EXPLORING THE MAGNETOSPHERIC BOUNDARY LAYER

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ABSTRACT

We show how, for most crossings of the boundary layer, one can construct a "transition parameter", based on electron density and temperature, which orders independent plasma measurements into well-defined patterns which are consistent from case to case. We conclude that there is a gradual change in the balance of processes which determine the structure of the layer and suggest that there is no advantage in dividing the layer into different regions. We further conclude that the mixing processes in layer act in an organised way to give the consistent patterns revealed by the transition parameter. More active processes must sometimes take place to give the extreme values (e.g. in velocity) which are seen in some crossings.

Keywords: LLBL, boundary layer, magnetopause, transition parameter, ordering.

1. INTRODUCTION

The magnetospheric boundary layer separates two regions (magnetosphere and magnetosheath) with very different plasma properties. There are shears in most plasma parameters — in plasma density, velocity and temperature, and in both the strength and direction of the magnetic field. Furthermore, the spatial and temporal scales of boundary layer plasma allow measurements of plasma properties to be made (in-situ by spacecraft) with a resolution that is difficult to achieve in laboratory plasmas. This region is, therefore, an excellent (possibly the prime) example of a transition region between two contrasting plasmas. Studies of this region are therefore of fundamental scientific interest and have the possibility to contribute to the general understanding of plasma physics.

The boundary layer is also of major interest as a critical component of the solar-terrestrial system. It is the site of energy, momentum and mass transfer between the solar wind and the magnetosphere. Thus studies of boundary-layer structure are also of interest for the light that they may cast on the continuing debate about the coupling processes which control these transfers.

Boundary layer data are difficult to interpret via the traditional approach of analysing time series, since the latter are usually complex and confused from a mix of temporal and spatial changes. Several authors have attempted to overcome this by interpreting the time series in terms of a moving boundary-layer structure which consists of a number of different regions (Ref. 1, 2, 3). We have proposed an alternative approach which reveals considerable order in the data (Ref. 4, 5, 6). We use measurements of electron density and temperature to define a "transition parameter". When plotted against this, independent plasma measurements (e.g. magnetic fields, bulk velocities, ion temperatures) form clear and consistent patterns. This suggests that the transition parameter is intimately related to the underlying structure of the boundary layer. In this paper we describe the basic principles underlying the derivation of this transition parameter, show several examples of its use and discuss the implications for models of the boundary layer.

2. THE UNDERLYING CONCEPT

The re-ordering technique is based solely on the existence, in boundary-layer data, of a marked non-linear anticorrelation between $\log_{10} N_e$ and $\log_{10} T_\perp$, where N_e is electron density and $T_\perp$ is perpendicular electron temperature. No other properties are required for the success of the technique. The anticorrelation is best seen in scatter plots such as those shown in the two examples in Figure 1. These show the typical behaviour which is revealed if one plots the data recorded during a boundary crossing:

- There are two major concentrations of points — one at high densities and low temperatures and the other at low densities and high temperatures. These represent magnetosheath and magnetospheric plasmas respectively.
- Between the two concentrations there is a band of points representing plasma states intermediate between the two extremes. The band is curved so that intermediate states have densities and temperatures lower than would be expected for a linear anticorrelation between $\log_{10} N_e$ and $\log_{10} T_\perp$. The degree of curvature varies considerably from crossing to crossing as can be seen in Figure 1. There is evidence that the degree of curvature increases for more tailward crossings (D. Hall, private communication).

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- The narrow band may be traversed many times during a crossing. This indicates repeated transitions back and forth between the magnetosheath and magnetosphere. The transition always follows the narrow track seen in the scatter plot.

These properties are very common. An examination of all low-latitude boundary-layer (LLBL) crossings recorded by AMPTE-UKS shows that this behaviour occurred in 27 cases out of the 31 for which data of suitable quality were available (Ref. 5). Similar behaviour, by both protons and electrons, can be seen inferred from the mirror image behaviour of published densities and temperatures recorded on other spacecraft in both the low- and high-latitude boundary layers (Ref. 1, 9, 10).

Note that it is important to use $T_\perp$ in these scatter plots rather than $T_\parallel$. Scatter plots of $\log_{10} N_e$ versus $\log_{10} T_\parallel$ show a curved band of points similar to that in Figure 1. However, the pattern is less distinct because the variable presence of "counterstreaming electrons" (Ref. 8) increases scatter within the band.

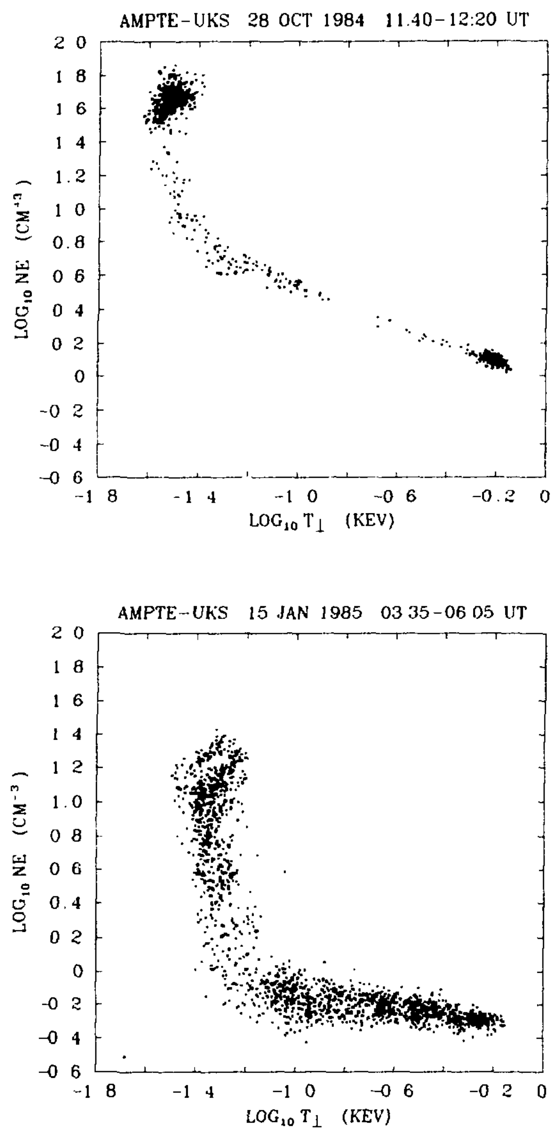

Figure 1: Scatter plots of electron density against electron perpendicular temperature for two LLBL crossings made by AMPTE-UKS. Note that the densities are partial densities, i.e. they are integrated over the observed energy range (not extrapolated to the full distribution). Similarly, temperature is the mean energy of electrons within the observed energy range.

3. THE TRANSITION PARAMETER

The scatter plots of electron density against temperature reveal a remarkable degree of order, which would not necessarily be expected from a cursory examination of time series. It seems very reasonable, therefore, to consider whether this may tell us something about the structure of the boundary layer. To explore this idea further, we examine measurements of other quantities using the order seen in the electron scatter plots. To do this we define a quantity which varies monotonically along the band of points shown in the scatter plots. We call this quantity the "transition parameter" since it tracks the transition from the magnetosheath to the magnetosphere. To calculate the transition parameter we adopt the following scheme, which is performed separately for each crossing:

1. We fit a curve through the band of points using a cubic fitted by least squares with $\log_{10} N_e$ as the independent variable. The transition parameter values are relatively insensitive to the choice of curve. This indicates that we should not assign any scientific significance to the curve. It is merely a mathematical tool that allows us to track the band of points in the scatter plots.
2. We map data points onto this curve, by finding the point P on the curve which is nearest to the data point D. Nearness is defined as minimising the distance $dx = \sqrt{(\Delta T^2 + \Delta N^2)}$ where ΔT is the difference in $\log_{10} T_\perp$ between D and P and ΔN is the corresponding difference in $\log_{10} N_e$. Given the curvature of the band of points seen in the scatter plots, this mapping is the best way of tracking that band.
3. We measure the distance, S, along the curve from some arbitrary origin to the mapped point P. S is calculated by integrating distance steps along the curve, where the steps are defined in a similar way to dx above.
4. The distance, S, is then normalised so that it varies from zero at the magnetosheath to 100 at the magnetosphere.
5. The transition parameter $\mathcal{T}$ is the normalised value of S.

Separate calculations for each crossing are essential to allow for changes, from crossing to crossing, in the observing mode of the instrument and in the space environment. A more comprehensive description of the calculation (including a discussion of sources of uncertainty) is given in Hapgood and Bryant (Ref. 6).

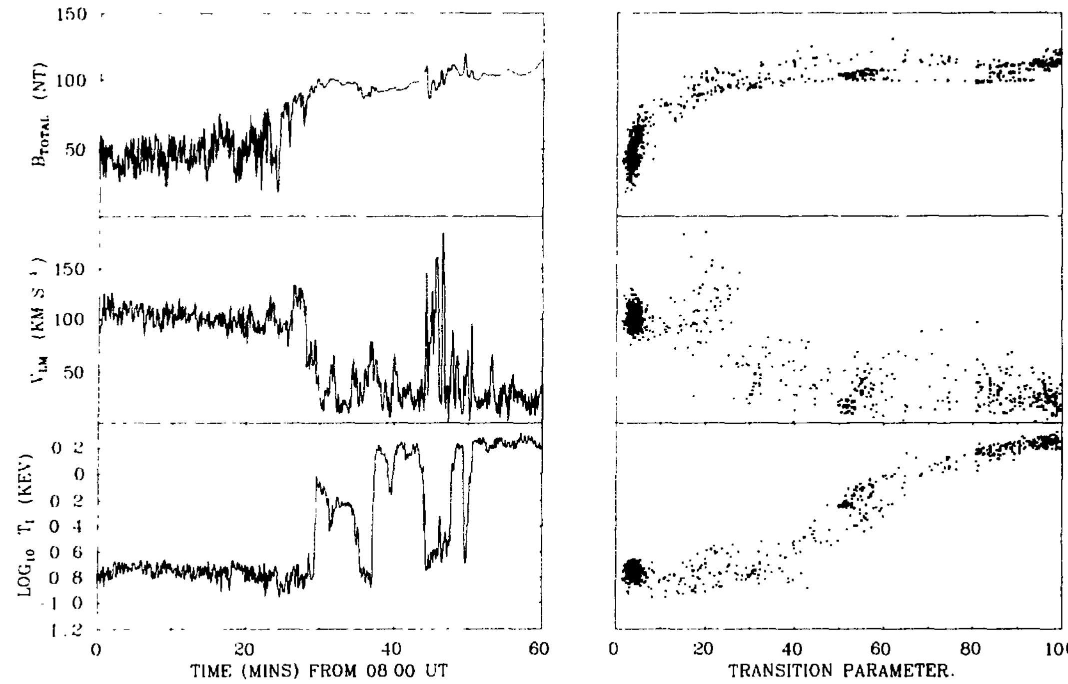

Figure 2: Magnetic field and ion data taken during the inbound LLBL crossing on 11 December 1984. The left panel shows the data as time series while the right panel shows them ordered by transition parameter.

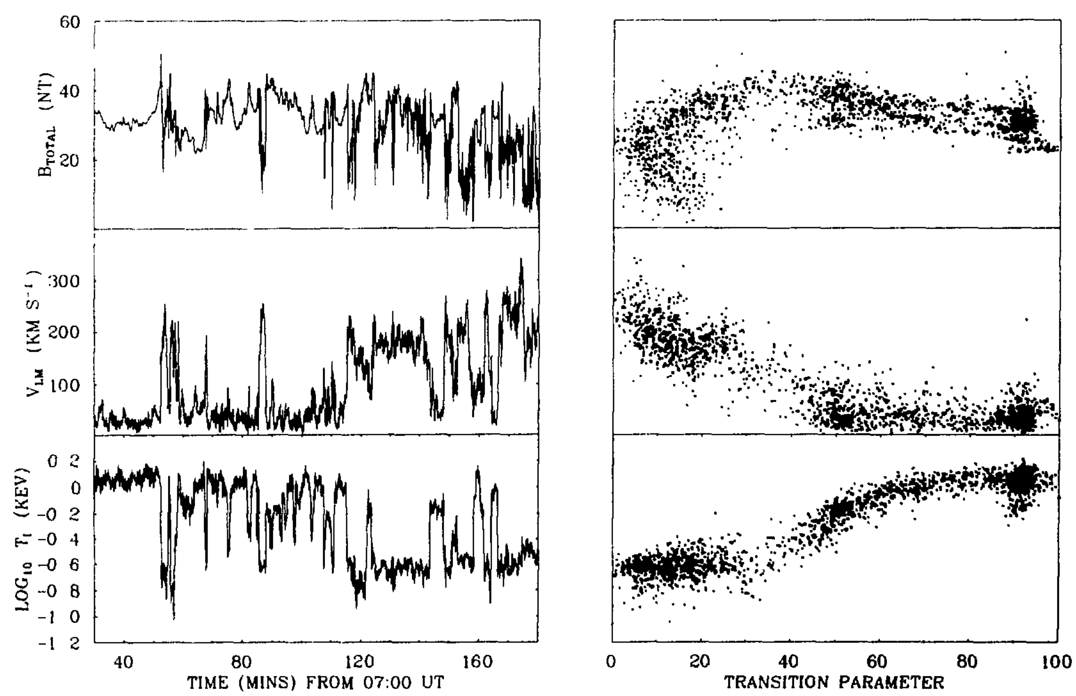

Figure 3: Magnetic field and ion data taken during the outbound LLBL crossing on 23 November 1984. Format as in Figure 2.

Note that it is critically important that the ordering parameter is based on both density and temperature because this allows data to be displayed with good resolution right across the boundary layer. It is possible to use either density or temperature alone as an ordering parameter, but this results in poor resolution in some part of the boundary layer. For example, Hall et al. (Ref. 7, 8) used electron temperature as a ordering parameter. This gives good resolution on the magnetospheric side of the layer where temperature changes rapidly. However, on the magnetosheath side the temperature changes slowly and so the resolution is poor.

4. RE-ORDERING

4.1 Data and Results

This section presents two examples which show how the transition parameter can be used to re-order a number of independent plasma measurements. By this we mean that a plot of quantity X against transition parameter yields a simple pattern, whereas the time series of X is much more complex. In the examples here we show three independent quantities: (i) B_{TOTAL}, the total magnetic field strength; (ii) V_{LM}, the plasma flow speed tangential to the magnetopause (i.e. in the LM plane of boundary normal coordinates); and (iii) T_I, ion temperature (shown on a logarithmic scale). The magnetopause orientation was determined by minimum variance analysis of vector magnetic field data. All examples use data from the AMPTE-UKS spacecraft (Ref. 11).

Note that, because of limited space, we can show only a small range of examples in this paper. We would, however, emphasise that the re-ordering process has been applied to more quantities — magnetic field components as well as total field strength and the direction of the plasma flow as well as its speed. Furthermore, the process has been used to re-order many more boundary-layer crossings and always yields clear patterns which are consistent from case-to-case. The two examples presented here were chosen at random from a larger set of equally good cases. For a broader range of examples, the reader is again referred to Hapgood and Bryant (Ref. 6).

Figure 2 shows time series and re-ordered (by transition parameter) displays of data for an inbound LLBL crossing on 11 December 1984 (UKS orbit 63). The time series display (left panels) suggests that this was a mildly disturbed crossing with a clear transition from magnetosheath to magnetospheric conditions between 09:25 and 09:30 UT. Before this time, the magnetic field was weak and noisy, flow speeds were high and ion temperatures low. After this time, the magnetic field was strong and fairly steady, flow speeds were generally low and ion temperatures generally high. There was a clear time shift between changes in the magnetic field and the ions; the magnetic field changed several minutes before changes in the ion measurements. Flow speeds were enhanced during this period. There was partial reversion to magnetosheath conditions at around 09:45 UT with very high flow speeds, low ion temperatures, but only fluctuations in the magnetic field. There was another, less-marked reversion at 09:37 UT with low ion temperatures but only a slight enhancement in flow speeds and minor fluctuations in the magnetic field.

The re-ordered display of the data (right panels) yields clear patterns. For magnetic field strength, there was a broad spread of values in the range $\mathcal{T} < 10$, values were well-defined but increased with increasing transition parameter for $10 < \mathcal{T} < 40$, and were high and steady for $\mathcal{T} > 40$. For flow speeds, there was a division into two regions: values generally decreased with increasing transition parameter for $\mathcal{T} < 40$ and were low for $\mathcal{T} > 40$. In the middle of the first region, there were also a substantial number of data points with very high values of flow speed (greater than values at $\mathcal{T} = 0$). For ion temperatures there was again a division into two regions: low and nearly constant values for $\mathcal{T} < 40$ and values increasing with increasing transition parameter for $\mathcal{T} > 40$. There was a slight flattening of ion temperatures near $\mathcal{T} = 100$, which is thought to be an instrumental effect.

Figure 3 shows time series and re-ordered displays of data for an outbound LLBL crossing on 23 November 1984 (UKS orbit 54). The time series display (left panels) suggests that this was a very disturbed crossings with many (about 20) transitions between the magnetosphere and the magnetosheath. The re-ordered display of these data (right panels) yields clear patterns which are similar, but not identical, to those seen in Figure 2. For magnetic field strength, a broad spread of values was again seen at low transition parameter (in this case for $\mathcal{T} < 30$) and high steady values were again seen at high transition parameter (in this case for $\mathcal{T} > 70$). However, in the intermediate range ($30 < \mathcal{T} < 70$), the magnetic field strength was well-defined but exhibited a maximum rather than simply increasing with increasing transition parameter. For flow speeds, there was again a division into two regions: values generally decreasing with increasing transition parameter for $\mathcal{T} < 50$ and low values for $\mathcal{T} > 50$. However, in this case, there were only a few data points in the first region with very high values of flow speed. For ion temperatures the behaviour was identical with that in Figure 2: low and nearly constant values for $\mathcal{T} < 30$ and values increasing with increasing transition parameter for $\mathcal{T} > 30$ subject to a flattening near $\mathcal{T} = 100$ due to an instrumental effect.

4.2 Summary of Results

The two examples presented above show most of the features that are revealed through use of the transition parameter to re-order independent plasma data. These features are consistent from case to case and are summarised below. This summary includes some parameters, such as the direction of plasma flow, which are not shown in Figures 2 and 3.

- All traces are continuous between the magnetosheath and magnetospheric extrema.
- Near the magnetosheath (low $\mathcal{T}$) the magnetic field strength is low and disordered, the plasma flow has a high speed and its direction is antisunward in the plane of ecliptic. The ion temperature is low.
- Near the magnetosphere (high $\mathcal{T}$) the magnetic field is high and steady, there is no significant plasma flow and the ion temperature is high.
- At intermediate values of $\mathcal{T}$, the following trends are always observed with increasing $\mathcal{T}$: declining flow speed, more closely field-aligned flow direction, increasing ion temperature.
- At intermediate values of $\mathcal{T}$, the following extrema are sometimes observed: a maximum in magnetic field strength, enhanced flow speeds (>V_{LM} at the magnetosheath).

- *These patterns are independent of the level of activity in the boundary layer.*

5. DISCUSSION

5.1 Implications

The results presented above demonstrate the clear and consistent patterns which we always obtain when we use $\mathcal{T}$, the transition parameter derived from electron data, to organise independent plasma data such as magnetic field and ion measurements. These striking patterns suggest that $\mathcal{T}$ is intimately related to the structure of the boundary layer in some way as yet unknown. We can, therefore, use these patterns to make some general inferences about the processes which determine the structure. These inferences will influence our subsequent interpretation but are independent of that interpretation. They are as follows:

- The smooth and continuous traces seen in $\mathcal{T}$ plots suggest that there is a gradual change in the balance of processes within the boundary layer. There are no abrupt changes, which would be expected if there were clear divisions within the layer. We recommend treating the boundary layer as a single layer subject to gradual internal change.
- Our experience suggests that it is difficult to sub-divide the layer in a systematic or objective manner. We recommend against treating the boundary layer as a sandwich of subsidiary layers.
- Nonetheless, changing gradients within the layer may lead to particular processes becoming dominant in some regions. However, these regions are not delineated by sharp subsidiary boundaries.
- Our approach is consistent with the two sub-layer model of the boundary layer (Ref. 1, 2, 8), which divides the layer into a magnetosheath-like region adjacent to the magnetosheath and a magnetosphere-like region adjacent to the magnetosphere. This is just what you would expect if there were continuous changes across the whole layer.
- The mixing process within the layer must act in an organised way to give the consistent patterns shown in Figures 1, 2 and 3.
- Sometimes, in addition to simple mixing, there must be active processes acting in the layer to generate the extrema occasionally seen in flow speeds and magnetic field strength, i.e. acceleration of bulk plasma, current sources.

Note that we have made no assumptions in deriving these inferences. They follow quite simply from the existence of a marked non-linear anticorrelation between $\log_{10} N_e$ and $\log_{10} T_\perp$.

5.2 Interpretation

We can now attempt a limited interpretation of our results. However, we first note that, as discussed in the introduction, the boundary layer is a region in which there are sharp gradients in the density and velocity of the plasma and in the magnetic field. We may, therefore, expect to encounter the corresponding shear-layer phenomena (diffusion, Kelvin-Helmholtz instability and tearing mode reconnection) and that these will act to mix the magnetosheath and magnetospheric plasmas.

The simplest interpretation of our results is that the boundary layer is laminar with all quantities changing gradually between magnetosheath and magnetosphere. In this case, $\mathcal{T}$ would simply be a monotonic function of position in the boundary layer. Such a layer might be the consequence of the two bounding plasmas mixing via steady-state diffusion. The irregular time variations in various quantities would simply be a consequence of the radial motion of the boundary layer in response to changes in solar wind ram pressure.

A more complex interpretation of our results would be to consider the boundary layer as a turbulent layer in which some or all of shear-layer processes listed above act to mix the plasmas. In this case, $\mathcal{T}$ would no longer be a simple function of position. Instead, the mixing processes would have to act on all scales to maintain the patterns shown in this paper.

The first approach satisfies all the tests that we have applied. Thus, following the principle of Occam's razor, we are forced to adopt this interpretation as it is the simplest viable interpretation. However, we wish to apply further tests to see if this result can be sustained. If not, then more complex interpretations such as the turbulent layer model must be considered. At present, re-ordering by transition parameter has been applied mainly to macroscopic quantities such as particle moments and DC magnetic fields. We now propose to apply the re-ordering technique to microscopic quantities such as particle and wave spectra.

6. SUMMARY

We have developed a method of re-ordering plasma measurements in the magnetospheric boundary layer, which reveals clear and consistent patterns unlike the confused pictures often seen in time series plots of the same quantities. This technique makes no assumptions about the data and rests on a single fundamental concept - the non-linear anticorrelation between $\log_{10} N_e$ and $\log_{10} T_\perp$. The consistency of the patterns revealed by the transition parameter suggests that this parameter is intimately related to the structure of the boundary layer.

We have made some general inferences from this result. In particular, we suggest that one should treat the boundary layer as a single entity across which there is a gradual change in the balance of process that determine its structure. We recommend against approaches which attempt to sub-divide the boundary layer into subsidiary layers with distinct properties. Our results indicate that there are no sharp subsidiary boundaries and so there are no objective criteria to interpret data in terms of such boundaries.

We also infer that the processes that mix magnetosheath and magnetospheric plasma must act in an organised way to give the consistent patterns seen in this paper — both the scatter plots of electron density and temperature, and the ordered plots revealed by the transition parameter. In addition to mixing processes, more active process (such as plasma acceleration) must take place from time to time in order to generate the extrema sometimes seen in the data.

We have attempted some interpretation of the data and find that a simple laminar model of the boundary layer is capable of explaining all our present results. We plan to extend these results by applying the re-ordering technique to microscopic quantities such as particle and wave spectra.

7. ACKNOWLEDGEMENTS

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