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Spacecraft potential variations inside the magnetopause during transient events: Geotail observations

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Abstract. We examine the spacecraft potential (SP) variations near the magnetopause. In the magnetosphere the Geotail satellite often observed transient SP increase accompanied by magnetic field enhancements. This signature (SP increase and magnetic field increase) was also observed inside the magnetopause during the outbound (from the magnetosphere to the magnetosheath) and/or inbound (from the magnetosheath to the magnetosphere) magnetopause crossings. For the interval of the SP increase, the plasma density and temperature were intermediate between those of the magnetosheath and the magnetosphere, and strong enhancements of the field-aligned bidirectional electron fluxes were observed mainly in the medium energy (~300-450 eV) range. These observations are consistent with previous studies in the inner part of the low-latitude boundary layer (LLBL). Thus we suggest that the transient SP increase in the magnetosphere may be a good indicator of the entry into the inner LLBL.

1. Introduction

The spacecraft potential (hereafter referred to as SP) is a balance between the photoelectron current from the spacecraft and the incoming thermal electron current from the plasma in the region where both currents are dominant current sources. SP is roughly proportional to $nT^{1/2}$, where n is the plasma density and T is the electron temperature, and can be used as a good indicator of the ambient plasma density [e.g., *Pedersen*, 1995]. That is, increases in SP correspond to decreases in the plasma density.

Transient SP increases accompanied by magnetic field enhancements just inside the magnetopause during a brief magnetosheath entry have been reported by *Kawano et al.* [1994] and *Mozer et al.* [1994]. The authors suggested that the SP increase can be attributed to a density decrease. However, neither study gave direct evidence for plasma density variations because plasma data were not available. Recently, we have reported similar signatures (SP increase and magnetic field increase) prior to magnetopause crossings in another paper [*Kim et al.*, 2001]. In that study, we showed that measurements of the SP in the magnetosphere and magnetosheath were a good indicator for identifying different plasma regimes near the magnetopause: larger in the magnetosphere (i.e., lower density) than in the magnetosheath (i.e., higher density). However, we found no ion density decrease for the interval of the SP increase and, in some intervals, SP increases were accompanied by small pulsed ion density events [see Kim et al., 2001, Figure 4]. The ion density of the pulsed plasma was intermediate between that of the magnetosheath and the magnetosphere, suggesting that the satellite encountered the low-latitude boundary layer (LLBL). This implies that the SP increase in the LLBL does not always respond to plasma density decrease.

In this paper, we examine SP increases observed inside the magnetopause, using magnetic and plasma data. Simultaneous observations of multiple parameters from the Geotail satellite are helpful in understanding the SP variations near the magnetopause. In section 2, we will describe the data for this study and present examples of the SP variations inside the magnetopause. In section 3, we will briefly discuss why the SP increase is observed in the LLBL.

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2. Observations

The Geotail data used in this study consist of the magnetic field data measured by the fluxgate magnetometer [*Kokubun et al.*, 1994], SP observed with a single-axis electric field probe [*Tsuruda et al.*, 1994], and ion and electron data obtained by the low-energy particle (LEP) experiment [*Mukai et al.*, 1994]. The spin (~3 s) averaged magnetic and SP data are resampled to the resolution (~12 s) of the LEP plasma moments to compare the field and SP variations with the plasma variations. The LEP sensors are usually changed from the energy-per-charge analyzer (EA) to the solar wind ion analyzer (SW) as the Geotail satellite crosses the dayside magnetopause from the magnetosphere to the magnetosheath. However, the SW data can have large errors near the dayside magnetopause because the plasma flow direction is largely deflected out of the field of view. Therefore we used only the LEP-EA data in this study.

Figure 1 shows the magnetic field in GSM coordinates, SP, ion bulk flow, and plasma density and temperature during an outbound pass through the morningside magnetopause on May 7, 1995. In the density and temperature panels, the ions (electrons) are plotted with the thick solid (thin solid) lines. Note that SP is plotted positive downward, so that larger (smaller) values indicate lower (higher) densities. The missing LEP data are the periods measured by LEP-SW sensor. Geotail was initially in the magnetosphere, as evidenced by strongly northward magnetic field, low plasma density, and high temperature. During the intervals of ~1811-1812 and ~1822-1823 UT, the satellite transiently entered the magnetosheath, characterized by the magnetic field rotations. Before the outbound magnetopause crossings at ~1811 and ~1822 UT and after the inbound crossings at ~1812 and ~1823 UT, the satellite observed sharply increased magnetic field strength. This suggests that the brief magnetosheath entries may be caused by the passage of a local compression of the magnetopause induced by external (solar wind/foreshock) pressure pulses [*Sibeck et al.*, 1989]. Multiple magnetopause crossings were observed during the interval from ~1846 to 1900 UT. These multiple

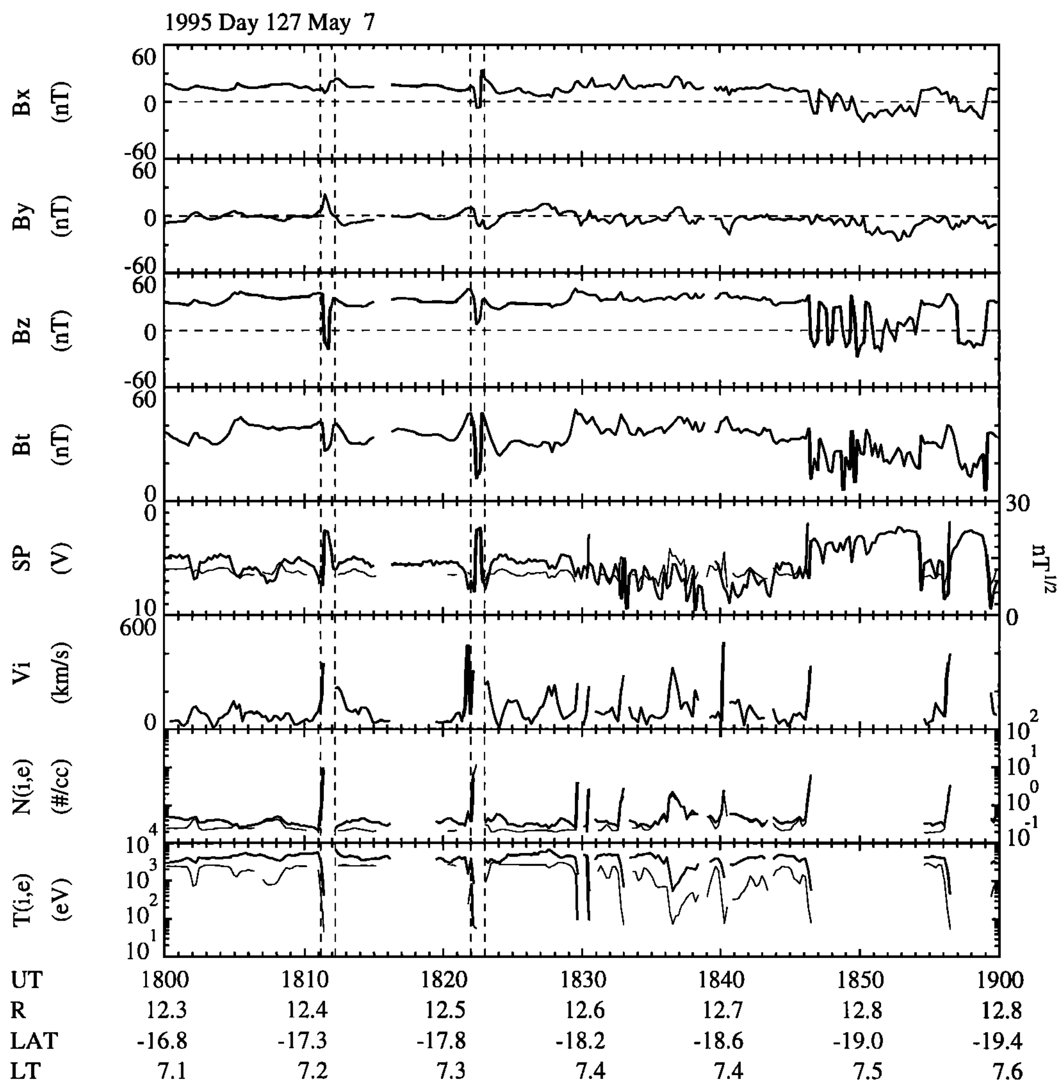

Figure 1. Geotail observations in GSM coordinates. From top to bottom are plotted magnetic field, spacecraft potential (SP), ion bulk flow, and ion (solid lines) and electron (thin solid lines) densities and temperatures. The thin solid line in the SP panel is the calculated $nT^{1/2}$.

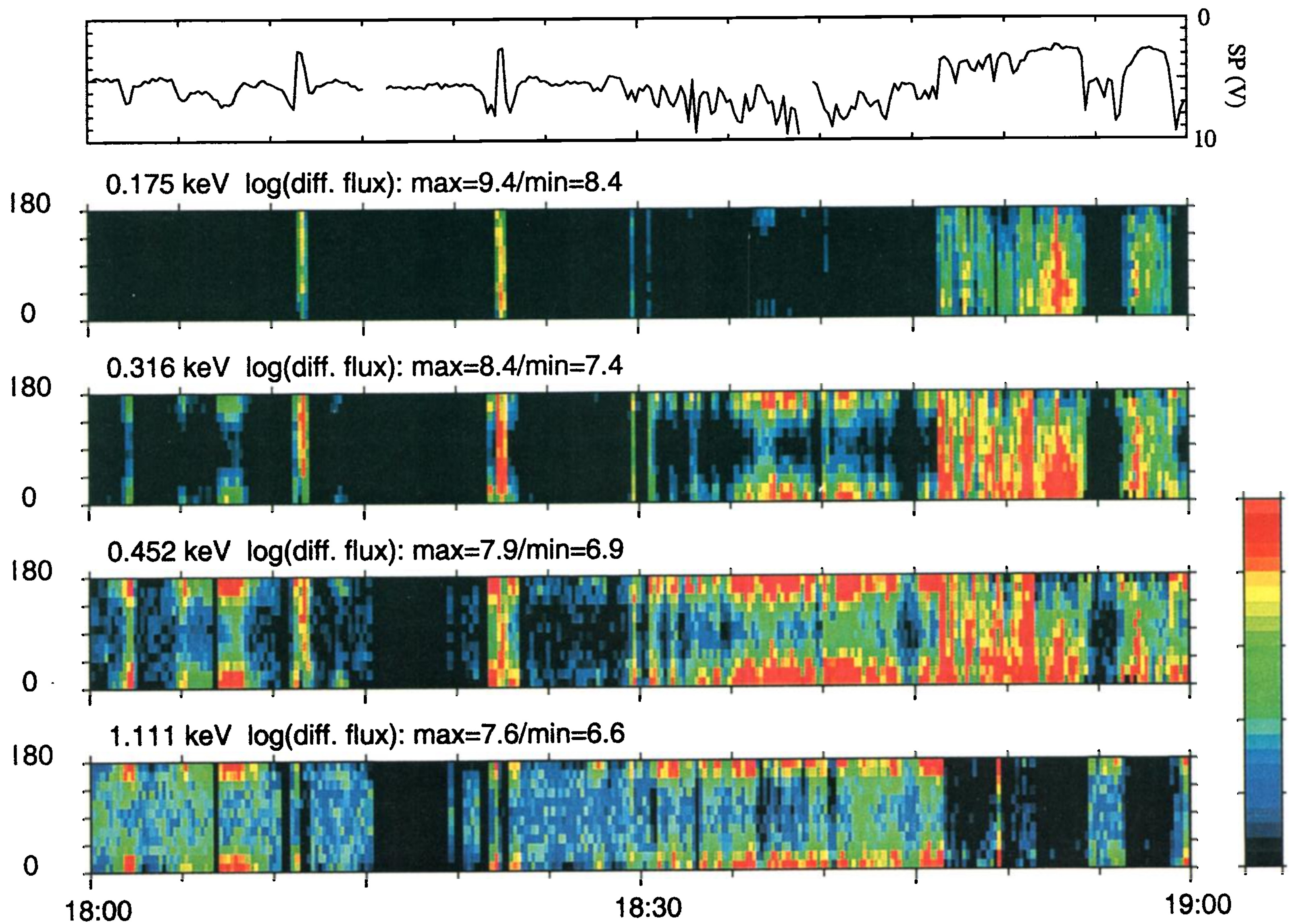

Plate 1. Spacecraft potential (SP) and electron pitch angle anisotropy. Differential fluxes ((cm^2 ster sec keV)$^{-1}$) from 0.175, 0.316, 0.452, and 1.111 keV energy channels are sorted by pitch angle and plotted versus time. The vertical axis gives the pitch angle and has a range of 0° to 180°. Color codes are assigned according to logarithms of fluxes (maximum and minimum are given on the top of each panel).

crossings could be due to external pressure variations [*Sibeck et al.*, 1989] or to the Kelvin-Helmholtz instability [e.g., *Aubry et al.*, 1971]. The plasma density and temperature measured by LEP-EA showed clear changes for the transient magnetopause crossings at ~1811 and ~1822 UT, but reliable plasma parameters in the magnetosheath were not obtained because the LEP sensor changed from EA to SW.

In order to compare the SP and $nT^{1/2}$, we plotted $nT^{1/2}$ with the thin solid line in the SP panel. Note that $nT^{1/2}$ was calculated with the electron density in units of particles cm^{-3} and the electron temperature in units of eV. The variations in SP are roughly consistent with those in the calculated $nT^{1/2}$. Although there are many LEP data gaps in the magnetosheath, SP is a good indicator of entry and exit into different regions near the magnetopause; in the magnetosphere, SP ~ 5 V, and, in the magnetosheath, SP ~ 2 V. An interesting feature to note is that the total magnetic field (B_t) enhancements just before the outbound crossings at ~1811 and ~1822 UT and after the inbound crossings at ~1813 and ~1823 UT were accompanied by an SP increase, plotted with the vertical dashed lines.

The simultaneous changes in both B_t and SP, just inside the magnetopause before the magnetopause crossing, are consistent with those reported by previous studies [*Kawano et al.*, 1994; *Mozer et al.*, 1994; *Kim et al.*, 2001]. Mozer et al. suggested that in the region of SP increase and B_t increase, the plasma density is lower than that in the magnetosphere. For the intervals of SP increase in our observations, however, the ion and electron densities did not show a significant depression; instead, they were intermediate between the magnetosheath and magnetospheric values (e.g., see the vertical dashed lines at ~1811 and ~1822 UT in the density panel), suggesting that the satellite entered the LLBL. At ~1802 UT and during the intervals of ~1804-1809 and ~1829-1845 UT, the signature of SP increase and B_t increase was observed. At ~1802 and ~1808 UT, there were small increases (decreases) in the ion and electron densities (temperatures), and their peaks occurred at SP maxima. Such small variations in the density and temperature would be interpreted as a brief encounter with the earthward edge of the LLBL.

Plate 1 shows the differential flux of the electrons from four channels (0.175, 0.316, 0.452, and 1.111 keV), as a function of time and pitch angle. The most remarkable feature in Plate 1 is that the enhancements of the bidirectional field-aligned electron fluxes at 0.316, 0.452, and 1.111 keV were observed for the intervals of SP increase. A similar bidirectional electron distribution was reported by *Hall et al.* [1991], who found that the inner part of the transition region (i.e., inner LLBL) is filled with "counterstreaming" electrons in the energy range of ~100-1000 eV.

Figure 2 exhibits another example of SP increase and B_t increase (marked by the vertical dashed lines) for the inbound pass from the magnetosheath to the magnetosphere on August 24, 1996, approaching the afternoon magnetopause. The magnetic field, SP, and LEP-EA plasma moments are plotted in the same format as in Figure 1. At ~0936 UT the satellite encountered the magnetopause, which is identified by the northward rotation of the magnetic field. Although one might consider that this northward turning was a temporal change in the interplanetary magnetic field (IMF) because we did not have the plasma parameters from 0900 to 0936 UT, comparison with IMP 8 data suggests that it was a magnetopause crossing. During the period from 0900 to 1200 UT, IMP 8 was upstream of the bow shock and moved from GSM (x, y, z) = (16.8, 7.2, −26.9) to (15.2, 8.2, −27.0) R_E. IMP 8 observed southward IMF before ~1055 UT and northward IMF from ~1055 to ~1200 UT (not shown here). The solar wind speed was not available from IMP 8, but we obtained it from the Wind satellite, which moved from GSM (x, y, z) = (70.6, −16.2, 3.5) to (71.7, −16.0, 3.6) R_E during the interval 0900-1200 UT. The solar wind speed was ~400 km s^{-1}. Using a solar wind speed of ~400 km s^{-1}, the propagation time from IMP 8 to Geotail was ~5 min. Thus we can identify that the satellite crossed the magnetopause at ~0936 UT, and the observed pulsed plasma variations in the density and temperature from ~0936 to ~1005 UT indicate that the satellite repeatedly encountered the LLBL without crossing the magnetopause. The pulsed LLBL plasma signatures were also observed during the interval from ~1012 to ~1200 UT, but the density and temperature variations were much smaller (i.e., lower density and higher temperature) than those in the earlier interval (~0936-1005 UT). This may be due to the satellite position relative to the magnetopause. That is, the lower-density pulsed events observed in the later interval (~1012-1200 UT) may be in the region closer to Earth (i.e., inner LLBL) and the higher-density pulsed events in the earlier interval were closer to the magnetopause (i.e., outer LLBL).

As mentioned above, SP is a good parameter for identifying different magnetospheric regions. The $nT^{1/2}$ variations plotted with the thin solid line in the SP panel are very consistent with the SP variations. SP was ~1 V in the magnetosheath from 0900 to ~0936 UT and ~4 V in the magnetosphere (~1012-1200 UT). A very interesting feature in Figure 2 is that in the first interval (~0936-1005 UT) the variations in SP were in phase with the pulsed density variations, while in the second interval (~1012-1200 UT) they were out of phase with the pulsed density variations. During the first interval the minima of the SP variations were intermediate between the magnetosheath and magnetospheric values, implying that the satellite was in the LLBL, while their maxima (~6 V) were larger than the magnetospheric value. The SP increases in the second interval were accompanied by magnetic field enhancements, and the maxima of SP during the B_t enhancements in the later interval were comparable to the SP maxima in the first interval. We note that for the interval of ~1100-1200

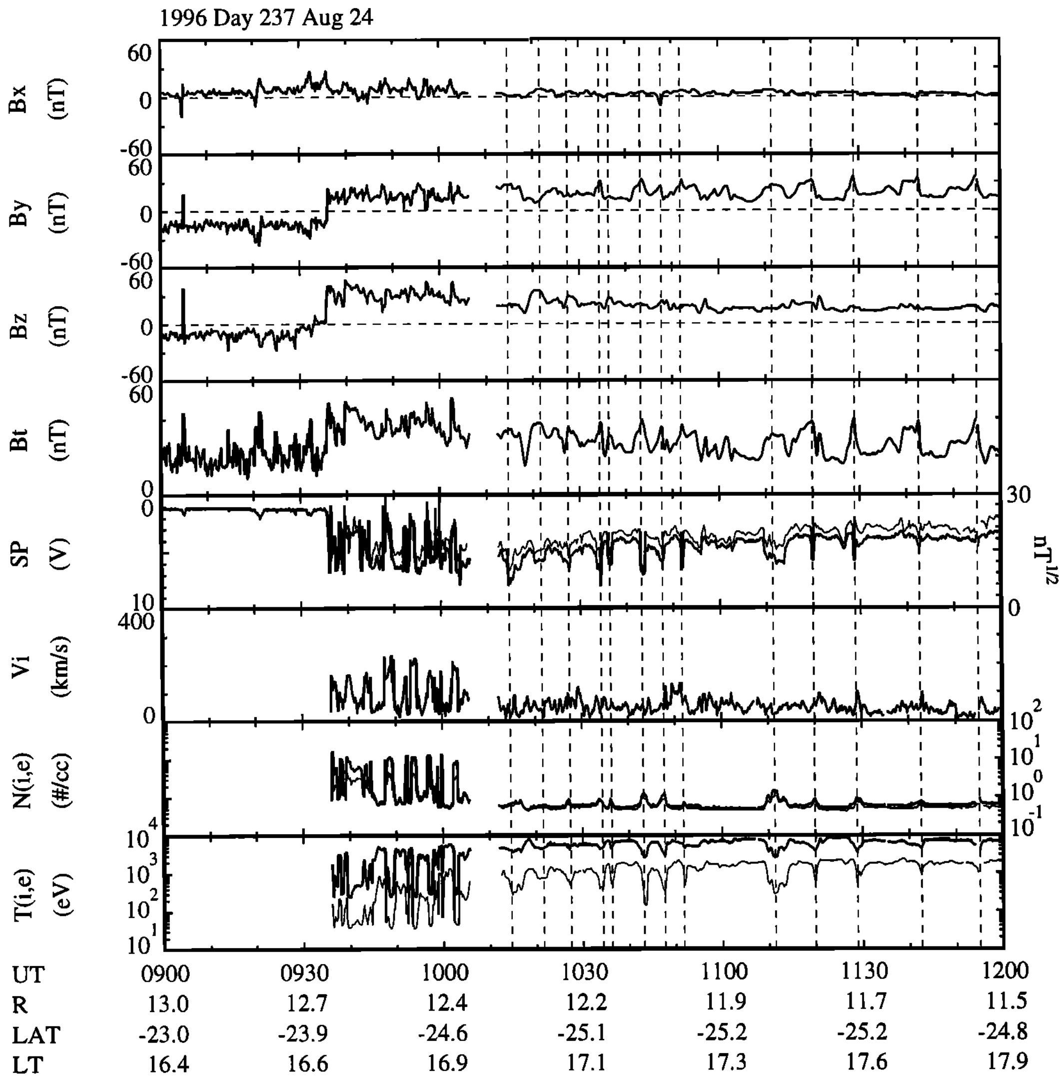

Figure 2. Same as Figure 1, except for the time interval from 0900 to 1200 UT, August 24, 1996. The vertical dashed lines indicate the transient SP increases.

UT, the IMF was northward. This implies that the occurrence of the SP increase does not depend on the IMF orientation. As in the previous example, bidirectional electrons were observed for the intervals of the SP increase (M. Fujimoto, personal communication, 2001).

3. Summary and Discussion

We have studied transient SP variations observed inside the magnetopause by the Geotail satellite. The observations can be summarized as follows: (1) The SP increases were accompanied by magnetic field enhancements and observed inside the magnetopause; (2) the occurrence of the SP increase does not depend on the IMF orientation; (3) the variations in SP and the plasma density were in (out of) phase in the region closer to the magnetopause (Earth); and (4) during the intervals of the SP increase, strong enhancements of field-aligned bidirectional electron fluxes were observed in the medium energy (~300-450 eV) range. Such a field-aligned distribution was present up to ~1000 eV.

These observations suggest that SP is a good parameter for identifying the inner and outer LLBL regions. In Figure 3 we schematically present the variations in the plasma density (N), SP, and total magnetic field (B_t) near the magnetopause during an outbound satellite pass. We assumed that the magnetic field in the magnetosheath (region 4) is smaller than that in the magnetosphere (region 1). Regions 2 and 3 are the inner and outer LLBL, respectively. The magnetopause is located between region 3 and region 4. The magnetic field enhancements indicate a transient compression of the magnetosphere.

One might interpret region 2 (SP increase and B_t increase) to be the plasma depletion region [*Zwan and Wolf*, 1976] because SP increase is indicative of a plasma density decrease. However, evidence against a depletion region is that the plasma density for the interval of tran-

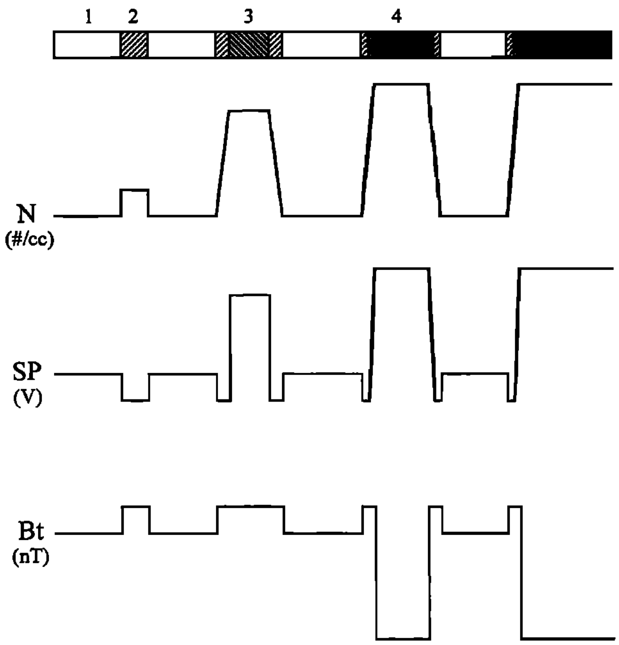

Figure 3. Schematic illustration of the plasma density (N), spacecraft potential (SP), and total magnetic field (B_t) variations near the magnetopause during an outbound satellite pass. SP is plotted positive downward. Regions 1-4 denote the outer magnetosphere, inner low-latitude boundary layer (LLBL), outer LLBL, and magnetosheath, respectively.

sient SP increase showed pulsed variation and its value is larger than that in the magnetosphere.

We note that SP depends on $(nP)^{1/2}$, where n is the plasma density and P is the electron pressure, so it is not necessary for the SP increase to always respond to plasma density decrease. The SP increase could be caused by an electron pressure decrease. In regions 2 and 3 (i.e., the LLBL), the electron population characteristics are intermediate between those in the magnetosphere and magnetosheath. The magnetospheric (magnetosheath) electrons are hot (cold) and decrease in density with increasing distance outward (inward) from the inner (outer) edge of the LLBL. Thus we might expect that SP, which depends on a combination of the density and electron pressure, would be larger in part of the LLBL than in the magnetosphere, even though the electron density increases. Strong evidence for this argument is that the variations in SP are very consistent with the $nT^{1/2}$ variations (see Figure 2).

Hall et al. [1991] observed pulsed electron boundary layer signatures (density increase and temperature decrease) in the inner part of the transition region, and during the pulsed events, transient magnetic field enhancements were accompanied by electron pressure depression (e.g., see Figure 12 in their study). In particular, they found counterstreaming electrons with a spectral peak in the medium energy (a few hundred electron volts) range in that region. These field and plasma signatures are very consistent with those for the intervals of SP increases in our study. Thus the region of SP increase may be the same region as the inner part of the transition region described by Hall et al.

In the outer LLBL (region 3), magnetosheath particles dominate, and SP shows a signature similar to that in the magnetosheath, but with a value intermediate between the magnetosheath and the magnetosphere values. If a satellite passes the inner and then outer LLBL, SP will show a change from its maximum to a value in the outer LLBL as plotted in Figure 3. This argument can explain why Geotail observed the maxima in SP during the interval of ~0936-1005 UT, that is, the satellite repeatedly encountered the outer and inner LLBL.

The enhanced magnetic field strengths observed during the SP increases may result from the transient compression of the LLBL inward to the location of the satellite rather than a steady state feature. We note that the magnetic field strength in the compressed LLBL will not always be larger than that in the magnetosphere because the compressed magnetic field in the LLBL may vary from event to event. The LLBL compression may be due to magnetopause motions produced by an external pressure pulse or the Kelvin-Helmholtz instability, or by the passage of a reconnected flux tube.

In conclusion, we suggest that SP may be a good indicator of the inner and outer LLBL. The transient SP increase in the outer magnetosphere may correspond to the electron pressure variation and indicate transient entry into the inner LLBL. In the future, it will be necessary to increase the number of observing points in space, such as the four-satellite Cluster II mission, near the magnetopause to clearly understand the SP variations during transient events.

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