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ON THE VOLTAGE AND DISTANCE ACROSS THE LOW LATITUDE BOUNDARY LAYER

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Abstract. A pass of the AMPTE-UKS satellite through the low-latitude boundary layer (LLBL) at 8:30 MLT is studied in detail. The magnetosheath field is predominantly northward. It is shown that multiple transitions through part or all of the layer of antisunward flow lead to overestimation of both the voltage across this layer and its width. The voltage is estimated to be only about 3 kV and this implies that the full LLBL is about 1200 km thick, consistent with previous studies.

Introduction

Two types of mechanism have been proposed for driving convection in the magnetosphere and ionosphere. The first involves the production of open flux by magnetic reconnection: these field lines thread the magnetopause and hence are transferred antisunward over the poles by the solar wind flow. All other mechanisms can be classed as 'viscous-like' interactions as they involve the antisunward transfer of closed field lines (which do not thread the magnetopause and connect the ionospheres of the two hemispheres). Viscous-like interactions must produce antisunward flows on northward-directed field lines within the low-latitude boundary layer, LLBL (see Cowley, 1982). Reconnection could produce such flows, even on the flanks of the magnetosphere, but only if the point where the field line threads the magnetopause remains at very low latitudes.

Observations of the voltage across the ionospheric polar cap during northward IMF, when reconnection is not expected, indicate that less than about 30 kV is due to viscous-like interactions (e.g. Reiff et al., 1981). However, Wygant et al. (1983) showed that this voltage decayed with time elapsed since the IMF turned northward. Lockwood and Cowley (1992) have shown how this, and the ionospheric flow patterns ascribed to viscous-like interaction, are well explained as resulting from continuing reconnection of residual open flux in the tail. Hence the observations of transpolar voltage indicate that the voltage due to viscous-like interactions are very small (about 5kV across each flank of the magnetosphere).

Similar conclusions were reached by Mozer (1984) who measured the voltage across the low-latitude boundary layer by integrating the along-track electric field of a traversing satellite. Generally the values obtained were as low as those inferred by Wygant et al., but some larger values (as well as some negative values showing nett sunward flow) were obtained. In this paper, we investigate the LLBL voltage using a similar technique, but allowing for the fact that the boundary is not stationary.

Method

Figure 1 illustrates a traversal of the LLBL by a satellite. The satellite trajectory is shown in the rest frame of the boundary layer. In the Earth's frame the boundary is moving at velocity $\underline{v}_b$ and the satellite moves at velocity $\underline{v}_s$ (both defined to be positive in the outward boundary normal direction $\underline{n}$). Hence in the rest frame of the boundary the satellite moves at $(\underline{v}_s - \underline{v}_b)$ and the thickness of the layer, ΔL, is the integral of $[(\underline{v}_s - \underline{v}_b).\underline{n}]$ over the residence time of the satellite within it, Δt. The voltage across the layer is given by integrating the electric field along the satellite track, both considered in the rest frame of the boundary:

$$V = \pm [\int_{\Delta t} (\underline{E} - (\underline{v}_s - \underline{v}_b) \times \underline{B}).(\underline{v}_s - \underline{v}_b)\, dt] \, , \qquad (1)$$

where $\underline{E}$ is the electric field as measured by the spacecraft. The plus or minus arises from the sense of the integration: the plus applies to a traversal of the LLBL from the magnetosheath into the magnetosphere, the minus to a reverse traversal. Vector algebra yields

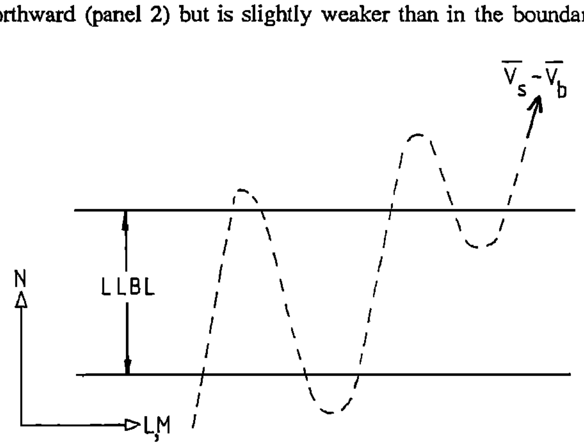
$$V = \pm [\int_{\Delta t} \underline{E}.\underline{v}_s\, dt - \int_{\Delta t} \underline{E}.\underline{v}_b\, dt] \qquad (2)$$

The first term on the RHS of (2) is the voltage deduced directly from the satellite data, neglecting any boundary motions ($=V_{sat}$). Thus, were the boundary motion neglected, when the boundary is moving inward for an outbound satellite pass ($v_b < 0$; $v_s > 0$), the magnitude of the true boundary layer voltage is underestimated ($|V| > |V_{sat}|$). However, the satellite may still emerge into the magnetosheath if the boundary is moving outward, but at a slower speed than the satellite ($v_s > v_b > 0$), then the potential difference is overestimated ($|V| < |V_{sat}|$). Note that our definitions mean that positive E and negative V (and V_{sat}) correspond to antisunward flow in the LLBL.

Observations

In this paper we study an outbound pass of the AMPTE-UKS satellite on 10 November 1984 (orbit 47), which encountered the boundary layer and magnetopause in the period 08:35-10:00 UT. At the nominal magnetopause crossing, UKS was at GSE coordinates ($X=5.26R_E$, $Y=-9.49R_E$, $Z=0.23R_E$), for which the MLT was 08:30 and the magnetic latitude was +14° in SM coordinates ($Z = 2.56R_E$).

Figure 2 presents the magnetic field and plasma observations as a function of time. When the satellite emerges fully into the magnetosheath (at the time marked d), the field is pointing northward (panel 2) but is slightly weaker than in the boundary



1. Schematic illustration of a satellite path across the boundary layer, in its own rest frame, when the boundary is oscillating in location in the Earth's frame.

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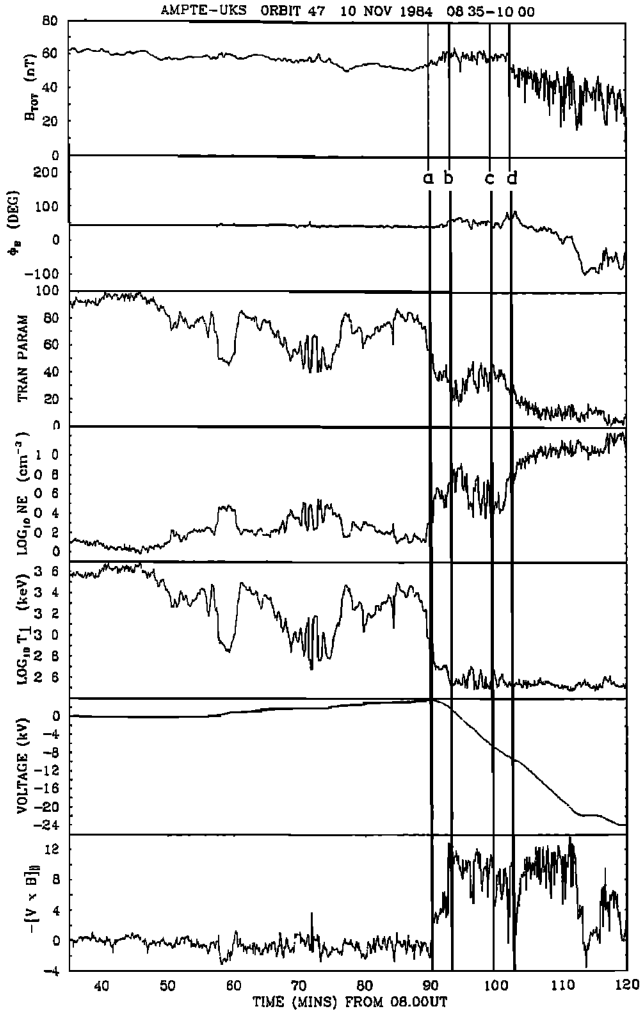


2. Plasma and magnetic field data from AMPTE-UKS from an outbound magnetopause crossing on 10 November 1984 (orbit 47): (1) magnetic field strength, B_{TOT} and (2) direction, ϕ_B (in the estimated LM plane of the boundary - positive values denote northward field); (3) the transition parameter, T; (4) the electron density, N_e; (5) the perpendicular electron temperature, $T_\perp$; (6) the voltage, V_{sat}; and (7) the electric field component along the satellite track, $-[\underline{v} \times \underline{B}]_{||}$. The times a - d are discussed in the text.

layer (panel 1). Moreover, at the time d there is an increase in the level of the field fluctuation, indicative of the more turbulent fields of the magnetosheath, and the field-perpendicular electron temperature, $T_\perp$, becomes constant and low (panel 5). As the satellite moves further into the magnetosheath, the plasma density, N_e, (panel 4) grows and the magnetic field decays, in accordance with pressure balance. Hall et al. (1991) identify the abrupt change in field orientation at 9:50 with the magnetopause. However, we note that this does not correspond to any change in any plasma parameter nor in the total field strength or fluctuation and we therefore consider this to be a temporal change in the sheath field orientation.

Panel 3 of figure 2 shows the transition parameter, T, as devised by Hapgood and Bryant (1990, 1992). This parameter is set to be 0 where the electron temperature and density clearly define the plasma to be magnetosheath and to 100 where the plasma is clearly magnetospheric. At any one time T is then defined by N_e and $T_\perp$. Panel 7 shows the along track component of the electric field $[-\underline{v} \times \underline{B}]_{||}$, where v is the plasma velocity measured in the spacecraft frame. Panel 6 shows the potential distribution obtained by integrating this component along the satellite orbit (giving a voltage V_{sat}).

Prior to the time t=a in figure 2, the field orientation was constant and magnetospheric (panel 2) and the flow was sunward (panels 6 and 7). The transition parameter indicates a number of partial boundary transitions, but the flow at such times was still sunward and was, indeed, enhanced. Antisunward flow was observed in the boundary layer between times a and d, marked by the outermost two vertical lines. In addition, a line has been drawn at the time b when N_e and $T_\perp$ (and hence T) were identical to their corresponding value at t=d. Similarly, the electron gas at time c was identical to that at t=a.

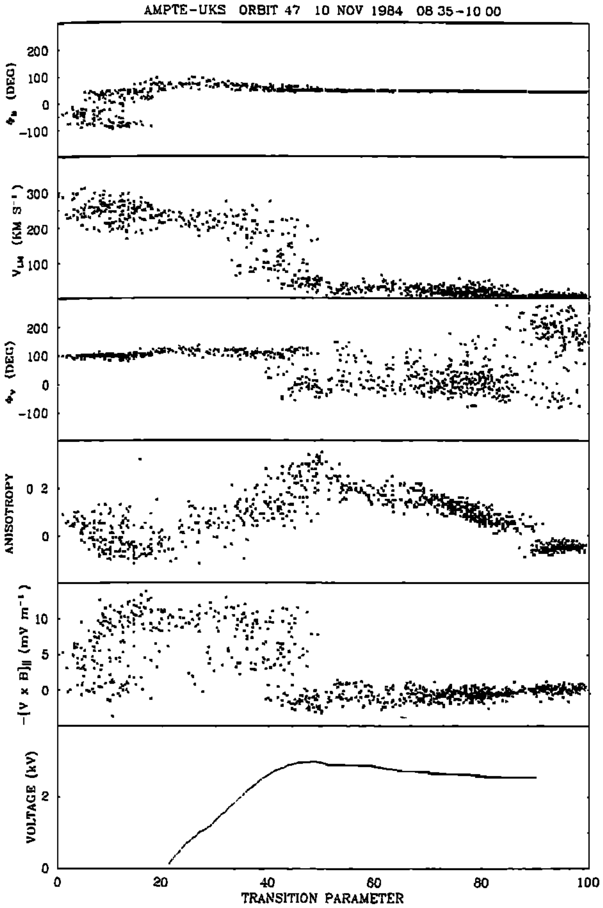
If we assume that the boundary did not vary in its electron characteristics in the 12 min. between t=a and t=d, the N_e, $T_\perp$ and T variations show that the satellite crossed the antisunward flow channel of the boundary layer three times. These three full traversals are in the intervals a - b, b - c and c - d. From panel 6 we find that the voltages observed in these intervals (V_{sat}) are -2 kV, -8.5 kV and -3 kV. Considering the interval b - c, the satellite was returning to more magnetospheric-like electron characteristics, i.e. we infer that the boundary was moving outward faster than the satellite ($v_b > v_s > 0$). Note that this means that -8.5 kV of the total V_{sat} of -13.5 kV was due to the second crossing of the antisunward flow layer and that a further -3 kV was due to a third crossing. During the periods a - b and c - d, the boundary may have been moving inward, in which case the $|V_{sat}|$ of 2 kV and 3 kV (respectively) would be underestimates. However at the times b and c we know $v_b = v_s > 0$, and such times act to make $|V_{sat}|$ values overestimates of $|V|$. Given the similarity of the two independent V_{sat} values for the two outward traversals of the layer (a-b; c-d), we estimate the true voltage across the antisunward flowing layer was 3 ± 1 kV, the uncertainty arising from the boundary motion. This value should be compared with the 13.5 kV derived if we assume the boundary to be static. In the following section we consider some implications of this estimate.

Transition Parameter and Thickness

Figure 3 shows the same data as figure 2, but plotted as a function of the transition parameter, T, rather than observation time. The idea behind such plots is that repetitive encounters of the same part of the boundary, due to boundary motions, are all plotted at the same T. Panel 1 shows that the transition parameter orders the field orientation well, showing only magnetospheric field directions at all values above about 20. Below T = 20 there is a range of values, reflecting variability in the magnetosheath field orientation. Panel 3 shows that the magnetosheath flow direction is maintained up to T of about 40, and Panel 2 shows that the flow speed in this antisunward-moving boundary layer is only slightly less than in the magnetosheath proper. At T above 40, the flow direction is variable but its speed is low. Panel 4 shows the electron anisotropy, defined to be $(T_{||} - T_\perp)/(T_{||} + T_\perp)$. This is also well ordered by T. The feature we wish to highlight is the clear onset of loss-cone type distributions at T > 90 which defines clearly magnetospheric plasma.

Hence we define the boundary layer to be between T of 20 and 90. Panel (5) of figure 3 presents the along-track electric field, showing an antisunward flow channel in the range 20 < T < 40 and weak sunward flow at 40 < T < 90. No significant flow was detected in the purely magnetospheric population at T > 90.

Panel (6) investigates the voltage across the boundary layer using T. In order to do this, we have assumed that T varies linearly with distance across the boundary and we then adopt various values for the spatial thickness of the boundary layer, ΔL, corresponding to the boundary layer range in T, ΔT = (90-20).



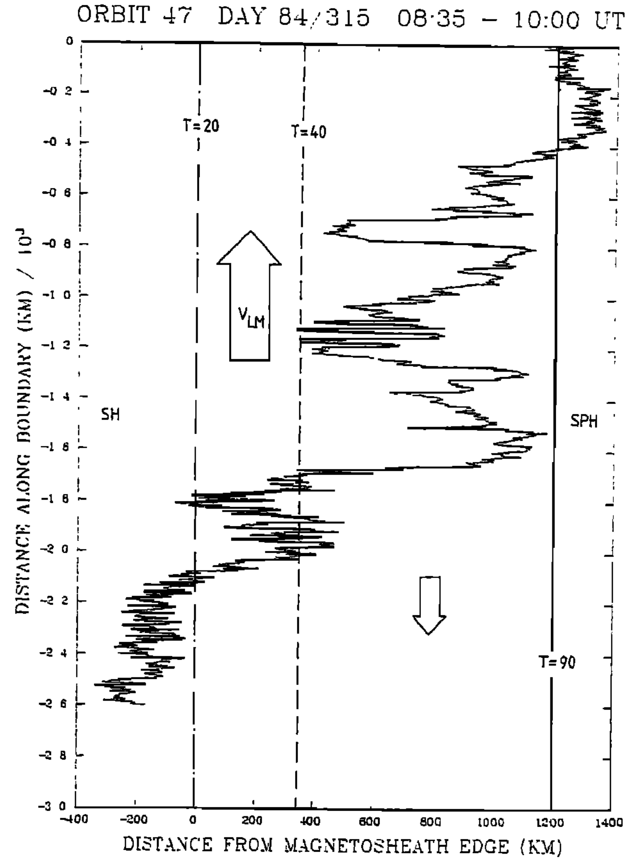
3. The data shown in fig. 2, as a function of transition parameter, T: (1) the magnetic field direction, ϕ_B; (2) the plasma speed in the LM plane, V_{LM}; (3) the plasma flow direction in the LM plane, ϕ_v; (4) the electron anisotropy, $(T_{||} - T_{\perp})/(T_{||} + T_{\perp})$; (5) the electric field component along the satellite track, $-[\underline{v} \times \underline{B}]_{||}$; and (6) the potential distribution for ΔL = 1200 km.

Hence for each element of T, dT, we can estimate a length dl, which we then combine with the average along-track electric field (for dT) and so derive the voltage drop. It should be noted that the assumption that T varies linearly with distance across the boundary (in its own rest frame) is employed here only because it is the simplest. However, figure 3 shows that the value of the along-track electric field is relatively constant in both the outer, antisunward-flowing layer and in the inner, sunward-flowing layer. This being the case, the errors introduced by the assumed form of the spatial variation of T are small.

In figure 3, we have taken ΔL = 1200 km. This figure has been chosen because it produces a voltage across the antisunward channel of 3 kV, as estimated in the previous section. Hence from this argument, we find that the whole boundary layer (including sunward flowing inner portion and antisunward flowing outer portion) is only 1200 ± 400 km wide. Furthermore, we find that the antisunward flowing portion between T of 20 and 40 is just 430 ± 140 km wide. This figure is roughly five gyroradii for a 1 keV proton and should be compared to a value of 1500km derived if we assume the antisunward flow channel to be stationary.

Discussion and Conclusions

A crossing of the boundary layer by AMPTE-UKS with generally northward magnetosheath field has been presented.



4. Locus of the satellite in the N, M plane of the boundary-normal co-ordinates, based on a linear spatial variation of T and the derived thickness ΔL = 1200km. The sunward and antisunward flow channels are shown between the magnetosphere (SP) and the magnetosheath (SH).

Analysis of the electron characteristics indicates that the anti-sunward flow channel was crossed three times as the satellite moved outbound, due to magnetopause motions. As a result, both the voltage and thickness of the boundary layer were probably less than a third of the value estimated by assuming the boundary to be stationary. Note that the results are very dependent on the identification of the edges of the boundary layer: we believe that it is much more satisfactory to examine several plasma and field characteristics. Use of a single parameter is more likely to cause confusion between temporal changes and spatial structure.

Figure 4 summarises the inferred trajectory of the satellite through the boundary, based on a linear spatial variation of the transition parameter, T, with the inferred ΔL of 1200 km (=0.2R_E). The distance along the boundary is almost exactly in the -M (sunward) direction for this case. Also shown are the boundary layer flow channels, deduced from the transition parameter. It can be seen that the satellite travelled a considerable distance inside the sunward-flowing portion, before traversing the anti-sunward channel three times and then entering the sheath. The outward velocity of the satellite (in the estimated boundary normal direction) was about 2 km s^{-1}, and the thickness derived here yields an average outward boundary speed of $\langle v_b \rangle$ = 1.6 km s^{-1} during the intersection period Δt = 53 min. However, the fluctuations in v_b about this mean are up to about 40 km s^{-1} in amplitude.

The voltage derived here is within the range, but smaller than the average, reported by Mozer (1984). The low value supports the suggestion by Wygant et al. (1983) and Lockwood and Cowley (1992) that much of the so-called 'viscously-driven' flow observed in the ionosphere when the IMF is northward is, in fact, the effect of reconnection in the magnetospheric tail.

In considering previous estimates of the voltage and thickness of the LLBL, the biases caused by boundary motion must be considered. Both thickness and voltage will be overestimated if the boundary is moving in the same direction as the spacecraft, whereas they will be underestimated if it is moving in the opposite direction.

Both Eastman and Hones (1979) and Mitchell et al. (1987) reported that the LLBL thickness increased with distance from noon. In their survey, Eastman and Hones found that the 12 crossings of the boundary layer by IMP-6 with GSM X in the range 5-6 R_E gave thickness ranging between 0.08 R_E and 0.98 R_E with a mean value of 0.34 R_E. Hence the value of 0.2 R_E derived here is within their range but a bit smaller than the average. In the absence of any bias in the average boundary motion, this average would reflect the true width of the boundary layer. Hones and Eastman did not find a dependence of thickness on the orientation of the magnetosheath field, however Mitchell et al. found that the ISEE-1 satellite tended to remain longer in low-latitude boundary layer if the IMF was northward.

Hence the boundary layer thickness derived here is in good agreement with previous estimates, supporting the low derived voltage of 3kV across the anti-sunward flowing boundary layer. A survey of all the AMPTE data is now underway, using the method described here to determine the variation of this voltage with MLT.

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