

LA-UR -78-2992

**MASTER**

**TITLE:** THE MAGNETOPAUSE LAYER AND PLASMA BOUNDARY  
LAYER OF THE MAGNETOSPHERE

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**SUBMITTED TO:** Submitted for the AGU Monograph on Quantitative  
Modeling of Magnetospheric Processes  
(Proceedings of the Chapman Conf. held  
9/19-22/78 at La Jolla Shores Beach, CA)

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THE MAGNETOPAUSE LAYER AND PLASMA BOUNDARY LAYER OF THE MAGNETOSPHERE

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ABSTRACT

Due to recent availability and analyses of high time resolution satellite data (including IMP 6 and the ISEE-1 and -2 satellite pair), the study of the magnetopause and boundary layer has entered a period of renewed activity. Plasma observations from the VELA satellites first established the presence of magnetosheath-like plasma with reduced density and flow velocity in a relatively thin ( $\lesssim 1 R_E$ ) layer bordering the plasma sheet at low latitudes and bordering the lobe environment at high latitudes. Recent analyses of HEOS 2, Explorer 33 and IMP 6 data have established the presence of this "plasma boundary layer" (PBL) over the entire sunward magnetosphere near the magnetopause. This review gives a brief summary of recent published results on two distinct regions of the PBL: that bordering open field line regions and that bordering closed field line regions. The magnetopause layer (i.e., current layer) can usually be identified by a change in magnetic field direction and

cannot be uniquely identified by any other field or plasma parameters. Immediately earthward of this magnetopause current layer, a PBL of magnetosheath-like plasma is usually observed that has dominantly magnetosheath-like energy spectra and flow characteristics. Observed plasma boundary layer thicknesses are highly variable and are generally much larger than the magnetopause layer thicknesses even near the subsolar region. Several suggested source mechanisms for the plasma boundary layer are discussed and compared.

## INTRODUCTION

Quantitative magnetospheric magnetic field models include, either directly or indirectly, a magnetopause current system (see the review by Roederer, 1975). The magnetopause currents are part of the basic boundary conditions of the magnetosphere and they contribute significantly to the outer magnetospheric field. Due to recent availability and analyses of high time resolution satellite data (including IMP 6 and the ISEE-1 and -2 satellite pair), the study of the magnetopause and plasma boundary layer (PBL) has entered a period of renewed activity. The many labels applied to the PBL may be simply describing a common region maintained by various entry and transport processes. We use the term "plasma boundary layer" (PBL) for lack of a more physically meaningful label that can only be chosen after the magnetopause interaction processes have been clearly and uniquely identified.

Satellite coverage of the sunward magnetopause and PBL is shown in Figure 1 for four satellites that include both plasma and field measurements. HEOS 2 provides excellent coverage of the higher latitude PBL whereas IMP 6 gives complementary coverage at lower latitudes. The ISEE spacecraft have recently provided dual spacecraft sampling with a spacecraft separation distance of  $\sim$  250 km. This separation distance will be gradually increased to provide a further delineation of space and time variations near the magnetopause and other transition regions. For the locations of more tailward PBL observations, the reader is referred to Figure 1 in Sokopke and Paschmann (1978).

Plasma observations from the VELA satellites first established the continued presence of magnetosheath-like plasma with reduced density and flow velocity in a relatively thin ( $\lesssim 1 R_E$ ) layer bordering the plasma sheet at low latitudes and bordering the lobe environment at high latitudes [Hones et al., 1972; Akasofu et al., 1973]. Recent analyses of HEOS 2 data [Rosenbauer et

al., 1975; Paschmann et al., 1976; Haerendel et al., 1978], Explorer 33 data [Crooker 1977] and IMP 6 data [Eastman et al., 1976; Eastman and Hones, 1978] have established the presence of this plasma boundary layer over the entire sunward magnetosphere near the magnetopause.

A confusing variety of labels have been applied to the PBL due to a wide variety of spacecraft trajectories, data sets and time resolution. Analyses of the IMP 6 [Eastman and Hones, 1978], VELA [Palmer and Hones, 1978] and HEOS 2 data [Paschmann et al., 1976] suggest an observational description in terms of a low latitude boundary layer (LLBL) bordering a closed field line region (the plasma sheet or outer ring current region) and a high latitude boundary layer (HLBL or plasma mantle) bordering a region of probably open field lines (the extended polar cap region or tail lobe environment). The distinction between these two regions of the PBL is based on the comparative profiles of observed plasma density and thermal energy in addition to energetic electron distributions. Both the density and thermal energy decrease with increasing distance inward from the magnetopause in the HLBL [Paschmann et al. 1976]. VELA magnetosheath-lobe environment crossings that we have checked also show this HLBL signature. The VELA energetic electron data indicate that this region is on open field lines (Palmer and Hones, 1978). In contrast, IMP 6 crossings of the LLBL and VELA magnetosheath-plasma sheet crossings show an increase in thermal energy, along with the density decrease, with increasing distance inward from the magnetopause. Energetic electron data from IMP 6 (Eastman and Hones, 1978) and VELA (Palmer and Hones, 1978) indicate that the LLBL is on closed field lines.

Magnetopause layer (i.e., the current layer), LLBL and HLBL are regions for which convenient empirical definitions can be specified (Eastman and Hones, 1978). It should be noted that the magnetopause layer and the PBL are

related but (usually) distinct regions so that any magnetopause model is incomplete without a corresponding treatment of the PBL.

### OBSERVATIONS

General characteristics of the PBL can only be evaluated by comparing many crossing examples since boundary motions and spatial variations are often dominant (as in multiple magnetopause crossings). Our description of LLBL characteristics is based on over 100 IMP 6 crossings of the magnetosphere's sunward surface. HEOS 2 results are based on a similarly large set of magnetopause and PBL crossings (e.g., see Haerendel et al., 1978). Fortunately, the ISEE-1 and -2 satellite pair are presently providing high time resolution measurements that can often separate the effects of boundary motion. However, space and time variations are sometimes large enough in the vicinity of the magnetopause that even careful analysis of the ISEE data does not always lead to a clear separation of these variations (see Paschmann et al., 1978).

Some characteristics of the LLBL as observed by IMP 6 are illustrated in Figure 2. The overall density and velocity decrease from the magnetopause layer to the inner extent of the LLBL (going from right to left in the left side of the figure) is accompanied by an increase in thermal energy and continued magnetosheath-level low frequency magnetic field fluctuations, given by the standard deviation  $SD_B$ . The plasma  $\beta$  (the ratio of plasma to magnetic field energy density) usually drops to  $\lesssim 1$  in the inner portions of the LLBL consistent with the decay of field fluctuations. This is because, for low  $\beta$ , the magnetic field is dominant and is not readily perturbed by the plasma. Within the boundary layer the plasma flow directions are more variable and usually shift into a direction (for the ecliptic plane flow component) that is farther from the  $X_{GSM}$ -axis than the nearby magnetosheath

flow direction. Some crossings show a significant cross-field velocity component; for example, the angle between the plasma flow and the field direction for the March 4, 1972 crossing shown in Figure 2 is  $> 20^\circ$ . Many cases of higher cross-field flow components have been sampled by IMP 6 in the LLBL as well as by HEOS 2 (Haerendel et al., 1978). The electron differential spectra shown at the upper right side of Figure 2 show the commonly observed similarity of electron spectra sampled on each side of the magnetopause layer. Although periods of local density minima in the LLBL can often have magnetospheric-like spectra, as shown in this example for a period near 1638 UT, electron spectra within the LLBL are often virtually indistinguishable from those of the nearby magnetosheath. This spectral similarity of plasma on opposite sides of the magnetopause layer with a gradation towards magnetospheric spectra farther into the LLBL has been noted in data from both IMP 6 and HEOS 2 (e.g., the October 10, 1973 crossing, Haerendel et al., 1978). Energetic electron pitch angle distributions are often pancake-shaped in the LLBL and adjacent magnetosphere (suggesting a closed field line region). A streaming distribution as shown is often observed in the adjacent magnetosheath.

IMP 6 plasma, energetic electron and magnetic field observations provide several results about the structure of the low latitude boundary layer and magnetopause layer in the region covered by IMP 5 as shown in Figure 1 (see Eastman and Hones, 1978):

1. In all IMP 6 crossings, some magnetosheath-like plasma is observed earthward of the magnetopause layer. The spectral intensities of LLBL electrons close to the magnetopause layer are often virtually indistinguishable from those of the adjacent magnetosheath electrons. Ion spectral intensities in the LLBL and local magnetosheath are also very

- similar. Many crossings show a significant magnetospheric contribution to the ion and electron spectra, especially farther earthward from the magnetopause layer and near relative density minima within the LLBL.
2. High temporal resolution (three-second average) data reveal that in 24 out of 40 IMP 6 magnetopause crossings, no distinct changes in density or electron spectra are observed at the magnetopause layer.
  3. The LLBL thickness is highly variable and, generally, is much greater than the magnetopause layer thickness.
  4. Nominal LLBL thickness values based on 90 IMP 6 boundary crossings show no statistically significant correlation with latitude,  $K_p$ , hourly averages of IMF  $B_y$  or IMF  $B_z$  or with the locally measured z-component of the magnetosheath magnetic field. Space and/or time variations of the LLBL thicknesses may conceal any real correlation.
  5. Observed LLBL bulk plasma flow almost always has an anti-sunward component, even in the near noon region equatorward of the cusp, and often has a significant cross-field component.
  6. Energetic electron (47 to 350 keV) pitch angle distributions indicate that the low latitude boundary layer is on closed field lines.

These observations are generally consistent with the HEOS 2 observations. However, Haerendel et al., (1978) report that the apparent plasma flow in the LLBL opposed the external flow in approximately 25% of all crossings. Such reversed flows in the LLBL have not yet been noted in the higher time resolution IMP 6 data except for brief intervals during three crossings near the cusp region. Multiple crossings of the inner PBL surface could explain the occasional HEOS 2 observations of sunward component flow in the LLBL; however, forthcoming analysis of ISEE data should resolve this difference. Another difference is that HEOS 2 data commonly show a density plateau in the

PBL with a sudden density change at the magnetopause layer and at the inner extent of the PBL. An ISEE-1 crossing on November 3, 1977 is shown in Figure 3 that clearly shows a density plateau signature. Such density plateau signatures are rarely observed by IMP 6; instead, the majority of IMP 6 crossings reveal no distinct changes in density or electron spectra at the magnetopause layer. The ISEE observations suggest a spatial change in PBL structure with increasing distance from the subsolar region when compared to the IMP 6 observations. This is further emphasized in the ISEE-2 crossing of November 8, 1977 shown in Figure 4. This crossing shows a PBL that is detached from the magnetopause layer, a situation that has not yet been clearly found in the IMP 6 data. The isolated PBL in this ISEE-2 crossing has magnetosheath-like spectra (Paschmann et al., 1978) although it is clearly located on magnetospheric field lines (see Russell and Elphic, 1978). Paschmann et al. (1978) describe a possible temporal model for these isolated PBL regions in which "plasma entry and/or transport along the boundary are 'switched' on and off." The flow parameters shown in Figure 4 during the detached PBL segment or plasma "intrusion" show a dawn-dusk flow reversal that suggests a vortex of plasma flow. Such possible vortices are evident in other segments of the ISEE PBL crossings near the noon meridian at  $25^\circ$  latitude. Paschmann et al. (1978) point out that the apparent PBL thickness may be produced by "temporally limited plasma entry" and/or the passage of plasma vortices.

A comparison of the ISEE and IMP 6 results shows that the PBL structure within  $\sim 30^\circ$  of the subsolar point is significantly different than its structure along the flanks farther from the subsolar region. The relationship between the available IMP 6, HEOS 2 and ISEE observations may be seen by comparing observed plasma flow directions from all four spacecraft for various

crossings as shown in Figure 5. All flow vectors drawn in the PBL in the equatorial plane or noon-midnight meridian plane are based on projecting observed flow vectors based on crossings that occurred within  $15^\circ$  of the GSM X-Y or X-Z plane, respectively. Other flow vectors are estimated projections of observed flow vectors projected onto the magnetopause surface. Substantial changes in plasma flow directions are frequently observed in two regions: the subsolar region and the cusp regions. The remaining HLBL and LLBL regions consistently show anti-sunward flow that is closely field-aligned in the HLBL (Rosenbauer et al., 1975) and generally field-aligned in the LLBL (except near the ecliptic plane and in the subsolar region) although significant fluctuations in the observed LLBL plasma flow field are superimposed on this pattern.

#### DISCUSSION

Classic merging signatures as predicted by most steady-state reconnection models (e.g., Levy et al., 1964) are singularly absent in the HEOS 2 (Haerendel et al., 1978) and IMP 6 data (Eastman and Hones, 1978). However, Crooker (1978) has proposed a geometrically updated reconnection model that does not predict accelerated net plasma flows along the dayside magnetopause. The model envisioned by Crooker (1977) is bimodal in that it incorporates an open field line boundary region maintained by reconnection processes overlaying a PBL on closed field lines. Hones (1976) has presented a related picture that, in addition, incorporates the relationship of magnetotail processes. The closed PBL in Crooker's model would be directly exposed to the oncoming magnetosheath plasma only in regions where reconnection processes were not occurring. Over the magnetopause region sampled by IMP 6, the PBL would be normally exposed, whereas in the cusp region and the HLBL, boundary layers maintained by reconnection processes would dominate.

Reconnection could be significant, even in the subsolar region, if "patchy," forced reconnection can operate as proposed recently by Sonnerup (1978) and Schindler (1978). Patchy reconnection would not result in the unobserved large scale laminar reconnection pattern. Schindler has developed a "patchy" reconnection picture which differs in some respects from the Lemaire et al. (1978) model of impulsive penetration of solar wind irregularities into the magnetosphere (see also Lemaire in this volume). These impulsive penetration models could be used to explain the disordered flow pattern often observed by ISEE at 25° latitude near the noon meridian (Paschmann et al., 1978). Haerendel (1978) has described a picture of eddy convection (leading to localized, sporadic reconnection) to explain HEOS 2 particle and field observations in the outer polar cusp (Paschmann et al., 1976). This model could also be used to explain the highly variable flow pattern observed by ISEE (see Figures 3 and 4) in the subsolar region.

The impulsive penetration models and turbulence models emphasize the three-dimensional, non-steady-state observed character of the magnetopause and PBL. Mechanisms that provide for highly space-and-time dependent regions of magnetosheath plasma penetration into the PBL could explain many of the IMP 6 observations including the observation that the PBL thickness is highly variable and, generally, is much larger than the magnetopause layer thickness. However, although the boundary layer plasma flow has significant fluctuations compared to the nearby magnetosheath plasma flow, the flow field is still always anti-sunward and is generally well ordered. Further ISEE observations may show that the PBL along the flanks of the magnetosphere, when analyzed in an averaged rest frame of the moving plasma, has a turbulent flow pattern that reflects conditions at the time of magnetosheath plasma penetration of the magnetopause. If not, a diffusion process may yet provide a viable

explanation if it can explain the thick PBL/thin current layer combination.

Roederer (1977) gave an excellent review in which he identified the number 2 problem of the International Magnetospheric Study as the identification of "the mechanisms for the entry of solar wind plasma into the magnetosphere." He also listed a closely related problem as problem number 1; namely, the "effect of the interplanetary magnetic field on topography, topology and stability of the magnetospheric boundary." It should be noted that the complexities involved in a study of the magnetopause and PBL, reflected in the trend towards time dependent, three-dimensional models, make it difficult to identify a unique mechanism for a given set of observations. However, the available observations place severe constraints on any viable self-consistent model for magnetopause currents. Such a model must include the effects of plasma and field on both sides of the boundary without assuming the frozen-field approximation and must incorporate the plasma boundary layer within its theoretical framework.

Acknowledgments The authors thank Drs. K. Schindler, B. Sonnerup, N. Crooker and D. Fairfield for helpful comments and suggestions. They acknowledge, gratefully, the assistance of Dr. D. N. Baker in reviewing this paper. This work was performed under the auspices of the U.S. Department of Energy.

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Figure Captions

1. Satellite coverage of the sunward magnetopause and plasma boundary layer (PBL) for IMP 6, HEOS 2 and the ISEE-1 and -2 satellite pair. ISEE coverage is given only for October-December, 1977.
2. Basic characteristics of the LLBL are illustrated by this March 4, 1972 IMP 6 crossing. Various plasma regions are identified at lower left based on both plasma ion and magnetic field signatures as shown in the eight plots on the left side of the figure.  $U$  and  $\beta$  denote the total energy density ( $\text{keV}/\text{cm}^3$ ) and plasma  $\beta$ , respectively. Energetic electron pitch angle distributions are shown at the lower right hand side of the figure. These pitch angle distributions indicate that the LLBL is on closed field lines. Electron differential spectra shown at upper right illustrate the similarity of LLBL energy spectra with spectra from the adjacent magnetosheath. Electron spectra at the 1638 UT density minimum, however, resemble spectra from the nearby magnetosphere. This crossing occurred at  $r = 11 R_E$ ,  $\phi_{\text{GSM}} = 328^\circ$  and  $\lambda_{\text{GSM}} = 44^\circ$ .
3. Two- and three-dimensional plasma parameters and magnetic field pressure for the ISEE-1 crossing of November 3, 1977. Solar magnetospheric (GSM) coordinates are used for spacecraft positions with  $R$  (in  $R_E$ ), local time (LT in hours) and latitude (in degrees). Solid lines denote protons and dotted lines denote electrons in the plots of density ( $N$  in  $\text{cm}^{-3}$ ) and temperature ( $T$  in Kelvin). Bulk flow directions are given in terms of azimuth ( $\phi_p$ ) and elevation ( $\lambda_p$ ) in spacecraft coordinates (close to solar ecliptic coordinates) based on both the 2D (solid line) and 3D (dots) moment analysis. M, E, N or S denote morning, evening, northward or southward flow components, respectively. Total plasma pressure (solid line) and magnetic field pressure (dotted line) are given in units of  $10^{-8}$

dynes/cm<sup>2</sup> (left scale). The dotted curve also gives the magnetic field strength (in gammas) by using the quadratic right hand scale. The magnetopause is marked by a solid vertical line and the inner surface of the plasma boundary layer is marked by a dashed line. Magnetosheath plasma is sampled prior to 0751 UT and magnetospheric plasma is sampled after 0803 UT. This figure is from Paschmann et al. (1978).

4. Two- and three-dimensional plasma parameters and magnetic field pressure for the ISEE-2 crossing of November 8, 1977. This figure uses the same format as Figure 3 except that an isolated plasma boundary layer is marked off by vertical dashed lines at 0254:50 and 0258 UT. The magnetopause layer is centered on the vertical solid line at 0252 UT. This figure is from Paschmann et al. (1978).
5. Summary of plasma flow in the sunward plasma boundary layer as observed by IMP 6, HEOS 2, ISEE-1 and ISEE-2. Approximate projections of observed flow vectors are given on the noon-midnight meridian and equatorial plane cross-sections of the PBL based on satellite crossings with an earth centered angle of  $< 15^\circ$  from the X-Z and X-Y planes, respectively. Flow vectors marked between the two cross-sections are observed PBL flow vectors projected onto the magnetopause surface. The magnetosheath bulk flow adjacent to the magnetopause was assumed to be parallel to the magnetopause surface for this plot. This drawing has been made to scale except that the PBL is enlarged 50%.

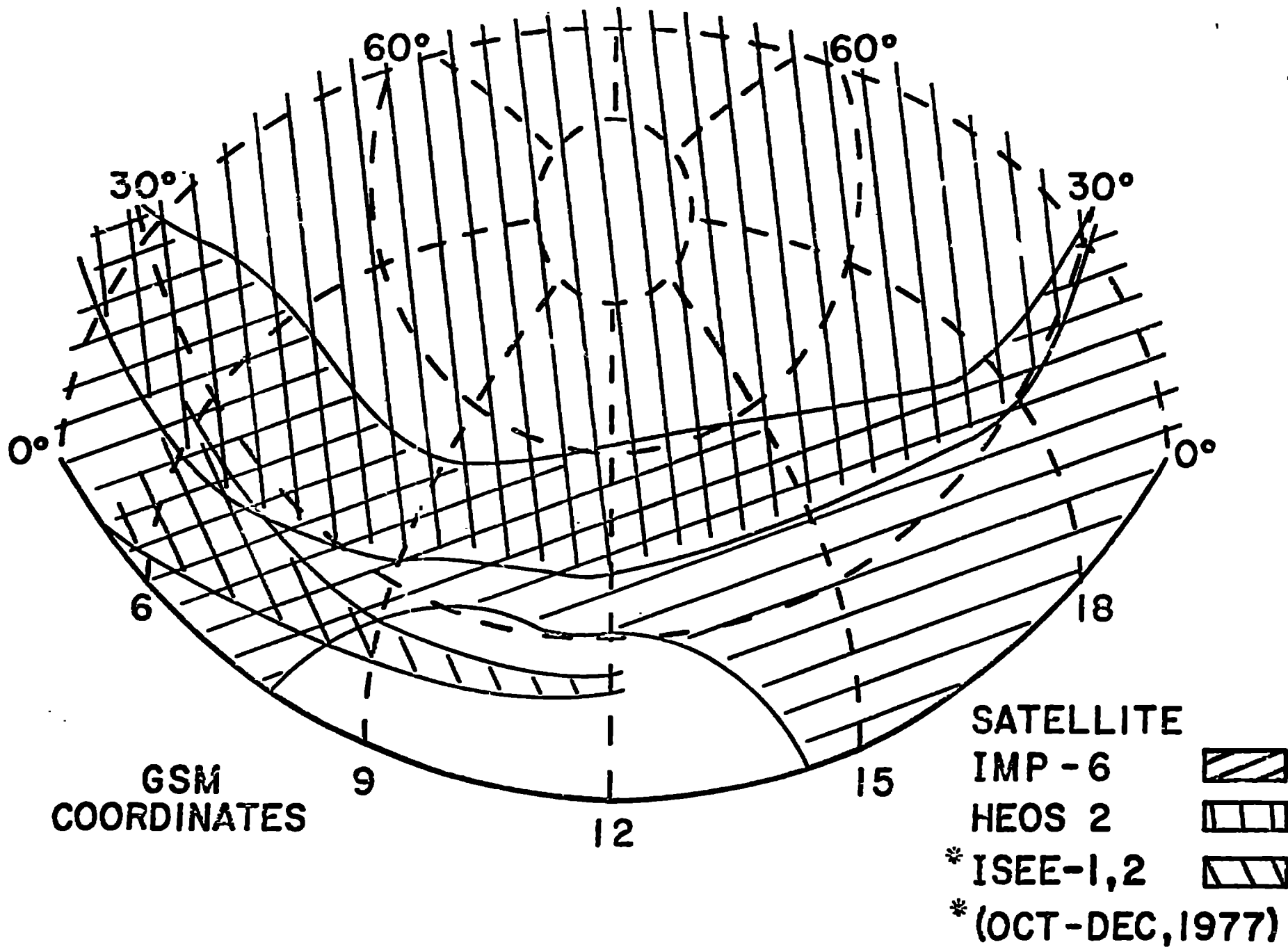


FIGURE 1

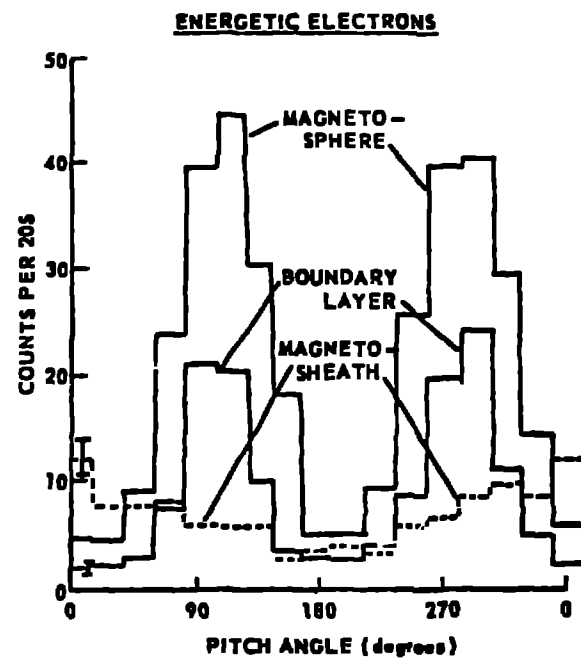
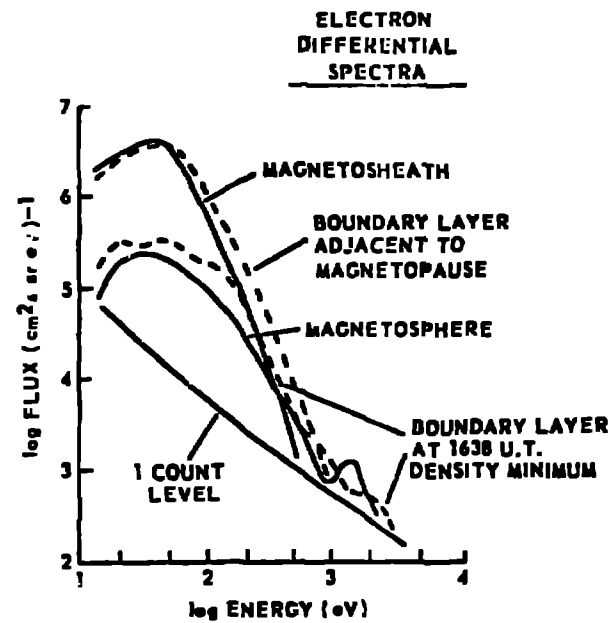
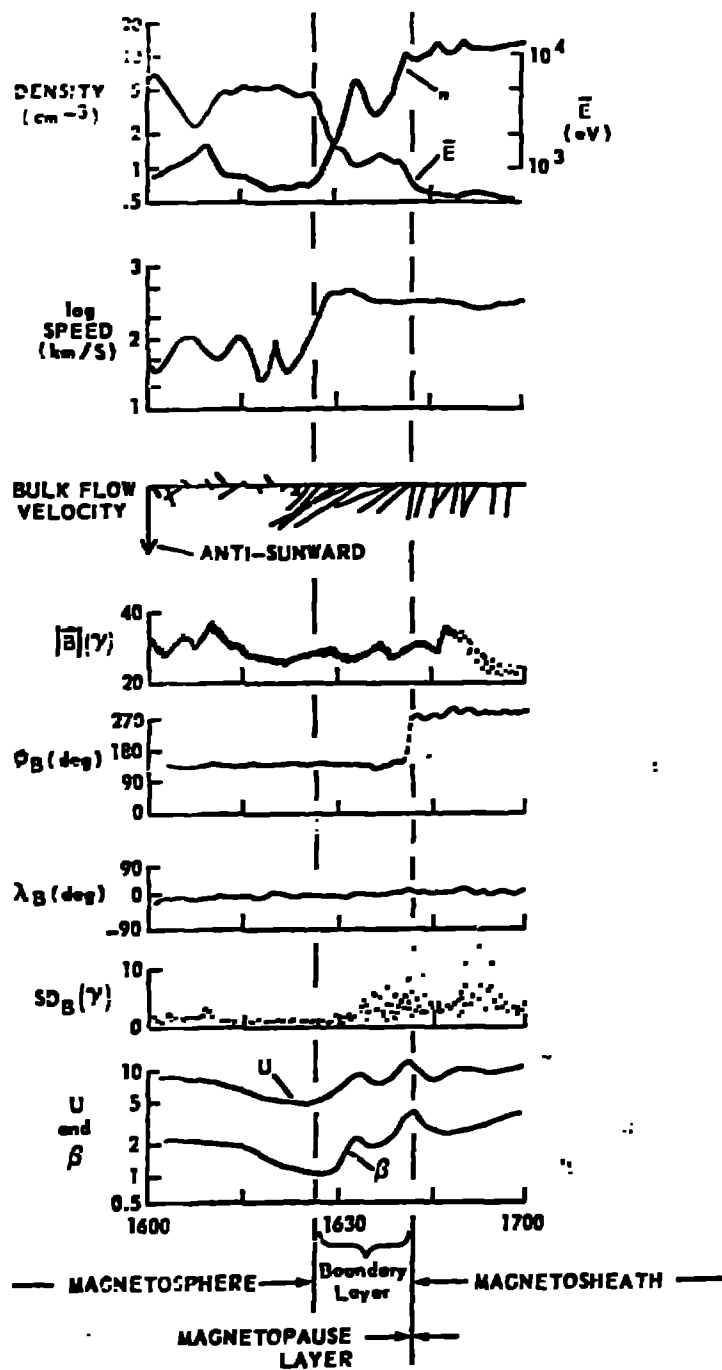


FIGURE 2

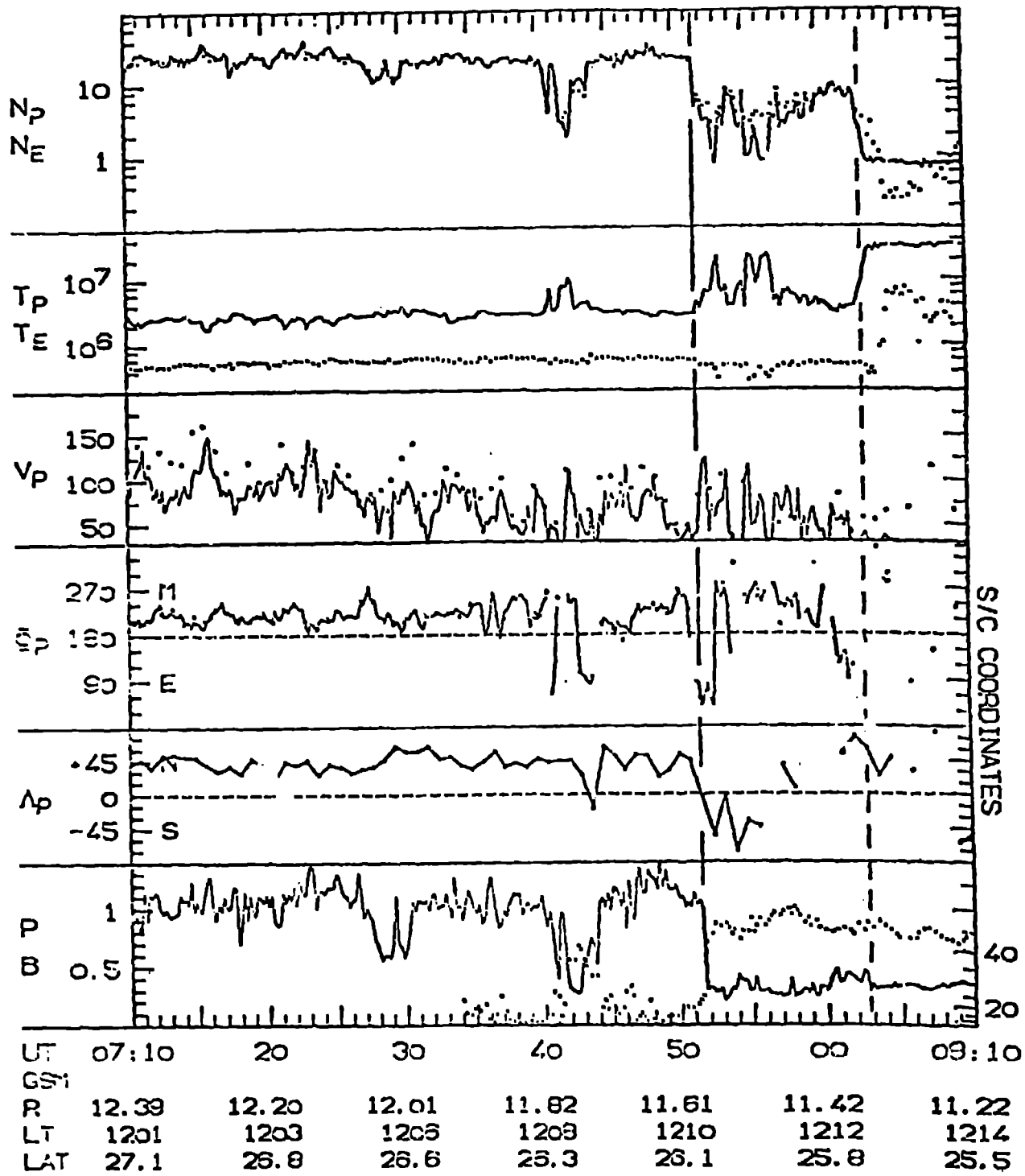


FIGURE 3

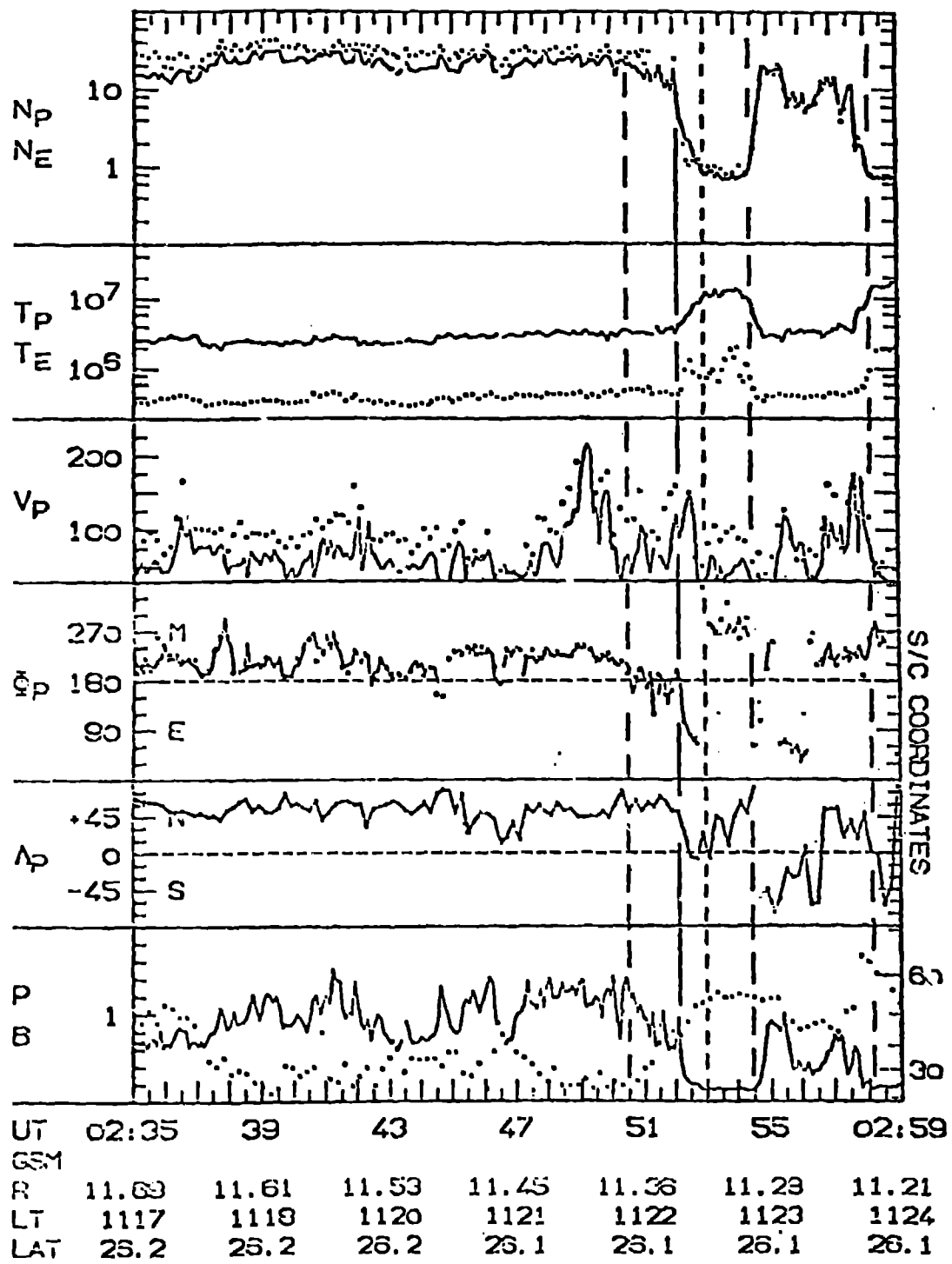


FIGURE 4

