Magnetotail Convection in Geomagnetically Active Times

1. Distance to the Neutral Lines

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The distances to the magnetic neutral lines in the magnetotail are derived from the observations of the convection in geomagnetically active times (K_p larger than 3). Observations at seven orbit segments of GEOTAIL that are distributed from $x = -36$ to $-169 R_e$ and longer than 24 hours are used. For each data set the ratio between the earthward-moving northward magnetic flux and the tailward-moving southward magnetic flux is derived. The ratio varies systematically with distance, and suggests that the distant neutral line tends to be located at about $140 R_e$ while the near-Earth neutral line tends to be formed inside $50 R_e$. Mainly the open field lines are reconnected at the distant neutral line, while mainly the closed field lines are reconnected at the near-Earth neutral line. The northward magnetic flux transported earthward from the distant neutral line is several times larger than the net southward flux transported tailward from the near-Earth neutral line; the open magnetic flux that is reconnected at the distant neutral line is substantially greater than that reconnected at the near-Earth neutral line. Observations of the field-aligned component of the flow velocity suggests that sometimes these two neutral lines exist together and produce the quasi-stagnant plasmoid.

1. Introduction

Reconnection of magnetic field lines is the fundamental process that regulates the large-scale convection in the magnetosphere. It has been considered that there are two preferred sites for the magnetic reconnection in the Earth's magnetotail. One is in the distant tail beyond the lunar orbit, and the other is in the near tail at a distance of a few tens of Earth radius (R_e). The distant neutral line is considered to be semi-permanently present, while the near-earth neutral line is thought to be a transient feature whose formation is associated with the substorm expansion phase (e.g. Hones, 1979).

An extensive survey of the distant tail beyond the lunar orbit was conducted for the first time in early 1980s by ISEE-3 spacecraft. The two parameters that reflect the site of the neutral line, that is, northward component B_z of the magnetic field and earthward component V_x of the flow velocity, were studied by Zwickl *et al.* (1984) and Slavin *et al.* (1985). From the occurrence pattern of the negative B_z , the latter concluded that the distant neutral line is curved and only its central $30 R_e$ wide portion is located inside $x = -200 R_e$. Heikkila (1988) challenged this view by showing that B_z in the neutral sheet is northward on average and contended that the neutral line is formed only in the near-Earth region of the magnetotail.

The distant tail was revisited about a decade later by GEOTAIL satellite. Its observations have shown that the magnetic field is directed northward on average even at the distances of $x = -150$ to $-210 R_e$ (Yamamoto *et al.*, 1994; Nishida *et al.*, 1994), while the average V_x of the hot plasma in the plasma sheet is directed tailward except in the $x = (0, -30) R_e$ bin closest to the Earth (Paterson and Frank, 1994). However, these observations do not necessarily contradict the presence of the neutral line on the earthward side of the spacecraft. This is because, in active times, the tailward flow tends to be faster when B_z is southward than when B_z is northward, so that there is a net tailward transport of southward field lines even if the average B_z is northward (Nishida *et al.*, 1995a). Hence the electric field E_y is directed from dawn to dusk on average in active times, although in quiet times it is dusk-to-dawn and the neutral line does not seem

to be present (Nishida *et al.*, 1995b).

Nishida *et al.* (1995a) have derived further information on the position and other characteristics of the neutral line in geomagnetically active times by comparing the flux transport by the four combinations of the B_z polarity and the $V_{\perp x}$ direction, where $V_{\perp x}$ is the x component of $V_{\perp}$ which is the component of the flow velocity perpendicular to the magnetic field, namely, the convection velocity of magnetic field lines. The four combinations are, northward B_z and earthward $V_{\perp x}$, northward B_z and tailward $V_{\perp x}$, southward B_z and tailward $V_{\perp x}$, and southward B_z and earthward $V_{\perp x}$. From the observations made at $x = -150 R_e$ and $-95 R_e$ in geomagnetically active times ($K_p \geq 3$), they have concluded that at least 75% of the reconnection of open field lines occurs inside $150 R_e$ and at least 39% occurs inside $95 R_e$, and that the reconnection rate of open field lines is a few times higher near the tail axis than at the flanks.

In this paper, which is part 1 of a set of two papers on the magnetotail convection in active times, we expand upon the above work and refine the determination of the neutral line position by using GEOTAIL observations at seven locations from $x = -36 R_e$ to $-169 R_e$ in geomagnetically active times. While the method used in the earlier paper (Nishida *et al.*, 1995a) may be influenced by the accuracy of the offset determination of B_z at the 0.1 nT level, the result obtained in this paper is more robust as it is based on the variation of the convection characteristics with distance rather than their values themselves. Part 2 of the paper (Nishida *et al.*, 1996) deals with the dawn-dusk component of the motion of magnetic field lines in the plasma sheet.

2. Data

This paper uses 12-s averages of the magnetic field obtained by the MGF experiment and 12-s moments of the ion velocity distribution function obtained by the LEP experiment on board GEOTAIL. These experiments are described in Kokubun *et al.* (1994) and Mukai *et al.* (1994). The velocity moments can be obtained by the LEP experiment with the 12-s resolution in tenuous plasma with densities down to 0.01 cm^{-3} . The electric field is derived from these by the $\mathbf{E} = -\mathbf{V} \times \mathbf{B}$ relation. The y component E_y of the electric field consists of both $V_x B_z$ representing the tailward/earthward convection of the northward/southward field lines and $-V_z B_x$ term representing the convection of the B_x component toward/away from the neutral sheet. In the magnetotail where the structure is symmetric with respect to the neutral sheet on average, these two terms are related; for example, the motion of tailward/earthward field lines in the plasma sheet boundary layer toward the neutral sheet turns into the earthward/tailward motion of northward/southward field lines in the neutral sheet. When the time variations are averaged out and the structure can be regarded as two-dimensional with much less variations in the y direction than in the x and z directions, E_y is uniform. Hence we take E_y in which the two terms are combined as the measure of the tailward/earthward convection of the northward/southward field lines.

Table 1 lists the seven intervals which constitute the present data set. These are the active intervals where the intervals with $K_p > 3$ (with only a few exceptions) lasted for 24 hours or more, and the average

Table 1. List of the active intervals.

$-x (R_e)$	$y (R_e)$	Interval (hr dy/mo/yr)	$\langle K_p \rangle$	Data points	$\langle E_y \rangle (\mu\text{V/m})$	$\langle B_z \rangle (\text{nT})$
169	20	00 26/09–12 26/09/94 00 27/09–12 27/09/94	4–	6902	104	0.35
155	8	12 09/10–24 13/10/93	4–	3277	152	0.06
126	14	00 16/07–24 16/07/94	4 ₀	6275	126	0.35
93	5	00 12/01–24 19/01/94	4–	24338	256	0.51
63	9	00 12/02–24 14/02/94	4+	6729	184	0.44
44	–2	03 02/12–03 03/12/94	4 ₀	5028	251	1.0
36	14	21 07/02–21 08/02/95	4 ₀	7107	328	2.4

Fig. 1. Projections of the GEOTAIL orbits in geomagnetically active times (with average K_p between 4- and 4+) to the Geocentric Solar Magnetospheric x-y plane in geomagnetically active times. The position of the tail axis is indicated assuming the 4.5° aberration. Times of the observation are given in month/day/year.

K_p is 4-, 4o or 4+. The last two columns show that in all cases the average E_y is positive (i.e., directed from dawn to dusk) and in the range of 0.1 to 0.3 mV/m while the average B_z is northward. The orbit segments for these intervals are illustrated in Fig. 1, and the position of the tail axis that corresponds to 4.5° aberration of the incident solar wind is indicated. The averages of x and y coordinates for each orbit segment are given in first two columns of Table 1. The x coordinates ranges from -36 to $-169 R_e$, and the y coordinates are within $15 R_e$ of the aberrated tail axis. (All the parameters in this paper are expressed in the Geocentric Solar Magnetospheric coordinate system.)

3. Position of Neutral Lines

For each interval B_z is plotted against $V_{\perp x}$, and two of these plots are shown in Fig. 2. Averages of E_y , $V_{\perp x}$ and B_z for each data set are given at top right. At $x = -169 R_e$ (panel (A)) $V_{\perp x}$ is negative for a great majority of the points, namely, the convection is directed tailward most of the time. At $x = -44 R_e$ (panel (B)) on the other hand, $V_{\perp x}$ is more often positive than negative. The difference between these two figures suggests that there tends to be a source, or sources, of earthward/tailward convection between these distances.

In order to find the position of the source, we use the properties of E_y which expresses the rate of transport of magnetic field lines. The grand total of E_y , which means the time integral of E_y , expresses the fluxes of the open field lines and products therefrom (by reconnection) that are transported tailward/earthward across the satellite over the duration of the data set. The products of reconnection are closed field lines on the earthward side of the neutral line and interplanetary field lines on its tailward side. The other closed field lines which do not originate from reconnection of open field lines would not contribute to the above grand total. This is because the same closed field line passes the satellite twice with opposite signs of E_y as it flows tailward and then returns earthward. The magnetic loops which result from reconnection of closed field lines are not included in the grand total either, since the contributions from the front part and the rear part of the loop cancel each other as they have the same magnitude but are opposite in sign. It is assumed throughout that the state of the magnetotail is kept the same (when averaged for individual disturbance events) for the duration of the data set.

The sums of E_y are calculated also for each quadrant of Fig. 2 separately, and they are written at the

Fig. 2. (A) B_z is plotted against $V_{\perp,x}$ for observations at $x \approx -169 R_e$ for a geomagnetically active interval. Averages of E_y , $V_{\perp,x}$, and B_z are given on the top right. ΣE_y given at the corners of the quadrants are explained in the text. (B) Same as Fig. 2(A) but for the observations at $x \approx -44 R_e$.

corners of the quadrants in % of the grand total. The use of the percentage means that these sums are normalized by the grand total of E_y , which differs by the data set. In the case of panel (B), 87% of the flux transport is due to earthward convection of northward field, and 57% is due to tailward convection of southward field, but 38% of the latter is canceled by tailward transport of the northward field which contributes negatively to E_y . The earthward transport of southward field has a small but positive value since the $-V_z B_x$ term dominates the $V_x B_z$ term in E_y in this case. In the case of panel (A), the flux transport due to tailward convection of southward field is as much as 220% of the grand total, but most of this is canceled by the tailward transport of northward field since roughly $151/220 = 68\%$ of the southward field is tied to the northward field by forming magnetic loops.

We now compare the net northward field that is transported earthward with the net southward field that is transported tailward. The former is given by the sum of ΣE_y in the first and the fourth quadrants, and the latter by the sum of ΣE_y in the second and the third quadrants. In the case of Fig. 2, the ratio of the former to the latter is $(24 + 7)/(220 - 151) = 0.45$ and thus less than 1 for panel (A), while it is $(87 - 6)/(57 - 38) = 4.2$ and larger than 1 for panel (B). This ratio is calculated for all seven data sets and they are plotted in Fig. 3. It is seen that the ratio takes relatively fixed values of 2 to 4 for the five data sets obtained at distances closer than about $140 R_e$, but is 0.2 to 0.4 for the other two data sets which were obtained at further distances. The former includes the data set of panel (A) and the latter the data set of panel (B). Thus there is a sharp transition around $x = -140 R_e$; inside this distance the earthward convection of the net northward field is dominant, while the tailward convection of the net southward field is dominant beyond it. The most likely nature of this transition is the occurrence of magnetic reconnection at the distant neutral line.

In the above estimate of the flux transport, the magnetic loops such as plasmoids are not counted since the transports of northern and southern field lines in the same direction have been combined. Hence the present result suggests that the open field lines are reconnected at the distant neutral line.

Next we compare ΣE_y of the first and the third quadrants. They represent the earthward transport of northward magnetic field and the tailward transport of southward magnetic field, respectively, and they

Fig. 3. The ratios between the net earthward transport of northward field lines and the net tailward transport of the southward field lines are plotted against x . The inferred position of the distant neutral line is indicated.

Fig. 4. The ratios between the earthward transport of northward field lines and the tailward transport of the southward field lines are plotted against x . The inferred positions of the distant and the near-Earth neutral lines are indicated.

contain the contribution from the magnetic loops in contrast to the net transport that was estimated earlier. The ratio between them is plotted in Fig. 4. Sharp decreases in this ratio are seen at two positions; the more distant one corresponds to the distant neutral line identified earlier, and another sharp decrease that occurs inside $50 R_e$ suggests that a source of the tailward convecting southward field is located there too. Since the corresponding decrease is not pronounced in Fig. 3, this southward field should mostly belong to the magnetic loops that are formed by reconnection of closed field lines. Thus the near-Earth neutral line is also identified by the present analysis. The inclusion of the southward field of the plasmoids has made the ratios of Fig. 4 a few times lower than the ratios in Fig. 3 except at the innermost data point at $36 R_e$.

We have used E_y as the measure of the tailward/earthward convection of the northward/southward field lines and have given reasons for that. Literally however the rate of such convection is expressed by the $V_{\perp x} B_z$ term in E_y . In order to make sure that the use of E_y has not produced misleading results we have repeated the analysis by using $V_{\perp x} B_z$ in place of E_y . The results are compared in Fig. 5 where ΣE_y (panel (A)) and $\Sigma V_{\perp x} B_z$ (panel (B)) of the first quadrant (squares), the second quadrant with the reversed sign (open circles) and the third quadrant (filled circles) are plotted against $-x$. In the $V_{\perp x} B_z$ analysis the data points satisfying $\beta_i > 0.5$ are only used, since $V_{\perp x} B_z$ tends to be small in the low β_i region away from the neutral sheet.

It is seen that the filled and the open circles corresponding to the sums for the third and the second quadrants show the similar two-step increases in both panels. These increases occur earthward of $60 R_e$ and also between 130 and $150 R_e$, and they suggest production of magnetic loops at these distances. The squares representing the sum for the first quadrant show a decrease at the latter distance range in panel (A), suggesting that the reconnection of the open field lines occurs in the 130 to $150 R_e$ range. In panel (B) this decrease is seen a few tens of R_e earthward of the above distance, but the size of the data set satisfying $\beta_i > 0.5$ is very small at the critical distance of $126 R_e$. Otherwise the squares in both panels show similar trends, except at a single point at $36 R_e$ which is the closest to the Earth in the present data sets. At this distance the open circle is located higher than the closed one in panel (B). This means that the tailward convection transports a greater flux of the northward field than of the southward field, and may

Fig. 5. Comparison of the two measures, namely E_y and $V_{\perp,x}B_z$, of the tailward/earthward transport of the northward/southward field lines. Panel (A) is for E_y and panel (B) is for $V_{\perp,x}B_z$. Sums of either of these in the first quadrant (characterized by earthward transport of northward field), the third quadrant (tailward transport of southward field), and the second quadrant (tailward transport of northward field) with the sign reversed are plotted with squares, filled circles, and open circles, respectively, against $-x$.

suggest that the tailward transport of the closed field lines by the viscous-like force becomes substantial inside about $40 R_e$. The effect of such transport could stand out more clearly in the $V_{\perp,x}B_z$ analysis where the data from the plasma sheet tends to be given a greater weight.

Figure 5, panel (A) provides additional information on the convection in active times. Earthward of about $140 R_e$ the squares tend to be well above the 50% line and are often in the range of 80 to 90%. This means that the earthward transport of the northward field from the distant neutral line is several times greater than the net tailward transport of the southward field from the near-Earth neutral line; substantially more open field lines are reconnected at the distant neutral line than at the near-Earth neutral line. The dominance of the earthward transport of the northward field over the net tailward transport of the southward field is seen also in panel (B).

Since the coverage of the present data set is limited to tailward of $36 R_e$, examination of the data obtained at closer distances is needed to further specify the distribution of the position of the near-Earth neutral line and to examine the contribution of the convection of the closed field lines generated by the viscous-like force.

4. Comparison with $V_{\parallel,x}$ Observations

In the previous section we have derived the positions of the neutral lines by examining the statistical properties of E_y or $V_{\perp,x}B_z$. These are the parameters that characterize the convection of the magnetic field lines that are frozen in the plasma. The parallel component $V_{\parallel,x}$ is not directly involved in the convection, but the mechanism that drives convection should affect $V_{\parallel}$ as well.

Figure 6 examines $V_{\parallel,x}$ for the observations at $x = -169 R_e$ where $V_{\perp,x}$ is directed tailward most of the time (see Fig. 2(A)). The horizontal axis is the ion beta β_i , and the vertical axes are $V_{\parallel,x}$ (top), $V_{\parallel,x}/V_{\text{thermal}}$ (middle), and ion temperature (bottom), respectively. The parameter $V_{\parallel,x}/V_{\text{thermal}}$ in the middle panel is a measure of the beam character of the field-aligned flow. Although the ion distribution function often departs significantly from the shifted Maxwellian (e.g. Hirahara *et al.*, 1994; Machida *et al.*, 1994), V_{thermal} gives a measure of the spread of the distribution function. $V_{\parallel,x}$ in the top panel is directed tailward for a great majority of the points. This is the same direction as that of $V_{\perp,x}$ for the same data set, but there seem to be two populations of the ions. In the higher β_i range ($\beta_i > 1$) there are hot ions whose $V_{\parallel,x}$ is tailward but highly scattered, while in the lower β_i range ($\beta_i < 0.1$) there is a cold ion population whose $V_{\parallel,x}$ varies systematically with β_i . In the intermediate β_i range both populations can occur.

For the high β_i population that constitutes the plasma sheet, the observation that $V_{\parallel,x}$ is tailward with few exceptions is consistent with the tailward acceleration of the ions in the reconnection region on the earthward side of the spacecraft. As for the lower β_i population, it belongs to the boundary regions with the lobe and with the magnetosheath, and is often beam-like as expressed by $V_{\parallel,x}/V_{\text{thermal}}$ of about 1 or larger. The nature and the driving process of these ions are discussed in other papers (e.g. Hirahara *et al.*, 1994, 1996).

Figure 7 shows the character of $V_{\parallel,x}$ for another data set obtained at $x = -44 R_e$. Since both earthward and tailward $V_{\perp,x}$ are observed at this distance (see Fig. 2(B)), the plots are made separately for the cases of the earthward and tailward $V_{\perp,x}$. In the top panel for the earthward $V_{\perp,x}$, $V_{\parallel,x}$ of the high β_i component is directed earthward in most cases so that $V_{\perp,x}$ and $V_{\parallel,x}$ can be attributed to the same source region, that is, to the reconnection region that is located tailward of the spacecraft. In the middle panel for the tailward $V_{\perp,x}$, however, there is a substantial number of points at the intermediate β_i range (0.1 to 1) where $V_{\parallel,x}$ is earthward and is thus directed opposite to $V_{\perp,x}$. These points are associated with relatively small values of $|V_{\perp,x}|$ so that they become much less frequent in the bottom panel which shows only the data points with the tailward $V_{\perp,x}$ faster than 20 km/s.

A possible reason for the association of the earthward $V_{\parallel,x}$ with the tailward $V_{\perp,x}$ when the latter is very slow is the formation of the stagnant plasmoid (Fig. 8). In the early stage of development of the reconnection at the near-Earth neutral line, the distant neutral line can still exist and the tailward $V_{\perp,x}$ generated at the near-Earth neutral line can be blocked by the magnetic tension of the closed field lines

Fig. 6. $V_{\parallel,x}$ (top), $V_{\parallel,x}/V_{\text{thermal}}$ (middle), and the ion temperature (bottom) are plotted against β of ions for the data set obtained at $x \approx -169 R_e$.

Fig. 7. $V_{\parallel,x}$ is plotted against the ion β for subsets of the data obtained at $x \approx -44 R_e$. Top: for the cases of the earthward convection ($V_{\perp,x} > 0$), middle: for the cases of the tailward convection ($V_{\perp,x} < 0$), and bottom: also for the cases of the tailward convection but faster than 20 km/s.

Fig. 8. Configuration of the field lines when two neutral lines coexist and the plasmoid is stagnant. The separatrixes are drawn with dashed lines.

Fig. 9. Anti-correlation between the field-aligned velocity $V_{\parallel,z}$ and the convection velocity $V_{\perp,z}$ in the z direction.

that exist on the earthward side of the distant neutral line. The earthward convection generated at the distant neutral line would also impede the development of the tailward convection. Hence the plasmoid would move only very slowly during this stage. The signatures of the quasi-stagnant plasmoid has been found in previous observations (Nishida *et al.*, 1986; Kawano *et al.*, 1994). The earthward and the tailward field-aligned flows from the two neutral lines need not compete against each other, since the separatrix defined by the distant neutral line is outside the separatrix of the near-Earth neutral line. For the cases of $V_{\perp,x} < -20$ km/s and $V_{\parallel,x} > 50$ km/s included in the data set of Fig. 7, both positive and negative B_z are observed almost equally (namely, $B_z = -0.1 \pm 2.2$ nT) in agreement with this conjecture. Case studies of individual events are needed to further confirm this interpretation.

The tailward beam of cold ions is seen in both earthward and tailward $V_{\perp,x}$ cases of Fig. 7, but at this

Fig. 10. In the plasma sheet, z components of the field-line motion (open arrows) and of the field-aligned flow (solid arrows) cancel each other and the net velocity (dashed arrows) tends to be parallel to the neutral sheet.

distance which is about $120 R_e$ earthward of the other example the cold ion beam is seen only in the region of very low β_i (< 0.01) and has not penetrated into the plasma sheet.

The z component of $V_{\parallel}$ is compared with the same component of $V_{\perp}$ in Fig. 9. The data set obtained at $x = -95 R_e$ which has by far the largest number of data is used. Both earthward and tailward $V_{\perp,x}$ cases are plotted together, but only the data of the plasma sheet ($\beta_i > 0.5$) is used. It is seen that there is a high degree of anti-correlation between $V_{\parallel,z}$ and $V_{\perp,z}$, and the regression coefficients is almost -1 . This means that, in the z direction which is perpendicular to the neutral sheet, the velocity of the field line motion toward the neutral sheet and the velocity of the field-aligned flow away from the neutral sheet essentially cancel each other. As illustrated in Fig. 10 the resulting net velocity vector is parallel to the neutral sheet. This character of the z component of the flow is consistent with the presence of a pair of shocks at the plasma sheet boundary where the flow direction is changed sharply and becomes parallel to the neutral sheet.

5. Discussion and Conclusions

The results given in Figs. 3 and 4 clearly show that in active intervals the distant neutral line and near-Earth neutral line are formed as separate entities. The distant neutral line is located mostly at a distance of about $140 R_e$, while the near-Earth neutral line is located earthward of about $50 R_e$. Thus the two neutral line positions are about $100 R_e$ apart. It seems that the field lines reconnected at the distant neutral line are mostly open ones, while those reconnected at the near-Earth neutral line involve closed field lines. Several times more open field lines are reconnected at the distant neutral line than at the near-Earth neutral line, when integrated for active periods longer than one day. The distinction between the two neutral lines confirms the earlier finding that the formation of the near-Earth neutral line is not due to earthward shift of the distant neutral line (Nishida *et al.*, 1988). The observed directions of $V_{\parallel,x}$ of the hot ions in the plasma sheet suggest that sometimes the two neutral lines coexist and the quasi-stagnant plasmoid is formed. In the distant plasma sheet $V_{\parallel,z}$ and $V_{\perp,z}$ tend to cancel each other and the total (i.e., convective plus field-aligned) flow velocity vector is parallel to the neutral sheet.

The present analysis which is statistical does not rule out the possibility that the neutral lines can sometimes be located at distances that are quite different from those obtained above. There was a case of the earthward flow observed by ISEE 3 at $x \sim -220 R_e$ which Schindler *et al.* (1989) interpreted in terms of temporary shift of the distant neutral line from its normal position of $x \sim -140 R_e$. GEOTAIL has also observed such instances.

An offset of a few times of 0.1 nT may remain in B_z since the spin axis of GEOTAIL is close to the z direction. The method used in this paper is immune to the resulting uncertainty as it relies upon the

variation in the ratio of the earthward/tailward transports rather than the value of the ratio itself. Any small offset in B_z would increase or decrease the ratios for all the data sets in the same manner and preserve the sharp changes that reflect the positions of the neutral lines. The method used in the previous paper (Nishida *et al.*, 1995a) was liable to be affected by the B_z offset, but a better method could be used in the present paper since several more data sets had since become available that represent the convection characteristics over a wide range of distances.

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