figure 11a. In Figure 11c the tail currents laterally recover during the recovery phase particularly in the mid-magnetotail [Pulkkinen et al., 1994].

As shown Figure 7, the lobe field magnitude depends positively on substorm activity. Since data included in this graph take $D_{st}$ values from $-45$ to $-15$ nT, we have confirmed that the features are due to the residual influence of storm activity. Further dividing the data set according to $D_{st}$ values (not shown here). Thus, contrary to the model in Figure 11c, it can be concluded that the neutral sheet current decreases during the recovery phase of substorms. This conclusion appears to contradict the observations that the lobe field magnitude increases immediately following the sudden reduction of the lobe field, when the $AT$ index is increasing [e.g., Jacquey and Sauvageot, 1994]. The events in Jacquey and Sauvageot’s study were observed during highly disturbed periods ($AT < -75$ nT), during which the solar wind was continuously supplying energy to the magnetosphere. They suggested that each cross-tail current disruption was generally followed by an increase in the cross-tail current while the intensity of the auroral electrojet simultaneously decreased. This discrepancy probably results
from both the difference in the intensity of storm activity and the difficulty in defining the substorm phases during intense storms, as discussed in the previous subsection. Indeed, we have confirmed, using data for $|A_\phi| < 45$ nT, that $\Delta B_\phi$ sometimes increases, but more frequently decreases in the lobe region during the declining phase of $A_{IL}$.

Pulkkinen et al. [1994] have argued that the increase in the current intensity is essential in explaining why the magnetic field configuration often becomes more tail-like in the mid-magnetotail during the recovery phase of substorms. However, Nakai and Kamide [1994] have demonstrated that the tail-like magnetic field does not necessarily mean an increase in the current intensity and that $\Delta B_\phi$ could be associated with a decrease in the radial gradient of the current intensity. In this view, our result, i.e., the current intensity decreasing primarily in the near-Earth region, can explain the extension of field lines during the recovery phase of substorms. Thus we suggest that during moderately disturbed periods the radial profile of the neutral sheet current must change in the manner shown in Figure 11a.

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