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Field-Aligned Currents Near the Magnetosphere Boundary

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Abstract

This paper reviews present thinking about the structure of magnetospheric boundary layers and their roles in the generation of the field-aligned currents that are observed in the polar regions. A principal effect of the momentum loss by magnetosheath plasma to the magnetosphere boundary regions just within the magnetopause, whether it be by a diffusive process or by magnetic reconnection, is the tailward pulling of surface flux tubes relative to those deeper below the surface. The dayside region 1 currents at low altitudes flow along field lines in the resulting regions of magnetic shear. The direction of the shear and its magnitude, measured in the boundary region, confirm that the polarities and intensities of the dayside region 1 currents can be accounted for by this process. The low latitude boundary layer, formerly thought to be threaded entirely by closed field lines, now appears to contain at least some open field lines, newly reconnected, that are in the process of being swept into the high latitude tail to form the plasma mantle. The open flux tubes of the flux transfer events, thought to be the product of "patchy reconnection" have a spiral magnetic structure whose helicity is such as to suggest currents having the polarities of the region 1 currents.

Introduction

The primary interaction of magnetosheath plasma with the magnetosphere is reflected in a boundary region hundreds to thousands of kilometers thick that lies just within the magnetopause (see Figure 1a). This boundary region is characterized by plasma, having density, temperature, and flow properties similar to those of the magnetosheath, but threaded by earth-tied magnetic field lines. While it is essentially continuous over the surface of the magnetosphere the boundary region is thought to consist of two major parts that can be recognized to some extent by differences in their observed properties but that are differentiated more clearly in the concepts of their means of formation. The first of these, the low latitude boundary layer (LLBL), covers the sunward surface of the magnetosphere generally equatorward of the polar cusps and extends, at low to moderate latitudes, to some unknown distance (perhaps 50-100 R_E) along the dawn and dusk flanks of the magnetotail. It is thought to contain closed magnetic field lines onto which magnetosheath plasma has penetrated by a diffusive process. It is often identified with the outermost region of the Axford-Hines (1961) model where magnetospheric plasma was set into motion by momentum transferred from the solar wind through a "viscous-like" interaction. The second part, the plasma mantle, covers the higher latitude surfaces of the magnetosphere from the polar cusps back to very large distances along the tail. It is thought to contain field lines that have recently become open by reconnection with the magnetosheath field and that are populated by magnetosheath plasma. The mantle is usually identified with the regime of open field lines, resulting from reconnection, pictured in the Dungey (1961) model of the magnetosphere. A third separately identified part of the boundary region comprises the two entry layers (Paschmann et al., 1978), small areas lying near and equatorward

of the two polar cusps. They separate the LLBL from the mantle near the noon meridian and perhaps are avenues for entry of some magnetosheath plasma to both.

Figure 1b is a projection, along magnetic field lines to the ionosphere, of the various boundary layers. Figures 1a and 1b show, also, a "plasma boundary layer" that is essentially the boundary of the plasma sheet. Although this region, too, is an important source of field-aligned currents, it will not be addressed directly in this paper. It must be said, regarding Figure 1b, that the mapping of field lines from the boundary regions to the ionosphere is subject to considerable uncertainty. That is because the boundary regions, containing greatly stretched and distorted field lines as they do, are the very regions to which existing magnetospheric models are least applicable. There is, in fact, no accepted theoretical model of these regions. Thus the apportioning of the ionospheric projection, in Figure 1b, to the various boundary regions should be regarded as only semi-quantitative, indicating that around local noon there is some mixture or arrangement of entry layer, LLBL, and mantle field lines, while at earlier and later local times there is increasing tendency to encounter LLBL and mantle field lines and finally plasma sheet boundary field lines.

It is primarily along the magnetic flux tubes of the LLBL and the mantle that momentum of the solar wind is imparted to the magnetosphere, stressing the magnetotail and providing the energy for internal magnetospheric phenomena. The process is entirely analogous to the functioning of a magnetohydrodynamic (MHD) dynamo although the geometry is different in the two regions. For the LLBL the plasma on closed boundary layer field lines plays the role of the flowing conducting fluid of the dynamo; for the mantle, the magnetosheath plasma outside the magnetopause (i.e., on the extensions of the

mantle field lines) largely plays this role. For both, the ionosphere plays the role of the dynamo's resistive load.

Electric fields, generated in the boundary region and conveyed along field lines to the ionosphere, drive Pedersen currents there. These force convective motion of the ionospheric plasma and where there is shear in this imposed flow (i.e., where the Pedersen currents are divergent) field-aligned currents flow so as to maintain current continuity. And since the flow of ionospheric plasma is a mapping along field lines of the boundary region flows, the field-aligned currents are associated with flow shears in the boundary regions. These shears are mainly in the sense that the flow speed increases as the magnetopause is approached from within and result in enhanced tailward draping of those field lines nearest the magnetopause. And such enhanced draping of the outer field lines implies the existence of field-aligned currents having the polarity of the region 1 currents of Iijima and Potemra (1976).

Boundary Layer Field Aligned Currents and Reverse Draping of Field Lines

We now turn to satellite observations of the boundary regions where large flow shear occurs and where, from the above introduction, the region 1 field-aligned currents originate. Information regarding direction and/or intensities of currents at these places is derived from the behavior of the local magnetic field. We shall find that field-aligned currents of intensities adequate to be identified with the region 1 currents are encountered there. But in these observations there remains some uncertainty as to whether the currents were driven by boundary layer or magnetosheath flow, i.e., whether they were on closed or open field lines.

Hones et al. (1982) conducted a survey of magnetic field variations measured with ISEE 1 during crossings of the dawn boundary of the magnetosphere, mostly at moderate northern solar magnetospheric latitudes where encounters with the LLBL was expected. The object was to identify the anticipated enhanced tailward draping of boundary layer field lines and to derive a measure of the associated field-aligned currents there. They identified the boundary layer by the density, temperature, and flow properties of the plasma. To their surprise they found no cases of obviously enhanced tailward draping of the field as they crossed from the plasma sheet into the boundary layer. But they found several cases of "reverse draping" of the field. That is, the boundary layer field rotated to more tailward orientation rather than to a more sunward orientation as had been anticipated. Using data from both ISEE 1 and ISEE 2, Hones et al. made a detailed study of one such dawn boundary crossing in which repeated encounters with LLBL, plasma sheet, and magnetosheath were experienced by the outward-bound ISEE satellites for a five-hour interval.

Figure 2 shows the components of the magnetic field at both satellites for one 8-minute interval of that crossing on January 5, 1978. The components are given in a boundary-normal system of coordinates, L, M, N, where N is outward normal to the magnetopause; L is tangent to the magnetopause, and approximately northward; M is tangent and approximately westward (tailward in this instance). The satellites were on the north dawn shoulder of the magnetosphere about $9 R_E$ above the midplane and were separated by 315 km along the N-axis. From 0929 to 0930 UT the satellites were in the plasma sheet where the field pointed northward (+L) and earthward (-M) as is expected in that sector of the outer magnetosphere. From ~09:30:30 to 09:32:30 and again from ~0936 to 0937 they were in the LLBL where the field was again northward

but now tailward (+M), the signature of "reverse draping". From 09:32:30 to 09:33:30 and from 09:34:00 to 09:34:20 the satellites were in the magnetosheath where B_L was negative (southward).

The observed spatial rate of shear of the magnetic field through the boundary (assumed quasi-two-dimensional) provided a measure of the density of current flowing in the L-M plane. Its components parallel and perpendicular to B are plotted at the bottom of Figure 2. The current was mostly anti-parallel to B . At the crossings from the plasma sheet to the LLBL at 09:30:30 UT and 09:35:30 UT j reached values of -3 A/m^2 . At crossings into and out of the magnetosheath j reached -7 A/m^2 . If the currents at the plasma sheet -LLBL interface flow undiverted along field lines to the (southern) polar cap where the field strength is 2000 times greater, their intensity at the ionosphere would be 60 A/m^2 , a value consistent with some region 1 currents measured by the DE-2 satellite.

The remarkable reverse draping of the LLBL field found on this and other occasions has several possible explanations, three of which are illustrated in Figure 3. (Top panel) Plasma enters the closed LLBL flux tubes primarily at the entry layers near the north and south polar cusps. Its expansion tailward around the magnetosphere stretches the field lines preferentially at high latitudes, leaving the equatorial segments to follow more slowly. Possibly the equatorial segments are still embedded in the plasma sheet whose plasma is moving more slowly or, perhaps, even moving sunward. (Middle panel) The field lines are pulled tailward but with their single apex pulled up to high northern latitudes. Such an asymmetry with respect to the equatorial plane might be a seasonal effect, the much larger Pederson conductivity in the sunlit southern polar cap diverting a larger portion of j into the southern hemisphere than into the northern one. (Bottom panel) Magnetic reconnection

occurs between magnetospheric field lines on the north-dawn surface of the magnetosphere and magnetosheath field lines. (Data from IMP 8 satellite showed the IMF to have a negative B_y component during the crossing discussed above, appropriate for reconnection in the location suggested). The field lines at ISEE 1 and 2 might then be segments from the southern polar cap that are being pulled tailward by their reconnected magnetosheath extensions, and that are on their way to becoming plasma mantle field lines. If the situation as depicted in the bottom panel is the true explanation for the reverse draping, the characterization of the LLBL as flowing plasma giving up momentum to closed field lines on that occasion is incorrect; at least part of the LLBL was on open field lines and the driving agent was the magnetosheath flow instead. (Cowley (1983) investigated the tangential stress balance condition across the magnetopause for the January 5, 1978 event, using the theoretical procedure of Sonnerup et al. (1981) and found it to be quantitatively consistent with the explanation in the bottom panel of Figure 3 but not inconsistent with the explanation in the top panel.)

Quasi-Steady Reconnection and Flux Transfer Events

In the previous section we found that the reverse draping of field lines sometimes observed in the LLBL might indicate that the LLBL is threaded with open, rather than closed, field lines on those occasions. In this section we shall examine some of the evidence for magnetic reconnection at the magnetopause that would result in an open LLBL and consider some of its implications with regard to field-aligned currents.

High resolution plasma, magnetic field, and energetic particle data that have become available through the ISEE 1 and 2 satellite program provide the first direct evidence that magnetic reconnection occurs at the magnetopause. This evidence grew from two paths of investigation that were followed concurrently and independently. One revealed that reconnection can occur in a quasi-steady manner enduring on time scales of tens of minutes and the other revealed that it can occur as a transient process, localized in both spatial and temporal extent. Future research may show that the two processes are not sharply distinct but simply represent different regions of a continuous spectrum of space and time scales (Cowley, 1982).

The situation that may prevail at the magnetopause during quasi-steady reconnection is depicted schematically in Figure 4. The reader is referred to the paper by Sonnerup et al. (1981) for a detailed discussion of those aspects of reconnection, illustrated in the figure, that have been important in identifying instances of quasi-steady reconnection in the ISEE satellite data. Briefly, it was found, in a substantial number of magnetopause crossings, that (a) the plasma velocity in the magnetopause and boundary layer, (V_2) was significantly larger than that (V_1) in the magnetosheath; (b) the difference in tangential plasma velocity ($V_{2t} - V_{1t}$) had the direction and magnitude appropriate for the Maxwell stress derived from the change of the tangential magnetic field across the magnetopause; (c) the normal component of the magnetic field (B_n) had the signs appropriate for the observed boundary layer flow ($B_n < 0$, i.e., inward, for northward flow, $B_n > 0$ for southward flow); (d) the normal component of the flow (V_n) at the magnetopause was inward; (e) energetic magnetospheric particles had directional anisotropies indicating outward escape along open flux tubes; (f) the outer separatrix, S_1 , could be identified in the flux of escaping magnetospheric particles.

A flux transfer event (FTE) is thought to result when a bundle of magnetic field lines (perhaps several thousand kilometers in cross-section) of the magnetosheath reconnects to a comparable flux tube in the surface of the magnetosphere. The magnetic tension of the reconnected flux tubes causes them to contract, as illustrated in Figure 5, while their magnetosheath sector continues to be carried tailward by the magnetosheath plasma flow. The feature in the ISEE magnetic data that first attracted attention to FTEs was a quasi-sinusoidal variation of the magnetosheath field component normal to the magnetopause in periods of 1 minute that was quite often seen when the satellite was a short distance outside the magnetopause. Russell and Eipheic (1979) interpreted this as the draping of the overlying magnetosheath field as the reconnected flux tube moved by underneath. Because of the orientation of the ISEE orbit early observations of FTEs were mostly at northern latitudes where the variation of the normal component was observed to be outward (+) then inward (-) and these were called normal polarity FTEs. Figure 5 illustrates how this variation occurs and shows that if reconnection occurs near the equator, the field variation at southern latitudes should be inward-then-outward. Examples of this latter variation have been found (Rijnbeek et al., 1982) and are called reverse polarity FTEs.

Within the open flux tube of the FTEs deflections of the plasma flow and the field direction are expected and are found in the data. In particular, the field in the magnetosheath portion of the tube will turn toward the direction of the earth's field, while the field in the magnetospheric portion of the tube will turn toward the direction of the magnetosheath field. The plasma flow inside the northerly contracting open tube will be deflected northward and westward relative to the ambient magnetosheath flow while the

plasma flow within the southerly contracting open tube should be deflected southward and eastward.

It is to be expected that the moving bulge associated with the contracting reconnected flux tube might be sensed in the underlying magnetospheric magnetic field just inside the magnetopause as well as in the overlying magnetosheath field. Indeed this is found to be the case and so there are magnetosheath FTEs and magnetospheric FTEs. As a moment's reflection will show, the polarity of the B_N change in magnetospheric FTEs will be the same as for magnetosheath FTEs (outward-inward in the northern hemisphere, inward-outward in the southern hemisphere). (The reader is referred to the paper by Paschmann et al. (1982) for a detailed account of plasma and magnetic properties of several magnetosheath and magnetospheric FTEs).

Sample Observations of Quasi-Steady Reconnection, Magnetosheath FTEs and a Magnetospheric FTE

Figure 6 shows plasma and magnetic field data for an ISEE 1 passage from the magnetosheath into the low-latitude dusk sector of the magnetosphere. ISEE 1 was in the LLBL between 1934 UT and 1953 UT, as is evidenced by the irregular flow velocity (V_p) and density (N_p) and by the northward orientation of the magnetic field (B_L positive). This is one of the intervals studied by Sonnerup et al. (1981). They deduced that quasi-steady reconnection was taking place near the spacecraft and, specifically, that the magnetopause/boundary layer region observed between 1934 and 1953 UT was located on open field lines southward of the reconnection region. The substantially increased plasma flow speed and the southward (V_z negative)

deflection of its direction during this interval were quantitatively consistent with the requirements of tangential stress balance across an open magnetopause with B_N positive (that is, on open tubes connected to the southern hemisphere of the earth). Note that during this interval the magnetic field pointed generally northward and tailward (B_M negative), whereas in the plasma sheet (after ~2011 UT) the field pointed northward and earthward, appropriate for the satellite's location at northern latitudes. This is the signature of "reverse draping" of field lines reported by Hones et al. (1982) and discussed in an earlier section of this paper. The tailward draping of the LLBL field lines (relative to those in the neighboring plasma sheet) implies a shear at their interface (which was not actually encountered in the 1934-1953 UT interval) requiring a field-aligned current parallel to $\vec{B}$ (i.e., away from the south polar region of earth). This is compatible with the direction of the low-altitude region 1 field-aligned currents at the post-noon sector of the polar cap. Note that the example of reverse draping of the dawn LLBL field reported by Hones et al. (1982) required FAC flowing anti-parallel to $\vec{B}$ which is also compatible with region 1 FAC if reconnection (Figure 1c) is the correct explanation of that event also.

Reverse polarity magnetosheath FTEs are seen at 1921 UT and 2004 UT in Figure 6, evidenced by the inward-then-outward perturbation of B_N . Accompanying this signature in each case was a northward rotation (increasing B_L) of the magnetosheath field toward the direction of the magnetosphere field. The LLBL is encountered several times again after the first entry into the plasma sheet 2011 UT. In the encounter at ~2015 there is a reverse polarity (inward-then-outward) perturbation of B_N together with a rotation of the field (increasing B_L , decreasing B_M) toward a less earthward orientation. This is possibly a magnetospheric FTE signature.

Field-Aligned Currents in FTE Flux Tubes

Several investigators (Paschmann et al., 1982; Cowley, 1982, Rijnbeek et al., 1982; Saunders, 1983) have noted that the inward-then-outward (or vice versa) perturbation of B_N that identifies an FTE often appears continuous even within the open flux tube, possibly indicating helicity of these flux tubes caused by field-aligned current flowing within them. Rijnbeek et al. (1982) deduced that there was field-aligned current flowing parallel to the field (i.e., from the magnetosphere to the magnetosheath) in the two magnetosheath FTEs in Figure 6, consistent with the low-altitude region 1 currents. Cowley (1982) has likewise noted that dawn-side FTEs are twisted in such a direction as to imply field-aligned currents in the magnetosheath-to-magnetosphere sense, again consistent with region 1 currents.

Saunders (1983) has analyzed the ISEE-1 crossing of the north, morning sector of the magnetopause that Scokpe et al. (1981) earlier described in detail. The crossing involved a ~50-minute passage through the LLBL that revealed a number of square-wave "pulses" of the plasma density and of the (tailward) flow speed (Figure 7). Saunders draws attention to the variations of B_N and of the angle, $\alpha_{LM} (= \tan^{-1} B_M/B_L)$, that accompany the nine identified square-wave plasma variations. The plasma pulses are accompanied by well-defined rotations of the magnetic field. In pulses 1-6, these are caused principally by positive (tailward) excursions of B_M that cause α_{LM} to change from its plasma sheet value ($\sim 345^\circ$) to $\sim 15^\circ$. This change of direction constitutes reverse draping of the field such as we have discussed earlier in connection with two other LLBL encounters. Pulses 8 and 9, which also display higher plasma flow velocity, are accompanied by negative (sunward) excursions of B_M . Variations of B_N resembling FTE signatures

accompany the individual pulses. Saunders regards the pulses as passages of FTEs; the variations of B_M then reflect samplings of the field within the open flux tubes as they pass over the satellite. The quasi-sinusoidal perturbation of B_N in each pulse, together with the change of the B_M signature from tailward excursions in the early pulses (1-6) when the satellite was near the inner edge of the LLBL to sunward excursion in the later pulses (8,9) when the satellite was near the outer edge, are all taken as signatures of field-aligned currents within the FTE open tubes. The situation is shown schematically in Figure 8. The northward contraction of the reconnected flux tube (connected to earth's northern polar cap) and tailward dragging of its magnetosheath end tilt the magnetosphere end toward the sun causing a negative B_M variation at its axis. But the twist caused by a field aligned current toward the earth (consistent with region 1 currents) can cause a net tailward tilt at the inner surface of the tube, along with an enhanced sunward tilt at its outer surface.

Saunders and Russell (1983) report that they have examined the spatial properties of FTEs with simultaneous magnetic data from ISEE 1 and 2 when they were separated by many thousands of kilometers. They find that the field perturbations inside FTEs are often oppositely directed at the two satellites, implying a spiral geometry of the FTE internal magnetic structure. The direction of field twisting is systematic both for FTEs seen in the magnetosheath and in the boundary layer, with the field in the FTE flux tube section furthest from (nearest) the magnetopause always tilting away from (towards) the ambient field direction within the neighboring plasma sheet.

Conclusions

The region 1 field aligned currents on the dayside of the polar cap are associated with magnetic shears in the plasma flowing just within the magnetopause at the sunward surface of the magnetosphere and along the flanks of the magnetotail. The magnetic shear results when tailward flowing magnetosheath plasma becomes entrained on earth-tied magnetic field lines and loses its momentum, imparting tangential stresses to the magnetic field. The entrainment of the magnetosheath plasma can take place by diffusion of plasma through the magnetopause or by reconnection, at the magnetopause, of magnetosheath flux tubes to those of the magnetosphere. In the latter case the entrainment of magnetosheath plasma occurs both by flow of plasma through the magnetopause to the magnetospheric sector of the open flux tubes and by constraint of motion of the magnetosheath sector of the tubes that occurs by virtue of their earth-connection. Whatever the means, the net effect of the momentum transfer is to pull the boundary region flux tubes tailward with respect to flux tubes lying deeper beneath the surface. The resulting magnetic shear is in the correct sense to explain the polarity of the region 1 field aligned currents at low altitudes (toward the earth in the pre-noon sectors; away from the earth in the post-noon sector). Also, the intensity of field-aligned currents in the LLBL and at the LLBL-plasma sheet interface deduced from the magnetic shear is of the correct order to account for observed intensities of the region 1 currents.

The boundary region is customarily considered to comprise two parts--the low latitude boundary layer, commonly thought to consist of closed flux tubes into which magnetosheath plasma penetrates by diffusion, and the plasma mantle, thought to consist of open field lines into whose magnetospheric

sectors (i.e., earthward of the magnetopause) magnetosheath plasma flows directly after reconnection. But now there are suggestions in the ISEE data that the LLBL may, when the IMF is southward (or at least not strongly northward), consist partly, or even largely, of open flux tubes. Among these suggestions are (a) the fairly common occurrence of reverse draping of LLBL field lines, (b) convincing demonstrations of quasi-steady reconnections occurring in the area considered LLBL, and (c) observations, within the LLBL, of FTE signatures. It appears that the LLBL may be a transitional stage of magnetospheric topology containing (at least some) newly reconnected flux tubes that are being pulled into the plasma mantle. The most severe magnetic shears occur in this stage and are the cause of the region 1 currents.

The magnetic field within FTEs is found to have a twisted structure, indicative of field-aligned currents. Remarkably the deduced field-aligned currents in the several cases analyzed has been in the appropriate direction (magnetosheath to magnetosphere, or vice versa) to account for region 1 currents at the location where the FTE is thought to connect to the earth. It is not obvious why this should be true and further investigation is required.

Acknowledgments

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Figure Captions

Figure 1. (a) (left) Schematic diagram of various observed magnetospheric boundary layers. The great extent of the low-latitude boundary layer into the night side is speculative. Open arrows indicate the flow of magnetosheath plasma.

(B) (right) Schematic diagram of the regions occupied by the various boundary layers, mapped down to the ionosphere along magnetic field lines. Hours indicate local time. The boundary between the low-altitude and the plasma sheet boundary layers is highly uncertain. (Adapted from Vasyliunas, 1979).

Figure 2. (top three panels) L, M, and N components of the magnetic field measured by ISEE 1 (solid curves) and ISEE 2 (dashed curves) from 0929 UT to 0937 UT, January 5, 1978. (Fourth panel) Total field measurements. (Fifth panel) Electric current density flowing parallel (solid curve) and perpendicular (dashed curve) to the magnetic field (and in the LM plane). Bars under the first and fourth panels indicate boundary layer. Dots indicate magnetosheath and blanks indicate plasma sheet. (From Hones et al., 1982).

Figure 3. Three tentative interpretations of the observed reverse draping of boundary layer magnetic field lines. (Top) Plasma entry around polar cusps causes high northern and southern segments of field lines to be pulled tailward faster than equatorial segments. Dotted field lines show line shape for "normal draping" anticipated for equatorial or uniform entry of plasma to boundary layer. (Middle) Unequal conductivity in northern and southern ionospheres may cause northward displacement of single apices. (Bottom) Magnetosheath field lines (dashed) reconnect with magnetospheric

field lines on north dawn shoulder of magnetosphere. (From Hones, 1983).

Figure 4. Meridional view of the reconnection configuration for antiparallel external and internal magnetic fields. The magnetic field lines are shown as solid lines. The magnetopause (MP) is shown as a current layer of finite thickness, with an adjoining boundary layer (δL) of comparable thickness. Those magnetosheath and magnetospheric field lines connected to the separator (or X line) form the outer (S_1) and inner (S_2) separatrices. Dashed lines are stream lines and the heavy arrows indicate plasma flow speed outside and inside the magnetopause. The reconnection electric field, E_t is aligned with the magnetopause current, I . (From Sonnerup et al., 1981).

Figure 5. Schematic view (from the magnetosheath) of two open FTE flux tubes shortly after a localized reconnection event at the dayside magnetopause. The LMN coordinate directions are included for reference in the top right hand part of the sketch. (From Saunders, 1983).

Figure 6. ISEE 1 plasma and magnetic field measurement of the magnetopause region for the inbound crossing on August 9, 1978. The top three graphs show the plasma number density (cm^{-3}), plasma flow speed in the ecliptic plane (km/sec) and plasma flow speed in the GSM z-direction (km/sec). The bottom four graphs show the L, M, and N components of B and its total intensity (nanoteslas). Reverse polarity FTEs are denoted by vertical guidelines at $\sim 19:21$ and $\sim 20:04$ UT. The dashed line at $\sim 20:11$ UT identifies the magnetopause. (From Saunders, 1983)

Figure 7. ISEE-1 plasma and magnetometer recordings for the November 6, 1977 outbound crossing of the low latitude boundary layer and magnetopause. Plotted parameters are the same as in Figure 6 except α_{LM} , which is the field angle in the LM plane (see text). The main intervals (or "pulses") of flowing boundary layer plasma are marked by vertical lines and numbered near the top of the diagram. (From Saunders, 1983).

Figure 8 Sketch of a tailward and northward propagating FTE observed from inside the magnetosphere. The field within the open tube is shown twisted as implied by the observed B_N perturbations. (From Saunders, 1983).

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

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Figure 7

Figure 8