Historical Review (pre-1980) of Magnetospheric Boundary Layers and the Low-Latitude Boundary Layer

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INTRODUCTION

This historical survey covers research on the magnetospheric boundary layers through 1979 with a focus on observations and on the low-latitude boundary layer (LLBL) of Earth's magnetosphere. An effort was made to identify and read every paper published prior to 1980 that made a significant contribution towards identifying and characterizing boundary regions of the outer magnetosphere. The total list of over 80 papers is available at http://www.plasmas.org /BL. A sketch of Earth's magnetosphere is shown in Figure 1, which illustrates the major regimes and boundary layers. The magnetospheric boundary layer denotes all exterior boundary layers adjoining the magnetopause, including the dayside and tail flank portions of the LLBL, the exterior cusp region and entry layer, and the plasma mantle. There is a plasma sheet boundary layer separating the lobe and plasma sheet regions, but that boundary layer is not reviewed here [see *Eastman et al.,* 1984]. The magnetotail boundary layer refers to both the plasma mantle and the tail flank portion of the LLBL.

THEORY RELATED TO BOUNDARY LAYERS

Table 1 lists key theoretical developments prior to 1980. Shortly before Birkeland's auroral campaigns, Lord Kelvin offered "absolutely conclusive" evidence against any connection between the sun and magnetic storms [*Kelvin,* 1892]. In this context, it is all the more amazing that *Birkeland* [1896,1901,1908] first suggested a continuous solar wind and a cavity surrounding the Earth that excludes solar particles. Before the direct confirmation of the magnetopause from Explorer 12 [*Cahill and Amazeen,* 1963] and other in situ observations, which conclusively demonstrated the continuous presence of both the solar wind and the magnetosphere, it was generally thought that both these systems and geomagnetic storms were intermittent phenomena. *Chapman and Ferraro* [1931] presumed such intermittence as they developed a model of the cavity boundary. *Ferraro* [1952] made this more quantitative and calculated the size, shape and thickness of the magnetopause.

Three major types of theories were proposed in the early 1960's for solar wind-magnetosphere interaction: dynamo models [*Piddington,* 1960], reconnection [*Dungey,* 1961], and viscous interaction [*Axford,* 1962]. A simple hydromagnetic flow model predicted solar wind plasma filling of the outer cusp region [*Spreiter and Summers,* 1967]. The increasingly successful reconnection model predicted cusp entry and convection into the magnetotail at high latitudes. Thus, by the early 1970s the focus was on observations in the cusp region and high latitudes, and *Frank* [1971] first clearly observed a cusp boundary layer using Imp 5 observations. In contrast, there was essentially no expectation at this time of finding a non-cusp boundary layer on the dayside at low latitudes. The viscous interaction and dynamo models remained without significant quantitative development with one notable exception. *Coleman* [1970, 1971] developed a comprehensive model for a dayside boundary layer using the dynamo concept, published in the Cosmic Electrodynamics and Radio Science journals, and which attracted little attention. Apparently unaware of these papers, *Willis* [1975] argued, on both theoretical and observational grounds, against any boundary layer other than the magnetopause layer for the dayside region at low latitude. He called attention to a clear crossing of the low-latitude magnetopause near local noon by Imp 5 presented by *Frank* [1971] who states that "the magnetopause near the magnetic equatorial plane appears to be an extremely effective barrier against the direct entry of solar plasma." In contrast, the theoretical expectation of boundary layer plasmas in the outer cusp region and tailward were clearly confirmed by a series of observations from 1971 onward as discussed in the next section.

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Geophysical Monograph 133
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10.1029/133GM01

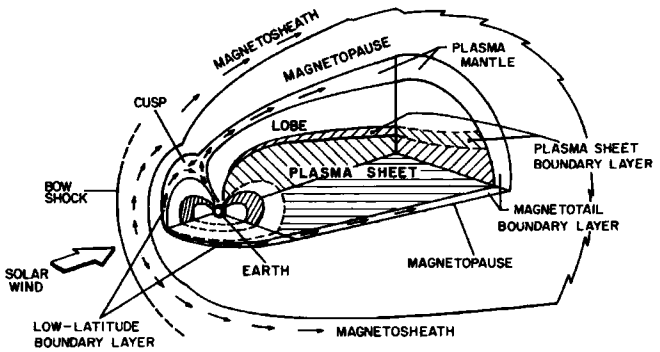


Figure 1. A sketch of the Earth's magnetosphere showing the boundary layers (adapted from *Eastman* [1979]).

Observations motivated four theoretical efforts in the late 1970's. One was the introduction by *Lemaire* [1977] of the impulsive penetration model, which emphasized the observed variability of solar wind input and analyzed the effect of filamentary current structures. Such filamentary structures were confirmed by *Russell and Elphic* [1978] who referred to them as "flux transfer events." The second was the evidence for high density gradients near the magnetopause based on high-resolution electron data [*Eastman and Hones,* 1979]. This was used by *Gary and Eastman* [1979] in an early quantitative study of the possible role of kinetic instabilities. Efforts to generate a boundary layer using MHD instabilities began to appear after 1980, although the Kelvin-Helmhotz instability was used in several earlier studies focused on the stability of the magnetopause [*Ong and Roderick,* 1972]. The third was the quantitative boundary layer to ionosphere coupling model developed by *Sonnerup* [1979] to test the suggestion by *Eastman et al.* [1976] that the LLBL acts as an MHD generator to drive field-aligned currents. The fourth key theoretical effort was that associated with magnetic merging or reconnection at the magnetopause and its associated energy dissipation. *Heikkila* [1975] clearly framed the problem and estimated the amount of energization expected, noting that available observations had so far failed to reveal the required energization. Indeed, finding such energization was a primary motivation for my analysis of Imp 6 plasma data near the magnetopause beginning late in 1975. Instead of finding the expected energization signatures, I instead confirmed the existence of the dayside LLBL and documented its primary signatures [see section below on the *Dayside Low-Latitude Boundary Layer*]. *Paschmann et al.* [1979] reported the first clear indication of plasma acceleration near the magnetopause as expected for magnetic merging.

The year of introduction for various terms relevant to magnetospheric boundaries is given in Table 2. Terminology for all major plasma regimes and boundaries was in place by the end of the 1970s.

CUSP AND PLASMA MANTLE OBSERVATIONS

Table 3 summarizes key observational results that provided indications and confirmation of the cusp, entry layer and plasma mantle regions. The cusp boundary layer was clearly identified by *Frank* [1971] using Imp 5 plasma observations combined with field model comparisons. Further confirmation was provided by *Russell et al.* [1971] and *Paschmann et al.* [1974].

In general, the direct confirmation of boundary layers near the magnetopause requires a combination of plasma and field observations. This is because magnetosheath and outer boundary layer spectra can be very similar, which creates the possibility that multiple magnetopause crossings with multiple magnetosheath segments can appear like a "boundary layer" to a plasma instrument. The Vela satellite series had no magnetometers because of their focus on the monitoring of atmospheric nuclear explosions. Nevertheless, *Hones et al.* [1972] showed possible boundary layer examples in Vela 4B plasma data that were primarily magnetosheath-lobe transitions and strongly suggested high-latitude boundary layer or plasma mantle. Working with Hones and the Los Alamos group, *Akasofu et al.* [1973] documented more cases with Vela 5 and 6, most of which were more than 5 R_E above the magnetotail neutral sheet. They interpreted this boundary

Table 1. Theory related to boundary layers

Year	Authors	Description
1896, 1901, 1908	Birkeland	First suggested solar wind and cavity around earth
1931	Chapman and Ferraro	First model of the magnetopause (MP)
1952	Ferraro	Calculated size, shape and thickness of the magnetopause
1957	Bierman	Estimated MP standoff distance
1961	Dungey	Reconnection model of solar wind - magnetosphere interaction
1964	Axford	Suggests complementary nature of reconnection, viscous interaction (*Axford*, [1962]), dynamo models (*Piddington,* 1960])
1964	Bernstein et al.	Production of broad MP transition from plasma instabilities
1967	Parker	Broadened MP from charge neutralization
1967	Spreiter and Summers	Predicted solar wind plasma filling of cusp region
1968	Eviatar and Wolf	Developed diffusive transfer theory for the magnetopause
1968	Stevenson and Comstock	Computer study of particle trajectories incident on magnetic field gradients
1970	Coleman	First comprehensive model for a low-latitude boundary layer; uses dynamo concept (*Piddington* [1960] and *Cole* [1960])
1975	Heikkila	Discusses problem of energy dissipation at the magnetopause
1975	Willis	Magnetopause review; argues against any boundary layer other than MP layer
1976	Lemaire	Impulsive penetration model; filamentary current structures
1979	Sonnerup	LLBL-ionosphere coupling model
1979	Gary and Eastman	Kinetic plasma model for boundary layer formation

layer as "the magnetic projection of the dayside cusps." An example of a magnetosheath-lobe transition with a boundary layer is shown in Figure 2a. The magnetopause is presumed to be associated with the first large density decrease during this inbound crossing. Temperature and bulk speed continue to decrease until the lobe is encountered sometime after 1800 UT. The latitude-longitude plot for the 18 R_E Vela sphere presented in Figure 2b shows that most cases occur at dZ > 5 R_E (or 16° latitude) and these crossings would be primarily transitions into the tail lobes as noted by the authors.

Haerendel [1974] reported the initial Heos 2 plasma mantle observations using both plasma and field observations. Confirmation of the plasma mantle was then completed by *Rosenbauer et al.* [1975] who provide a detailed report on Heos 2 observations. An example from their paper is shown in Figure 3, which shows a clear magnetopause near 1335 UT preceded by an extended boundary layer interval with intermediate density, speed, and temperature values. Evidence of ionospheric ions in a boundary layer were first reported by *Lundin et al.* [1979] based on Prognoz-7 observations in the plasma mantle.

Haerendel and Paschmann [1975] provided the first report and confirmation of the cusp-region entry layer, which has less turbulent flow signatures than the central cusp region. Figure 4 shows one example from their paper, which shows a clear magnetopause at 0657 UT. Unlike the dayside LLBL discussed below, they report a "lack of consistent flow direction" in the entry layer. Indeed, the example shown here has sunward flow convection in contrast to the anti-sunward flow component in the nearby magnetosheath. They also find the entry layer to be closely associated with the cusp region. *Haerendel and Paschmann* [1975] proposed that it is "causally related" in that magnetosheath plasma first enters the magnetosphere via the entry layer, followed by mirroring within the lower altitude cusp region, and then is convected upward and tailward to produce the plasma mantle. *Crooker* [1977] provided further confirmation of the entry layer using Explorer 33 observations.

Haerendel et al. [1978] discussed mantle, entry layer, and the LLBL observations with an emphasis on Heos 2 observations. The term "LLBL" was first coined in this paper.

TAIL FLANK BOUNDARY LAYER

Magnetotail boundary layer observations are summarized in Table 4. Cases specifically identified as magnetosheath-lobe transitions or plasma mantle are not included in this list. The flank tail boundary is noted by *Gosling et al.* [1967] as sometimes "not well defined." One or two possible boundary layer cases associated with magnetosheath-plasma sheet transitions are shown by *Hones et al.* [1972] although the lack of magnetometer data prevents clear magnetopause identification. The clearest example is shown in Figure 5 wherein a boundary layer is marked as an intermediate plasma region between the plasma sheet (high relative proton counts) and magnetosheath (highly spin modulated proton counts). *Akasofu et al.* [1973] show a similar case of probable flank boundary layer and refer to other cases in a dZ versus theta orbit plot. However, as noted above, most Vela cases were at high dZ and would have been primarily plasma mantle intervals.

Using a model combined with statistics of lunar orbit plasma data from Explorer 35 led *Howe and Siscoe* [1972] to infer a tail boundary layer with 2 R_E thickness. Similarly, *Hardy et al.* [1975] report flank boundary layer signatures at lunar distance. *Eastman et al.* [1976] state that "the boundary layer is nearly always present at all latitudes and longitudes at which Imp 6 crossed the magnetopause," which includes crossings back to about X = -6.6 R_E. Their focus and examples, however, were on dayside LLBL cases (see below).

Within a paper focused on magnetotail dynamics and plasma jetting, *Frank et al.* [1976] showed both plasma and field data for several plasma sheet to boundary layer transitions. The first interval in Figure 6a, prior to 0945 UT, appears to be a tail flank boundary layer although comparison magnetosheath plasma is not immediately adjoining this interval and a check of distribution functions would be needed to distinguish it from plasma sheet boundary layer. Within a paper by *Scarf et al.* [1977] focused on plasma

Table 2. Introduction of magnetospheric terminology

Year	Authors	Term or Concept
1946	Giovanelli	reconnection
1958	Parker	solar wind
1959	Gold	magnetosphere
1963	Sonett, Abrams	magnetopause
1964	Dessler	magnetosheath
1966	Bame et al.	plasma sheet
1972	Hones et al.	boundary layer
1975	Haerendel	plasma mantle
1978	Haerendel et al.	LLBL
1979	DeCoster, Frank	plasma sheet boundary layer

Table 3. Cusp and plasma mantle observations

Year	Authors	Observations
1971	Frank	Confirmation of cusp boundary layer; Imp 5 observations
1971	Russell et al.	Ogo 5 in high-altitude polar cusp
1972	Hones et al.	Indications of plasma mantle; MS-lobe transitions; Vela-no B
1973	Akasofu, Hones	~Hones; most cases dZ>5 Re; best two cases shown are magnetosheath to lobe
1974	Paschmann et al.	Polar cusp observations from Heos 2
1974	Haerendel	Initial plasma mantle observations
1975	Rosenbauer et al.	Detailed Heos 2 report on the plasma mantle; plasma and B data
1975	Haerendel, Paschmann	Confirmation of entry layer
1977	Crooker	Explorer 33 observations of entry layer
1978	Haerendel et al.	Review of Heos observations for mantle, entry layer, and LLBL

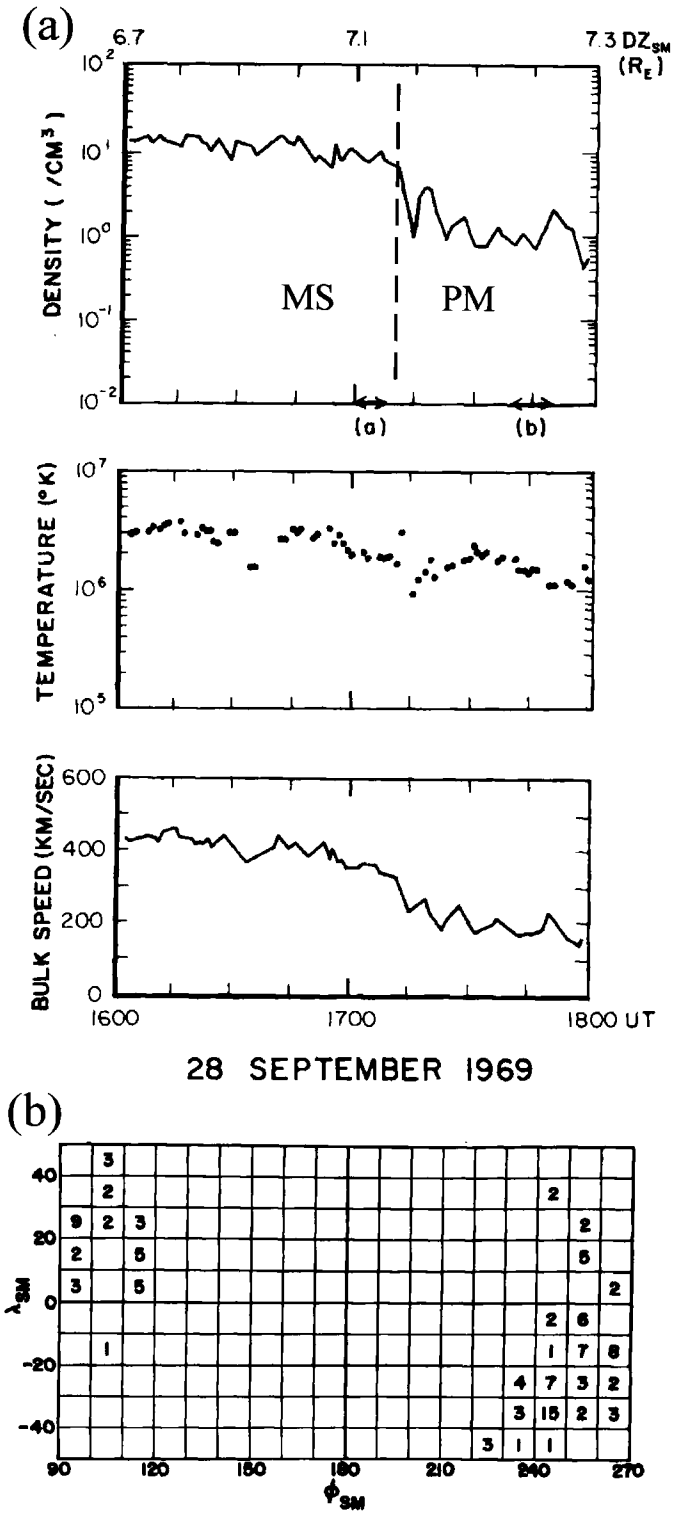


Figure 2. First indications of plasma mantle. (a) Magnetosheath (MS) - lobe transition by Vela 5B with plasma mantle (PM) followed by lobe after 1800 UT (from *Akasofu et al,* [1973]) - Vela satellites had no magnetometer; (b) number of Vela 4B boundary crossings shown in 10x10 degree bins on the 18 R_E Vela sphere (from *Hones et al.,* [1972]).

waves, there is a clear Imp 7 crossing of the flank LLBL shown here in Figure 6b and referred to by the authors as a "low-density mantlelike region." *Haerendel et al.* [1978] further documented characteristics of the flank LLBL and, as shown in Figure 6c, provided one example at 0535 local time. All together, these Imp 6, 7 and 8 and Heos 2 observations confirmed the presence and basic characteristics of the tail flank boundary layer.

Using Imp 6 plasma and field observations, *Eastman and Hones* [1979] reported statistics on 40 LLBL cases, including cases at X<0 of which one is shown in the paper. The most comprehensive study of the LLBL to date is my Ph.D. thesis, which provided detailed plasma and field data for 28 crossings, including four cases at X<0 [*Eastman,* 1979].

Dayside Low-Latitude Boundary Layer

The cusp and magnetotail boundary layers, either plasma mantle or flank type, are generally considered to be cusp-

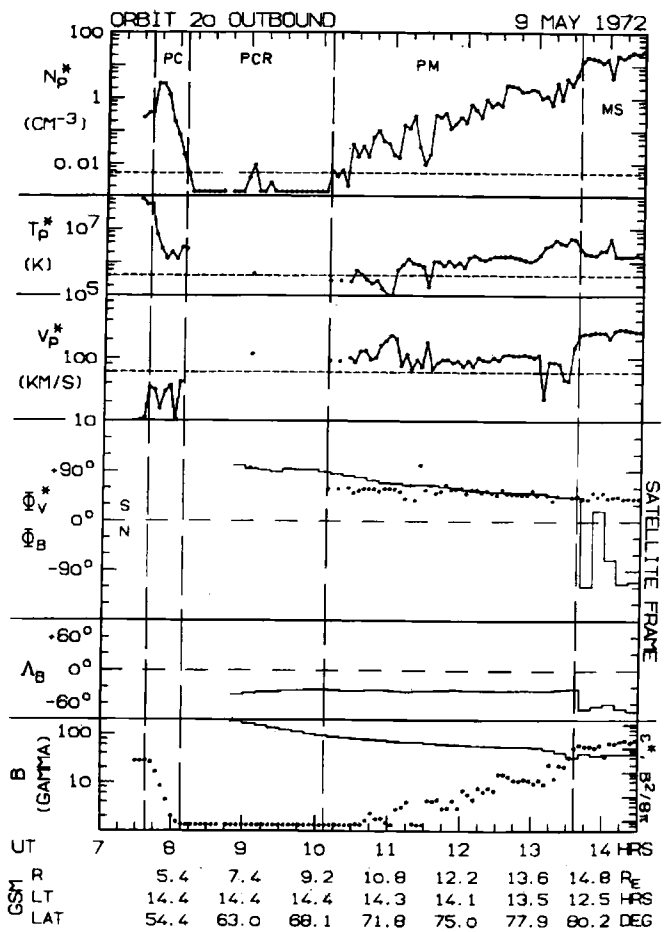


Figure 3. Confirmation of plasma mantle. Lobe (marked PCR for polar cap region) to magnetosheath transition from Heos 2 with plasma mantle; magnetopause clearly indicated by magnetic field rotation near 1335 UT (from *Rosenbauer et al.* [1975]).

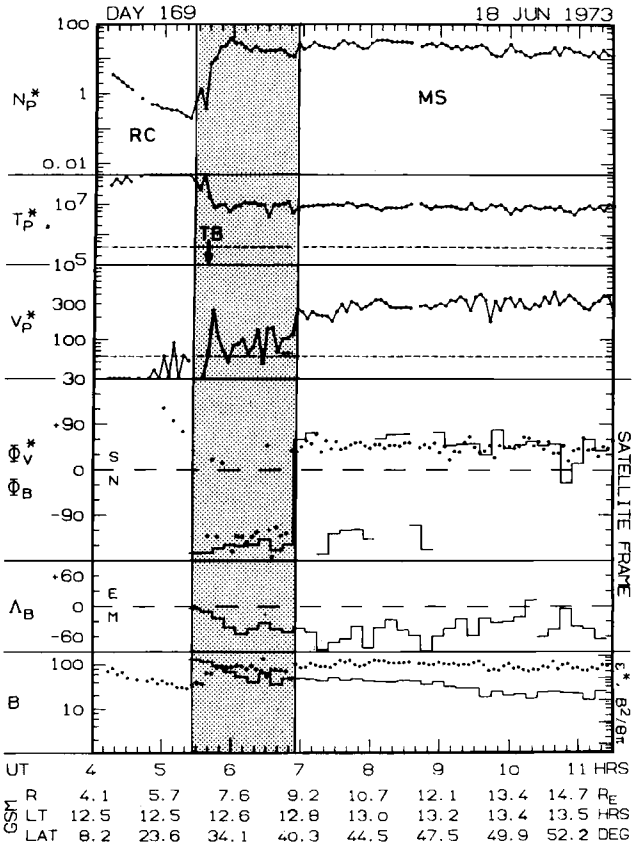


Figure 4. Confirmation of entry layer. Heos 2 transition from outer magnetosphere or ring current (RC) to magnetosheath with entry layer marked by shaded region (from *Haerendel and Paschmann* [1975]).

associated in this sense because plasma flows there are directed away from the subsolar region and not away from the cusp region [*Eastman and Hones,* 1979]. In contrast, flows can be either into or away from the cusp in the entry layer region. For example, the entry layer case in Figure 4 has sunward-directed plasma flow moving away from the cusp. As noted in the theory section above, early observations from Imp 5 presented by Frank [1971] indicated that the magnetopause at low latitude is "an extremely effective barrier." In addition to the arguments provided by *Willis* [1975] against any such boundary layer, many theorists were convinced that ideal MHD precluded direct entry of solar wind plasma across the magnetopause.

Table 5 summarizes dayside LLBL observations. As of the mid-1970s, there were no clear observations of the LLBL. The Vela results were all in the magnetotail, mostly sampled the plasma mantle, and lacked magnetometer data. Some papers in the mid-1960s refer to a "transition region" which, in context, is the magnetosheath. *Bonetti et al.* [1963] described some complex transition regions in the Explorer 10 data. The best early indication of a dayside boundary layer crossing is one unusual ATS 1 synchronous orbit magnetopause crossing reported by *Freeman et al.* [1968], which is shown in Figure 7a. Retarding potential analyzer (RPA) fluxes and flows are shown in two integral energy channels, E>0 eV and E>50 eV. A trade off is made between measuring flows and spectra, so spectra are unavailable. Some magnetosheath-like flows are shown near 0053 UT simultaneous with magnetospheric field levels based on high total field magnitudes. Later, *Ogilvie et al.* [1971] published examples of Ogo 5 electron and field data for some magnetopause crossings between 6.4 and 7.6 hours local time with a focus on transition intervals overlapping the current layer. As shown in Figure 7b, one Ogo 5 crossing shows a 50-second interval of elevated electron fluxes on magnetospheric field

Table 4. Magnetotail boundary layer observations*

Year	Authors	Spacecraft	Observations
1967	Gosling et al.	Vela 2	Outer tail boundary sometimes "not well defined"
1972	Hones et al.	Vela 4b	Indication of mantle and flank boundary layer (no B data)
1972	Howe, Siscoe	Exp 35	Tail boundary layer at lunar distance; model & statistics
1973	Akasofu et al.	Vela 5,6	Indication of mantle and flank BL; most cases dZ>5 Re
1975	Hardy et al.	Apollo	Indication of flank BL at lunar distance
1976	Frank et al.	Imp 8	Focus on plasma jetting; two examples of tail flank BL
1976	Eastman et al.	Imp 6	Frontside LLBL focus; tail flank LLBL cases noted
1977	Scarf et al.	Imp 7	Focus on plasma waves; one example of tail flank BL
1978	Haerendel et al.	Heos 2	Heos summary of plasma mantle, entry layer and LLBL
1979	Eastman, Hones	Imp 6	Statistics for 40 LLBL cases; one example shown at X<0
1979	Eastman	Imp 6	Ph.D. thesis on LLBL; details for 28 crossings; 4 at X<0

*Table does not include papers specifically focused on "plasma mantle."

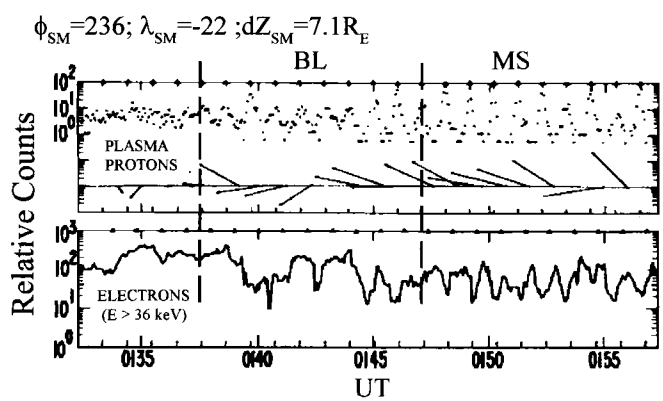
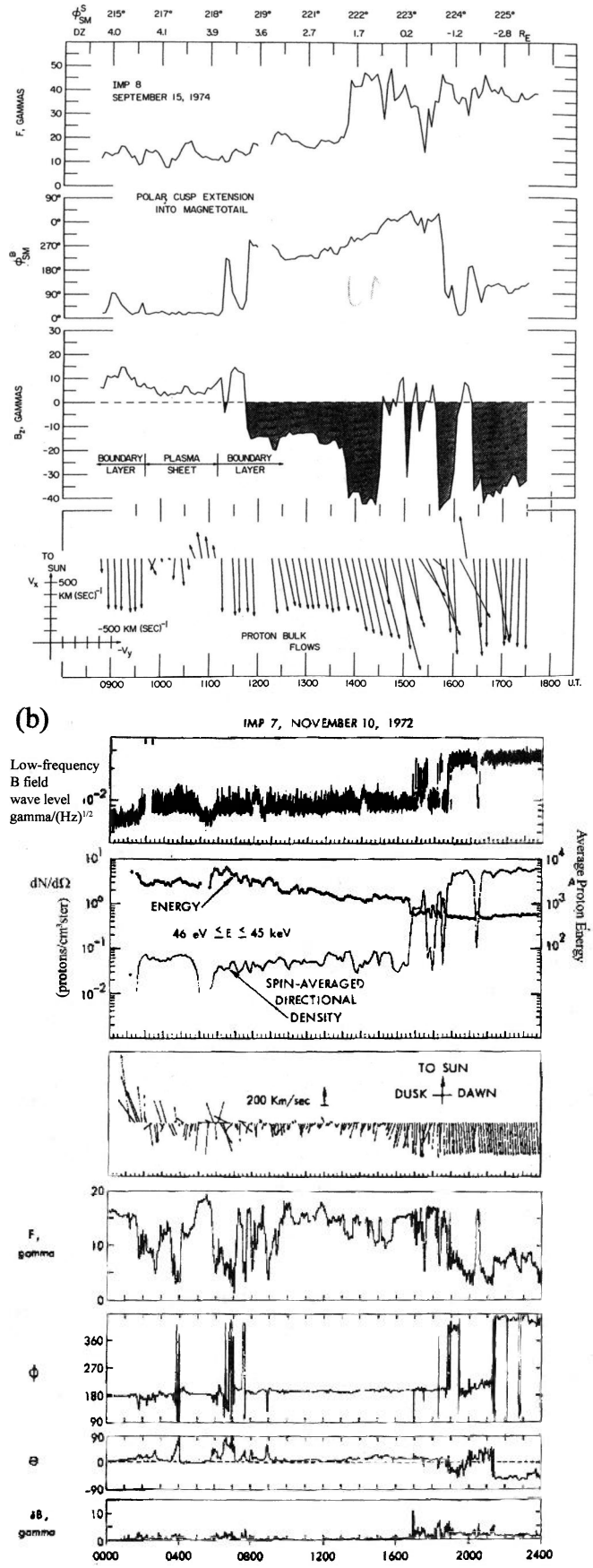


Figure 5. First indication of tail flank boundary layer. Vela transition from plasma sheet (PS), through possible boundary layer, to magnetosheath (from *Hones et al.*, [1972]).



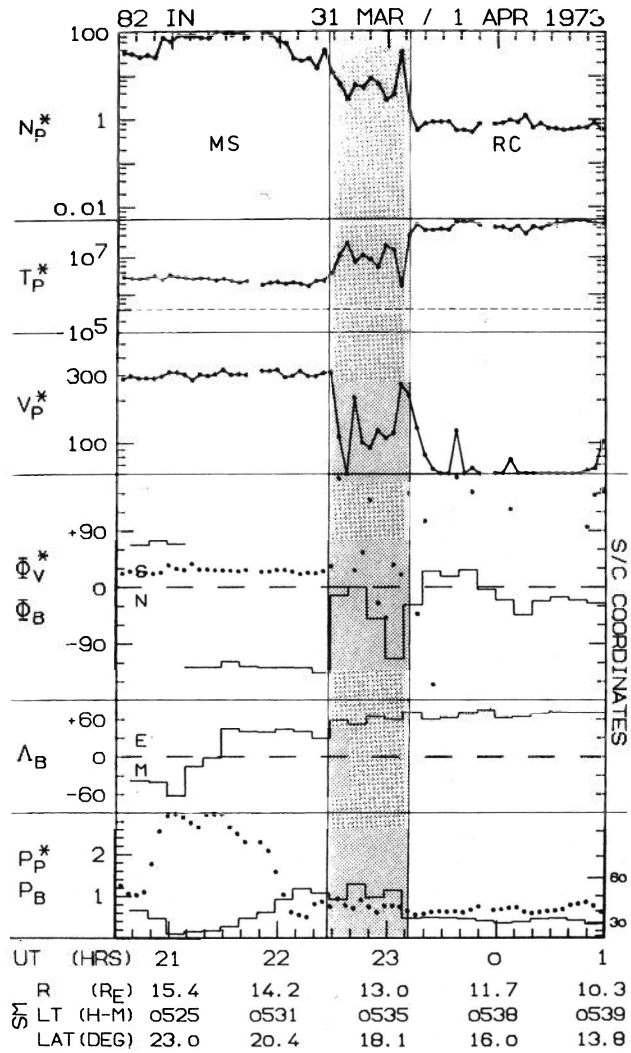


Figure 6. Confirmation of tail flank boundary layer. (a) Possible tail flank boundary layer from Imp 8 shown prior to 0945 UT (from *Frank et al.* [1976]); (b) Clear tail flank LLBL from Imp 7 showing both plasma and field data (from *Scarf et al.* [1977]); (c) Heos sample of tail flank LLBL (from *Haerendel et al* [1978]).

lines (not noted by the authors). Although ion data and flows were not presented, this interval suggests the presence of a boundary layer distinct from the magnetopause layer. Convection electric fields were measured by Aggson in a thin layer adjacent to the magnetopause but plasma densities were not reported [see *Heppner,* 1972]. In a review paper presented at the International Symposium on Solar-Terrestrial Physics in Boulder (June 7-18), *Sonnerup* [1976] included a section entitled "Front Lobe Boundary Layer." He states that "While the existence and properties of the high latitude plasma mantle are well documented, little direct experimental information exists concerning the presence or absence on the front lobe of the magnetosphere of a similar plasma boundary layer adjacent to the magnetopause."

Simultaneous with Sonnerup's review presentation, AGU received our manuscript, which provided details on combined ion and magnetic field data for two dayside crossings

shown here in Figure 8 [*Eastman et al.*,1976; see Appendix for personal reflections]. This research with the Los Alamos group was based on an extensive study of Imp 6 ion, electron, and field data for the low-latitude boundary region from the tail flank at X = -6.6 R_E to the subsolar region. Although full documentation for 28 LLBL crossings was delayed for the thesis itself [*Eastman,* 1979], this paper confirmed the existence of the dayside LLBL. The magnetopause location and thickness is unambiguous for the February 4, 1972 LLBL case. Detailed magnetic field plots show the current layer interval to be at 0050 to 0052:30 UT. Magnetosheath-like flows and intermediate density and ion energies clearly mark the boundary layer interval. The magnetopause interval is much less distinct in the June 16 case but extends no later than about 0406 UT based on full field and plasma characteristics [see Figure 2.3.4.2 in *Eastman,* 1979]. This crossing represents an unusually smooth boundary layer transition. Electron density samples at 12.5-s time interval suggested substantial sub-structure within the LLBL [*Eastman and Hones,* 1979], which led *Gary and Eastman* [1979] to propose a possible role for drift instabilities, especially the lower-hybrid drift instability.

Only one of the 28 LLBL crossings shown in *Eastman* [1979] has a possible density plateau signature as reported for some Heos 2 crossings by *Haerendel et al.* [1978]. Apparent plateaus can result from instrument cycle times, which were 256 seconds for Heos 2 compared with 100 seconds for the Imp 6 ion data. Clear density plateau cases were later published based on ISEE observations, but a plateau signature was not common for boundary layer crossings reported prior to 1980.

SUMMARY

Observational papers demonstrating the existence of major boundary regions of Earth's magnetosphere are listed in Table 6. *Sonett* [1959] reported an early observation of a probable magnetopause crossing from Pioneer 1 and 5. However, the presence of a magnetopause is inferred from patchy field samples. First confirmation or completion of the discovery process was accomplished with the following papers: *Cahill and Amazeen* [1963] for the magnetopause; *Frank* [1971] for the cusp boundary layer; *Haerendel* (1974) and *Rosenbauer et al.* [1975] for the plasma mantle; *Haerendel and Paschmann* [1975] for the entry layer; and *Eastman et al.* [1976] for the dayside LLBL.

The discovery process is often not based on any single observation or even any single publication. Confirmation of a boundary layer crossing requires a combination of plasma and field measurements. Magnetic field measurements are usually required to uniquely identify the magnetopause or current layer interval. Multiple magnetopause crossings could give the signatures of a boundary layer when sampling with a low-resolution plasma instrument.

For many researchers, *Hones et al.* [1972] "discovered" the tail flank LLBL. As shown above and specifically stated by Akasofu et al. [1973], most of the probable Vela boundary layer crossings occurred at high dZ values in association with magnetosheath-lobe transitions. Thus, if Hones discovered the tail flank LLBL, then he discovered the plasma mantle as well. However, discovery of the plasma mantle has long been credited to the Heos 2 group. Further, the Vela satellite had no magnetometer and unique magnetopause identification was not possible. Boundary layer intervals distinct from the magnetopause layer could be inferred or suggested, but could not be confirmed.

In my opinion, it is appropriate to credit *Hones et al.* [1972] with first indications of both the plasma mantle and tail flank boundary layers - in their own words, the "magnetotail boundary layer." Confirmation then followed with the Heos 2 results of *Haerendel* (1974) and *Rosenbauer et al.* [1975]. However, first confirmation or completion of the discovery process is more complicated with the tail flank LLBL. *Eastman et al.* [1976] noted that the boundary layer is "nearly always present at all" local times, which for Imp 6 means crossings back to about X = -6.6 R_E. A later study of magnetopause crossings without a boundary layer indicate that "such crossings constitute about 10% of all magnetopause crossings" [*Eastman,* 1996]. Although confirming the dayside LLBL, *Eastman et al.* [1976] did not include any tail flank LLBL crossings. Such cases were published in our 1979 papers [*Eastman and Hones*, 1979; *Eastman*, 1979]. *Frank et al.* [1976] showed a possible tail flank boundary layer crossing without identification as such. A clear tail flank LLBL case with both plasma and field data was later published by Scarf et al. [1977]. *Haerendel et al.* [1978] further documented characteristics of the flank LLBL with combined plasma and field signatures. In combination, observations from Imp 6, 7, 8, and Heos 2 confirmed the existence of the tail flank LLBL and documented its basic characteristics.

Table 5. Dayside LLBL observations

Year	Authors	Spacecraft	Observations
1963	Bonetti et al.	Exp 10	Associated complex transitions with possible BL (MS ?)
1966	Wolfe et al.	Imp 1	Some passes with gradual ion flux decrease near MP
1968	Freeman et al.	ATS 1	Indication of LLBL with one event at geostationary orbit
1971	Ogilvie et al.	Ogo 5	Possible LLBL in electron data near dawn meridian
1976	Eastman et al.	Imp 6	Confirmation of dayside LLBL; two examples
1978	Haerendel et al.	Heos 2	Heos summary; six examples; first used "LLBL"
1979	Eastman, Hones	Imp 6	Statistics for 40 LLBL cases; 11 examples presented
1979	Eastman	Imp 6	Ph.D. thesis on LLBL; details for 28 crossings
1979	Paschmann et al.	ISEE	First indication of merging acceleration at magnetopause

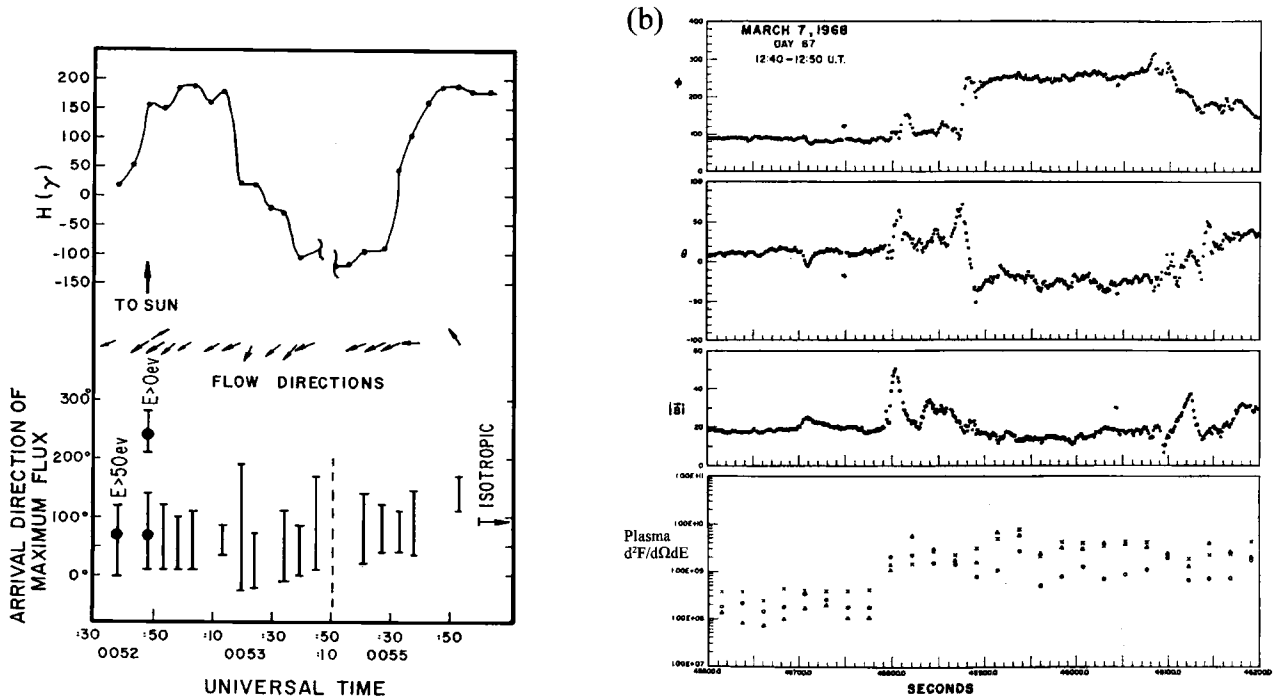


Figure 7. First indications of dayside LLBL. (a) ATS 1 synchronous orbit crossing at 14 hours local time showing total magnetic field H and RPA fluxes and flows for E>0 eV and E>50 eV (from *Freeman et al.* [1968]); (b) Possible brief LLBL period in Ogo 5 electron data (from *Ogilvie et al* [1971]).

CONCLUSION

The period from the advent of the space age in the late 1950s up through the 1970s was a great period of discovery for magnetospheric physics in which most of its major regimes and boundaries were first identified and characterized. This review has attempted to encompass all publications that enabled these discoveries with a focus on major plasma regions and boundaries of the Earth's outer magnetosphere. Magnetospheric physics has continued to be a major area of space physics studies, most recently with a focus on "Space Weather" and space environment impacts on technological systems. However, the discovery mode so dominant prior to 1980 is now replaced by a much greater balance of theory, modeling, laboratory experiment, and in situ observation that promises continuing progress in quantitative understanding of one of the most complex, large-scale physical systems in science.

APPENDIX. PERSONAL REFLECTIONS

Working with Ed Hones and the Los Alamos group, I began in mid-1975 to carry out a systematic analysis of Vela and Imp 6 magnetopause crossings. Dr. Hones was busy working on magnetotail and substorm issues and graciously allowed me to focus my thesis work, with the Geophysical Institute of the University of Alaska, on the boundary layer question, which he had initiated earlier with the Vela studies. The Ph.D. thesis topic proposal of July 23, 1975 refers to "A Study of the Magnetotail Boundary Layer." For the Fall 1975 AGU meeting, my presentation was on "Recent Vela satellite observations of the magnetospheric boundary layer." After that presentation (results unpublished), I turned my attention entirely over to the Imp 6 data set with Hones' encouragement and our mutual recognition of the importance of simultaneous plasma and magnetic field measurements in the dayside magnetopause region. My initial analysis encompassed some 225 Imp 6 magnetopause crossings which I quickly pared down to about 133 cases for thickness estimates and a search for any correlations with solar wind input and geomagnetic activity. Ultimately, detailed analysis focused on 28 LLBL crossings for the thesis [*Eastman*, 1979]. Early on, my objective was to look for evidence of accelerated flows near the magnetopause on the dayside or other evidence of energization expected for merging. Based on a comprehensive search of Imp 6 magnetopause crossings at all local times, and using combined ion, electron, and magnetic field data, I instead found clear evidence in many crossings for a distinct boundary layer located earthward of the current layer. Recognizing the importance of these results, I worked rapidly to prepare a paper for the newly formed journal, Geophysical Research Letters. My first draft, dated April 1, 1976, used the term "transfer layer" for the dayside boundary layer. In the final published work, we used the term "magnetospheric boundary layer" [*Eastman et al.*, 1976].

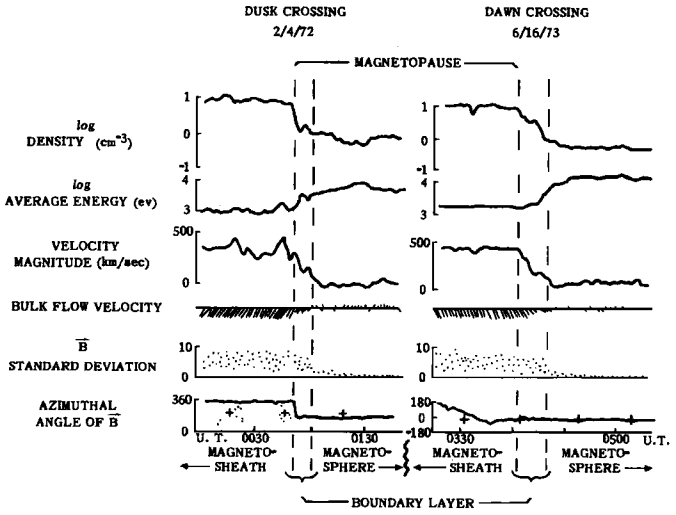


Figure 8. Confirmation of dayside LLBL. Duskside and dawnside LLBL crossings by Imp 6 (from *Eastman et al.* [1976]).

Table 6. Magnetopause and boundary layer observations

Year	Authors	Spacecraft	Observations
1963	Cahill, Amazeen	Exp 12	Confirmation of magnetopause
1968	Freeman et al.	ATS 1	First indication of dayside LLBL
1971	Frank	Imp 5	Confirmation of cusp boundary layer
1972	Hones et al.	Vela 4b	First indication of plasma mantle and tail flank boundary layer
1974	Haerendel	Heos 2	Initial report of plasma mantle
1975	Rosenbauer et al.	Heos 2	Confirmation of plasma mantle
1975	Haerendel and Paschmann	Heos 2	Confirmation of entry layer
1976	Frank et al.	Imp 8	Possible tail flank case
1976	Eastman et al.	Imp 6	Confirmation of dayside LLBL; noted tail flank cases
1977	Scarf et al.	Imp 7	First clear flank LLBL case with both plasma and field data
1978	Haerendel et al.	Heos 2	Heos summary; further confirmation of tail flank and dayside LLBL
1979	Eastman, Hones	Imp 6	Statistics for 40 LLBL cases; both dayside and tail flank crossings

Karl Schindler was visiting Los Alamos at about that time. I recall in particular how skeptical Dr. Schindler was about my evidence for a boundary layer distinct from and earthward of the current layer. We noted how energetic electron data indicated, at least for some intervals, that the boundary layer is on closed field lines. Dr. Schindler understood that ideal MHD would not allow for the transfer of magnetosheath plasma across the current layer from a region of open to closed field lines. He asked us whether what we are observing was really just an extended current layer or whether there might be a problem with the data. I spent many additional hours checking for any possibility of data errors, such as a timing error between the magnetic field and plasma data. These checks were helpful in insuring the validity of our results as we prepared for publications in 1976 and later.

The title of our 1976 paper was "The Magnetospheric Boundary Layer: Site of Plasma, Momentum and Energy Transfer from the Magnetosheath into the Magnetosphere." In addition to documenting the presence and characteristics of the LLBL, we presented qualitative model and observational tests for such transfer by treating the boundary layer as an MHD generator. The earlier theoretical study by *Coleman* [1970, 1971] had many similar features as an MHD generator model but Coleman's work was unknown to us before the final draft. In addition to various specifics on the generation and mapping of field-aligned currents into the ionosphere, we emphasized the "longitudinal spreading of depolarizing currents" due to large non-dipolar field distortions near the outer magnetospheric boundary. As I reported in a paper presented at the Second Magnetospheric Cleft Symposium in St. Jovite, Quebec in October 5-8, 1976, one consequence of this mapping is that a set of localized boundary interactions on the dayside outer boundary would map down to the ionospheric cusp region as a set of "cat whisker" features. In that presentation, I pointed out the striking similarity of our prediction with optical data from DMSP [*Snyder and Akasofu,* 1976]. Later modeling and dayside cusp observations confirmed this early suggestion of a close association between cusp auroral features and the dayside LLBL [*Crooker and Siscoe,* 1990].

Acknowledgments. I am grateful to the many scientists that encouraged my work in the field of space plasma physics. For the period relevant to this review, I am especially thankful for the inspiration and support provided by Edward Hones, Jr., S.-I. Akasofu, S. Peter Gary, Karl Schindler, and Walter Heikkila.

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