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Neutral Sheet Crossings in the Distant Magnetotail

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Abstract. We have analyzed the magnetic field data from ISEE-3 in the distant magnetotail for 18 crossings of the cross-tail current sheet (or so-called neutral sheet) to determine the direction of the normal component B_z. The crossings occurred near the middle of the aberrated magnetotail ($0 < y < 30$ R_e, $-10 < z < 5$) in GSM coordinates, at a distance of about 220 R_e, January 28 to February 12, 1983; in each case the plasma flow velocity was tailward. In 2 cases we found B_z negative (southward), as would be required with a magnetic neutral line (reconnection line) earthward of the spacecraft. In 12 cases B_z was clearly northward ($B_z > 0.4$ nT), consistent with closed field lines connected to the earth. In 3 cases B_z was very close to zero; in several instances there was structure in B_y, suggesting localized currents with x or z directions. One may have been a magnetopause crossing. The strong preponderance of northward B_z favors a model of the magnetotail which is dominated by boundary layer plasma, flowing tailward on closed magnetic field lines, which requires the existence of an electric field in the sense from dusk to dawn. Since the observed flow was usually less than the magnetosheath flow speed, these observations are consistent with the idea that magnetospheric processes are powered by a boundary layer dynamo; this is a form of viscous interaction first proposed by Axford and Hines. The steady state reconnection model of Dungey is not supported by these observations.

INTRODUCTION

The presence of an extended magnetotail at all times has had considerable influence on our concepts of the plasma physics of the magnetosphere. Many workers (see the reviews by Cowley, 1980; 1982; 1983; 1984a, b) believe that models based on the reconnection process (Dungey, 1961) are supported by the observations, especially now that ISEE-3 has accomplished its Geotail Mission (see the special issue of Geophysical Research Letters, 11, October, 1984). In particular, the z-component (in GSM coordinates) of the magnetic field beyond 200 R_e was reported to be slightly negative (pointing southward), implying that the steady state reconnection line, or X-line, was inside of that distance (Tsurutani et al., 1984). Perhaps the most convincing evidence has been the observation (Zwickl et al., 1984) that the plasma velocity was always tailward at the greatest distances (more than 97% of the time when the spacecraft was in the magnetotail at $x < -180\ R_e$). With the usual dawn-dusk electric field across the magnetosphere, the magnetic field would have a southward component so that the plasma velocity $\underline{V} = \underline{E} \times \underline{B}/B^2$ would be tailward. Zwickl et al. (1974) concluded that the X-line was ". . . usually within 120 R_e of earth, and rarely beyond 180 R_e." Slavin et al. (1985), using 5-minute average values of the data in boxes 10 R_e in the x and y directions, concluded that the reconnection line was curved (see their Figure 20 and our Figure 1a), supporting a prediction made earlier by Russell (1977). They found weak southward B_z from y(GSM) = 0 to 30 R_e, at $-180 < x < -225\ R_e$, in the central part of the aberrated magnetotail (aberration of approximately 4° because of the earth's orbital velocity).

On either side of this interval Slavin et al. (1985) found northward B_z (see their Figure 12 and our Figure 1a). Since the plasma velocity was tailward, this finding implies that the convection electric field was directed from dusk-to-dawn (see also Heikkila, this meeting in the Dialog on the Phenomenological Model of Substorms in the Magnetotail). This sense is opposite to the dawn-dusk electric field in the plasma sheet closer to earth for earthward convection, or the region of the deduced interplanetary magnetic field (IMF) lines for tailward convection in the distant tail. However, it is in the same sense (Eastman et al., 1976; 1979; Heikkila, 1979; Rostoker, 1984; Lundin and Dubinin, 1985; Lundin and Evans, 1985) as the electric field in the low latitude magnetospheric boundary layer (LLBL). Consequently, it is tempting to conclude that the broad regions (≈15 R_e) on the flanks of the distant magnetotail are a continuation and enlargement of the LLBL closer to the earth. This conclusion is reinforced by the quantitative statistical result that the average electrostatic potential is the same, namely about 20 kV for both the dawn and dusk layers (Heikkila, 1986a; also Dialog this meeting).

The early statistical studies of the ISEE-3 observations are also difficult to reconcile with Villante's (1976; 1977) analysis of Pioneer 7 data obtained in September, 1966, at the still greater distance of 1000 R_e. In a detailed study of 14 magnetic field reversals (neutral sheet crossings), Villante found an average northward B_z of 1.5 nT. Cowley (1984a) has dismissed this result, saying that it is "considerably at odds with expectations". However, Cowley apparently had only the reconnection model in mind in reaching his negative conclusion; Villante's result is in excellent agreement with a model in which the LLBL is assumed to dominate the physics of the magnetotail (Heikkila 1979; 1983; 1984a, b). In this model it is a reversal of the electric field (rather than the magnetic field) that is associated with tailward flow in the distant magnetotail (Heikkila, 1984b).

It is true that a number of difficulties and uncertainties can indeed occur in the interpretation of the data; some of these have been discussed by Heikkila et al. (1985). There is usually a flapping motion of the tail, as indicated by the large standard deviation (B_z = −0.22 ± 1.29 nT at x = −200 R_e in the work of Slavin et al., 1985). The B_x component introduces "false" B_y and B_z components by its tilt, as can be seen for B_z in Figure 1(b) within the dashed box; it is expected that this false B_z component will be reduced by averaging over sufficiently long times. That such flapping motion does occur is shown by the fact that ISEE-3 entered the magnetosheath on almost every day when it was within the nominal magnetotail.

Still another difficulty is the presence of localized structure, turbulence, and wave activity. These often occur in association with magnetic islands, or plasmoids (Baker et al., 1984; Hones et al., 1984a,b), when a new reconnection line is created (shown by X' in Figure 1(b)). These are transient features, associated with substorms, which can occur several times a day during periods of intense geomagnetic and auroral activity. In this case, the X-line is not across the entire magnetotail, but is internal to it, connected to an O-line (O' in Figure 1(b)). Such short-lived events may be produced by very different physical processes, and should not be included in an analysis of steady state features.

What really matters for the reconnection models is the sense in which the magnetic field crosses through the neutral sheet, and not so much its orientation within the lobes, which can be affected by the flapping motion. The spacecraft was at its apogee tailward of the deduced curved X-line only for about 2 weeks (January 28 to February 12, 1983), and unusual solar wind conditions may have affected the result. In addition, a lumpy structure as shown in Figure 1(c), perhaps caused by a filamentation of the cross-tail current, might show negative B_z with long term averaging, together with inadequate sampling. Finally, the level of geomagnetic activity may have an effect, as negative values do occur when plasmoids (magnetic islands) are present (Baker et al., 1984). Such difficulties and complications can be avoided by concentrating attention on the magnetic field exactly at the field reversal (or the so-called neutral sheet) region.

Here a complication could arise since B_y may also have a characteristic change at the same time. If, however, the field changes all occur in a constant (inclined) plane, then it may be possible to find a new coordinate system in which one component (essentially the cross-tail B_y component) is negligible, and to follow changes in the other two when the primary field reverses; thus if $B'_y = 0$, and $B'_x = 0$ at the reversal, then the field has only the one component, an adjusted B'_z, where the primes denote values in this slightly inclined coordinate system. This can be accomplished by doing a minimum variance analysis, and is what Villante (1976) did with the Pioneer 7 data.

It is the purpose of the present paper to analyze the ISEE-3 data with similar methods, using high resolution data, in order to resolve this controversy. The total amount of data produced by ISEE-3 in the distant magnetotail is enormous, and in this first analysis we will focus our attention on the central part of the tail when the spacecraft was tailward of the curved X-line as deduced by Slavin et al. (1985). The actual event locations that were analyzed are shown in Fig. 1(a).

ISEE-3 MEASUREMENTS

We have used data from the Jet Propulsion Laboratory vector helium magnetometer on ISEE-3 (Frandsen et al., 1978), as well as the Los Alamos National Laboratory plasma analyzer (Bame et al., 1978). The magnetometer makes 6 measurements per second, with negligible drift; these can be averaged for the kind of temporal resolution required, commonly 1s, 3s, 1 minute, 5 minute, or 1 hour. The plasma instrument performs a 3 second electron measurement with 16 energy sweeps repeated every 84 seconds. A detailed discussion of the methods used to derive plasma bulk parameters from the electron measurements and their limitations is found in Zwickl et al. (1984). These parameters are the bulk density, temperature, flow speed and direction.

As has been pointed out before (Zwickl et al., 1984; Slavin et al., 1985), we do need to look at both kinds of data in order to identify correctly the various regions; this we have done for all the events analyzed in this paper. A sample of representative data is shown in Figure 2, 3, and 4 for a one hour period on 5 February, 1983. Geomagnetic activity was rather high with Kp = 6 (Σ kp = 57 for this day). The magnetic record in Figure 2 shows a slightly variable field from 1500 to 1510 UT, followed by a more tail-like field up to 1510 UT of slightly increased magnitude. At the beginning of the interval the plasma was observed to have uniform constant properties, such as density N = 3 cm^{-3}, electron temperature T = 2.5×10^5 K (22 eV), and a tailward (look angle ϕ = 0°) velocity V = 700 km/s (rather high but verified by IMP-8). The electron fluxes in Figure 4 show an enhancement in counting rates in line with the sun pulse at the lowest energies upon which the magnitude and direction of the velocity in Figure 3 was based; we also note counterstreaming flow in Figure 4, perhaps a result of mirroring of the electrons at the higher magnetic field strength nearer the earth on open or interplanetary field lines (see Bame et al., 1983; Baker et al., 1986). These plasma properties are characteristic of the magnetosheath, and it is virtually certain that the spacecraft was in the magnetosheath until 15:10 UT. The magnetic field had the garden hose orientation in a toward-sector, with a sizable southward component; however, it may be influenced by draping around the magnetopause.

At 15:10 UT some changes are noted in B_x and B_y. At the same time there are slight changes in the plasma properties, Figure 3 showing a slightly decreased density and velocity. The individual sweeps in Figure 4 show a slight reduction in flux, especially at the lowest energies, tailward streaming at the lowest energies, and again some counterstreaming at the higher energies. The decrease in density and velocity suggest that the spacecraft was in the magnetospheric boundary layer at this time. It may be in the dusk side boundary layer, since B_y is negative with B_x positive. Unfortunately, the computed tail region signature at the bottom of Figure 3 does not include any indicator for the boundary layer.

Suddenly, at 15:17:14 UT, the plasma is considerably energiz d; by comparison with data shown by Hones et al. (1984, their Figure 4), we recognize the signature of a plasmoid. The magnetic record confirms this, with B_z going strongly positive followed by negative values for 6 or 7 minutes. We state again that we want to avoid transient effects such as plasmoids in our effort to analyze steady state features.

After a photoelectron measurement at 1520 UT, the next sweep four minutes later indicates a high plasma density with magnetosheath-like characteristics, a feature continued for the next 18 minutes. The magnitude of the magnetic field suggests the magnetosheath again; however, the peculiar PHI trace (e.g. the repeated 180° swings at 1532 and 1534 UT suggest some ordering, perhaps by the magnetopause current. Perhaps the spacecraft was in a region of magnetosheath plasma entry as proposed by Gosling et al. (1984) and Baker et al. (1986). Thus, we propose that the spacecraft was wandering in the magnetopause/lobe/boundary layer regions during this period of 18 minutes. A single set of sweeps beginning at 15:42:25 UT shows a still higher density, lower temperature, and higher velocity, and the spacecraft now appears to be clearly in the magnetosheath; the magnitude of the field is lower, in conformity with this identification.

After another magnetopause crossing at 15:43:30 UT the spacecraft again enters a low density region. The flow speed and direction indicators are erratic (because of the low counting rates), but still counterstreaming appears to be present. Within this region there is a crossing from the southern lobe into the northern lobe at 15:55:50 UT that appears to be at a uniform speed, judging by the smooth B_x record. This is the kind of crossing we wish to analyze.

We note that at the precise moment of the field reversal when $B_x = 0$, and the magnitude $|B|$ was very small, the component B_z has a sharp positive peak. It is slightly negative on either side, when B_x is over 10 nT, corresponding to a slight tilt as in Figure 1(c). We also note that a longer term average (e.g. 5 minutes) might show a negative result for the interval 1555-1600 UT, whereas at the crossing B_z was strongly positive. Many models have assumed that B_z is constant across the neutral sheet, but this crossing shows this assumption may not be accurate.

There is also a characteristic change in B_y at the same time. A minimum variance analysis of the magnetometer data (Figure 5) has been done for this field reversal region (see also Table 1 and Figure 3 of Heikkila et al., 1985); we used the method of Siscoe et al. (1968) in which one component is assumed to be negligible, so the change occurs through rotation in a constant plane. (We have also used Sonnerup and Cahill's (1967) method, which does allow a finite normal component, with essentially the same results.) In this case B3 is the minimum variance direction, and we identify B3 with B'_y since the rotation was only about 30° (Heikkila et al., 1985); the average value of B3 near the crossing was 0.4 nT, and showed only small variability. The maximum variance direction is B1 (i.e., the earthward component). The normal component B2 (a modified B'_z) is indeed positive, as shown by the hodogram track remaining above zero in the hodogram as B1 reverses, being 3.7 nT at the reversal of B1. Therefore, this neutral sheet crossing is clearly earthward of the X-line, not tailward as implied by Slavin et al. (1985).

Figure 6 presents a hodogram for another crossing, that at 01:46:27 UT on January 28. The main difference between the two is that Figure 6 shows more wave activity than Figure 5. The plot of B3 vs B2 indicates a wave of circular polarization (with a period of about one minute, as deduced from the recorded data). It is likely that the observed value of the B_z component at the crossing of -0.1 nT should be increased to B'_Z = +0.5 nT for a measure of the true normal component, as an allowance for the wave activity. By the same token, B_Z for the crossing on 5 February should be reduced to B'_Z = 2.0 nT. These qualitative corrections are listed under B'_Z in Table 1.

The next crossing at 02:09:40 shows that the amplitude of the waves can be small (Figure 7). However, most of the crossings that we have analyzed showed appreciable wave activity, and also the characteristic W pattern exemplified by Figure 5.

Actually, we have found that the record of the magnetic field is often sufficient to recover the sign of B_z in the neutral sheet. For example, on February 10 at 21:20 UT (Fig. 8) the spacecraft dipped into the neutral sheet for about 5 minutes, and again at 22:35, 23:30 and 23:45 UT, with actual crossings at 23:42 and 23:50 UT. Each time the B_z component increased when the magnitude $|B|$ decreased to low values. This fact underscores the weakness in trying to estimate B_z from its value away from the field reversal region. The plasma data for this interval are shown in Figure 8(b). When the density was low (N = 0.1 cm^{-3}) the flow speed V was small; at higher densities (N = 0.5 cm^{-3}), V was higher, 200-400 km s^{-1}. The direction was tailward throughout, but modified B'_z) is indeed positive, as shown by the hodogram track remaining above zero in the hodogram as B1 reverses, being 3.7 nT at the reversal of B1. Therefore, this neutral sheet crossing is clearly earthward of the X-line, not tailward as implied by Slavin et al. (1985).

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We have studied the magnetic record, using 1 minute averages as well as 3 second averages for the two weeks in the central magnetotail tailward of the hypothesized curved X-line. Time and again, we have found the behavior exemplified by Figure 8 (see also Fig. 9).

Nevertheless, there are a few cases when B_z was negative at the neutral sheet crossing when apparently plasmoids were not present. Of the 18 cases we studied in this time interval, we have found only two such cases. One was the crossing on January 30 at 9:52:14 UT (Fig. 9) (but note that there are several cases when $B_Z > 0$ when $|B| < 2$ nT in this record). The hodogram (Fig. 10) shows a clearly negative B_z (= B_z), with some small wave activity present. Fig. 11 shows heating 20 s after the neutral sheet crossing when the magnitude at the crossing was 3 Nt, mostly because of the sizeable B_y component. In view of the high activity during this period (Kp = 3+), we suspect that a small plasmoid may be present.

The other event when B_z was negative was on February 2 at 22:22:56 UT. Figure 12 displays the hodogram; we feel that the instantaneous measurement of $B_z = -0.6$nT should be increased to +0.5 nT as an allowance for the wave activity. Figure 13 displays the individual sweeps of the plasma instrument; again, there is strong heating for one set of sweeps, exactly when the magnitude was approaching its minimum value (see Fig. 14). In this case, it could be argued that wave activity has influenced the result. Alternatively, a plasmoid may have been present.

We present the results of the minimum variance analysis of 18 neutral sheet crossings in Table 1. Twelve of the crossings show B_z clearly positive (B_z >

[illegible] nT). In two other cases, [illegible] allowance is made for the wave activity. One case was very close to zero, and another was possibly a magnetopause crossing, and should be excluded. Only one (or possibly two) showed that B_z was clearly negative, consistent with an X-line earthward of the spacecraft.

In addition, a perusal of the magnetic recordings, with 3 s and 1 m averaging, showed a consistent increase of B_z to positive values as the magnitude of the field decreased below 2 nT.

Consequently, we estimate that the average value of B_z at $x = -220\ R_e$ was $B_z \sim 1.1$ nT.

Conclusions

Our findings suggest the following conclusion:

(1) The component B_Z normal to the neutral sheet (or field reversal region) points decisively northward in 12 out of 17 cases (70%).

(2) This component was largest at the actual crossing, and became smaller on either side.

(3) B_Z was negative in one, or perhaps 2, of the crossings.

(4) B_Z was very close to zero in 3 cases.

(5) Average uncorrected B_Z = 1.1 nT.

(6) Average $B'_Z \approx 0.8$ nT, corrected for wave activity (by eye).

(7) There was usually wave activity present, suggesting waves travelling along the magnetic field with circular polarization.

Discussion

It is generally a good idea (in some cases a necessity) to hypothesize a model based on fundamental physical principles in approaching a new problem, especially if the total amount of data available is very limited in quantity or quality. Such is the case for the magnetosphere, where measurements are usually made on only a relatively few moving spacecraft. It goes without saying that any model must be falsifiable on the basis of observational evidence.

One such model is provided by the idea, or process, of magnetic reconnection pioneered by Dungey (1961); Cowley (1980) has given a remarkably clear qualitative explanation of it. This idea seems to be especially clear for a southward interplanetary magnetic field (IMF). A key feature is a magnetospheric electric field which always points from dawn-to-dusk (see Figure 1 and 8 of Cowley, 1980). The magnetic field forms steady state X-lines, or reconnection lines, one in the sub-solar magnetopause, the other in the magnetotail. The merging rate at each X-line is dependent on the magnitude of this electric field along it. The convection velocity, $\underline{V}_E = \underline{E} \times \underline{B}/B^2$, depends on this topology of the magnetic and electric fields; it is earthward on the earthward side of the X-line in the tail, but tailward on the opposite side. Thus, when the ISEE-3 data at the distant apogee showed tailward convection in all plasma regimes (lobe, boundary layer, and plasma sheet) it was natural to conclude that the steady state X-line was earthward of the apogee (Zwickl et al., 1984).

However, the low latitude boundary layer (LLBL) just inside the magnetopause seem to have been overlooked in the analysis carried out thus far. This LLBL provides a form of viscous interaction, in a totally different model of the magnetosphere first proposed by Axford and Hines (1961). Figure 15 is based on their ideas, but with the addition of a magnetospheric boundary layer.

Two important recent findings now enter the picture. One is the conclusion that the low latitude boundary layer (LLBL) closer to the earth is polarized to tens of kilovolts (Foster, 1984; Eastman et al. 1985; Lundin and Dubinin, 1985; Lundin and Evans, 1985; Heikkila, 1986). The same is true of the distant tail (Heikkila, this meeting on Dialog on the phenomenological model of substorms in the magnetotail). Slavin et al. (1985) did note that the plasma flow was tailward everywhere at the distant apogee of 220 R_e, in marked contrast to the reconnection model, according to which it should have been earthward on the earthward side of the X-line. In particular, the flow was tailward in the broad regions on the flanks where B_z was directed northward. This requires that the electric field was directed from dusk-to-dawn, and we identify it as the boundary layer. The data in the article by Slavin et al. (1985) allow the calculation of the potential difference due to the LLBL, and Heikkila (Dialog this meeting) deduced 40 kV for the dawn and dusk boundary layers combined. This leaves only about 20 kV that might be due to reconnection, out of an observed 50-60 kV on average across the polar cap.

Slavin et al. (this meeting) have now found that at low levels of geomagnetic activity (AL < 100 nT), the direction of B_z was northward across the entire magnetotail at 200 R_e. Since the flow was still tailward, they have concluded that "the low latitude boundary layer extended across the full width of the quiet-time plama sheet." This feature of the magnetotail was predicted by Heikkila (1983, 1984a, 1984b). According to this model, the plasma sheet closer to the earth is a small cavity filled with low density plasma with earthward convection and energization, engulfed by boundary layer plasma flowing tailward. The number flux of ions in the LLBL is quite high ($\approx 10^{27}$ s^{-1}), according to a comment by Heikkila (this meeting). It has adequate power to maintain earthward convection in the plasma sheet, to generate Birkeland currents, and to produce auroras.

Our present study has concentrated on B_z during the two weeks when ISEE-3 was tailward of the curved X-line deduced by Slavin et al. (1985), a period when considerable geomagnetic activity occurred, but also with some quiet periods. We have found that B_z was clearly northward most of the time. This finding negates (falsifies) the presumed existence of the curved X-line at all times, and along with it the hypothesized importance of steady state reconnection. Instead, it bolsters the notion that tailward boundary layer flow is the primary agent for plasma sheet processes, including auroral phenomena. Transient processes, including magnetic merging or reconnection (but with curl E ≠ 0) can produce plasmoids, a totally different phenomenon (Heikkila, 1984b; Heikkila and Pellinen, 1984; Heikkila and Treilhou, 1984; Heikkila, Dialog this meeting).

A crucial question now centers on the process of entry of solar wind plasma through the magnetopause, and its exit at large distances downtail. Most of this plasma cannot return (there is too much to be returned via the plasma sheet, and its momentum is too great), implying that frozen field convection of magnetic flux in the magnetotail must somehow be violated. The circulation that produces viscous interaction is not cyclic (as proposed by Cowley, 1982), but rather open-ended. This point has been addressed by Heikkila (1986b), who concludes that it is meaningless to apply the frozen field condition within the thin magnetopause. What really matters is what the plasma particles do, and apparently they are able to cross the magnetopause into the LLBL (on closed field lines) quite easily, to produce a new MHD inside. The magnetopause should be regarded as a sink of magnetic flux on one side and a source on the other; frozen flux tubes have no meaning in the thin magnetopause. In this scheme, there is no requirement for a return convection of magnetic flux in the magnetotail, any more than a return flow of all the plasma in the LLBL.

In summary, we have found that in the vast majority of the neutral sheet crossings (under quiet conditions when there were apparently no plasmoids) the component of the magnetic field normal to the neutral sheet was positive, pointing towards the northern lobe of the magnetotail. This result poses considerable difficulty for models of the magnetotail in which it is assumed that a steady state reconnection line, or X-line, stretches across from dawn to dusk at moderate distances down the tail. These data from ISEE-3, as well as the earlier data from Pioneer 7 and 8 are consistent with a model of the magnetotail which is dominated by boundary layer plasma.

Thus, it appears to be a reversal of the electric field, and not the magnetic field, that explains the tailward flow at these locations far downtail. The driving force for magnetospheric convection, including the plasma sheet, and the creation of auroras is, in this model, the boundary layer flow. This is a form of viscous interaction, as first proposed by Axford and Hines (1961). In this model, the night-side X-line is at the distant magnetopause (somewhere to the far right in Figure 15), the latter being assumed to be a closed surface, not an open surface as assumed by Cowley (1980).

Perhaps it is possible that both processes (reconnection as well as viscous interaction) can operate at certain times, or certain locations (as has been suggested before, e.g. Cowley, 1983); however, such a combination has yet to be elucidated (what happens to the X-line in the boundary layer?). Whatever the true answer is, it must be in agreement with our present result, namely that we have found a persistent northward B_z where all previous interpretations have suggested that only southward B_z should be present.

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