Mapping the Auroral Oval into the Magnetotail Using Dynamics Explorer Plasma Data

L. A. WEISS¹, P. H. REIFF¹, R. V. HILMER¹, J. D. WINNINGHAM², and G. LU³

¹*Department of Space Physics and Astronomy, Rice University, Houston, Texas, U.S.A.*

²*Southwest Research Institute, San Antonio, Texas, U.S.A.*

³*National Center for Atmospheric Research, Boulder, Colorado, U.S.A.*

(Received January 10, 1992; Accepted June 8, 1992)

The mapping of the nightside auroral oval into the magnetotail is investigated using DE-1 and -2 plasma data in combination with the Tsyganenko '89 and the Hilmer-Voigt '91 magnetic field models. In an attempt to clarify the relationship between magnetospheric regions and the BPS and CPS, data from the Low Altitude Plasma Instrument (LAPI) are used to determine the invariant latitude of the polar cap boundary, the poleward edge of the discrete aurora, the discrete-diffuse (BPS/CPS) auroral boundary, and the equatorward edge of the diffuse aurora. When these field lines are traced into the magnetotail, both models indicate that the region of discrete aurora (BPS) maps to an extended region (usually $>20 R_E$ in width) of the main portion of the plasma sheet outside the more dipolar, inner plasma sheet (CPS). Since BPS field lines map to such a wide range of neutral sheet crossing distances, we propose a less confusing and more descriptive terminology in which the term "BPS" is divided into two regions: the Plasma Sheet Boundary Layer (PSBL) and the "IPS", for Isotropic (Boundary) Plasma Sheet.

Auroral zone-magnetotail topology is further examined by using data from the High Altitude Plasma Instrument (HAPI) to determine values of electron number density and temperatures at 1° intervals across the auroral zone. The corresponding field lines are traced into the magnetotail to a distance of $\sim 15 R_E$ and compared with magnetotail ($10\text{--}25 R_E$) mean plasma sheet ion densities and temperatures for low- and mid-activity levels from HUANG and FRANK (1986). We find a very good correspondence between the density and temperature measurements mapped from DE-1 altitudes and those measured in the mid-tail, suggesting that both models successfully reproduce the average magnetospheric configuration at this distance. The mean of the ion temperatures mapped with the Hilmer-Voigt model were slightly higher than those reported from the ISEE data, indicating that the model may be slightly too stretched. A significant region (between $\sim 5\text{--}7 R_E$) of overlap between the hotter ring current and the cooler, fresher plasma sheet is observable at DE-1; these hotter electrons are so anisotropic (with a trapped pancake distribution) that they are not observable at the 1000 km altitude of DE-2.

1. Introduction

Significant controversy persists regarding the regions in the magnetotail to which the discrete and diffuse aurorae map (FELDSTEIN and GALPERIN, 1985; SANDAHL *et al.*, 1990; GALPERIN and FELDSTEIN, 1991; ELPHINSTONE *et al.*, 1991; SERGEEV, 1992; ZWOLAKOWSKA and POPIELAWSKA, 1992). One view, as established by FELDSTEIN and GALPERIN (1985) and

references therein, proposes that discrete auroral forms map to the main, or central, plasma sheet region while the diffuse auroral zone equatorward of the oval maps to the inner magnetosphere L-shells of the outer radiation belt. The other view, proposed by, e.g., WINNINGHAM *et al.* (1975) and LUI *et al.* (1977), contends that the discrete aurora maps to a Boundary Plasma Sheet (BPS) and the diffuse aurora maps to the Central Plasma Sheet (CPS).

Part of this controversy certainly stems from a misuse or misunderstanding of the terminology used to describe the regions in question and can be laid to rest by simply clarifying the definitions of the terms "BPS" and "CPS". These terms were originally coined on the basis of the low-altitude electron precipitation signatures, with the BPS identified as the region associated with discrete auroral arcs and the CPS with the region of diffuse precipitation (WINNINGHAM *et al.*, 1975). Although the authors speculated that the BPS was related to the "upper and lower regions of the plasma sheet", the BPS was not originally intended to describe a relatively thin ($\sim 1 R_E$) region at the outer edge of the plasma sheet, a boundary region now termed the Plasma Sheet Boundary Layer (PSBL), but rather the entire region outside and bordering the central (dipole-like) plasma sheet. This situation has been reviewed and clarified by WINNINGHAM (1992). Although early interpretations of the terms may have equated the BPS with the PSBL (EASTMAN *et al.*, 1984; FRIIS-CHRISTENSEN and LASSEN, 1989), it is clear that the nightside discrete aurora (which can span up to 10° of invariant latitude) cannot be magnetically connected only to the PSBL. Although WINNINGHAM *et al.* (1975) and FELDSTEIN and GALPERIN (1985) differ in the use of their terminology, they do agree that the diffuse aurora maps that portion of the plasma sheet inside the trapping boundary (i.e., the inner, dipolar plasma sheet as defined by the anisotropy of the >35 keV electrons).

In an effort to investigate and further clarify the relation between magnetospheric regions and the BPS and CPS, the projection of the nightside auroral oval into the magnetotail was studied using Dynamics Explorer (DE-1 and -2) plasma data near magnetic conjunctions in combination with the Tsyganenko '89 (TSYGANENKO, 1989) and the Hilmer/Voigt '91 (HILMER and VOIGT, 1992) magnetic field models. The DE satellites provide a unique opportunity to examine the mapping of the nightside auroral zone since their orbits frequently result in the spacecraft being in close proximity to the same magnetic field line, with one at high altitudes (DE-1) and one at low altitudes (DE-2) (HOFFMAN, 1981; BURCH *et al.*, 1981; REIFF *et al.*, 1988). We use the low-altitude measurements to determine the boundaries of the "BPS" and "CPS" as defined by WINNINGHAM *et al.* (1975), and at the same time use the high-altitude data to determine the electron number density and temperature of the plasma sheet plasma on field lines in each of these regions. Since the DE-1 spacecraft is typically well above the auroral acceleration region, the derived densities and temperatures should approximate those of the source distribution, if that distribution is isotropic (REIFF *et al.*, 1988, 1989). The Hilmer/Voigt (HV) and Tsyganenko (T89) models are then used to trace these field lines into the tail. Comparison with average ion densities and temperatures in the tail between 10 and $25 R_E$ (HUANG and FRANK, 1986) serve as simple tests of the models, while the field line tracings establish the equatorial magnetotail extent of the BPS and CPS regions, allowing us to clarify the misconceptions surrounding these regions and to propose an improved nomenclature.

A presentation of data from northward and southward IMF B_z passes follows in Section 2, a brief description of the two magnetic field models used in the study is given in Section 3, and the results of the field line tracings and the statistical analysis are presented and discussed in Section 4.

2. Data

A total of six nightside DE auroral passes were used in this study: three occurring during northward IMF and three during southward IMF. All were chosen to be close to midnight; all but one had nearly simultaneous passes at low altitude by DE-2 and at high altitude by DE-1. Due to the limited lifetime of the DE-1 plasma instrument and the precession of the DE orbits, these 6 cases represent a significant fraction of the total number of such passes. The high-(HAPI) and low-altitude (LAPI) plasma instruments are described in detail by BURCH *et al.* (1981) and WINNINGHAM *et al.* (1981), respectively.

The *AE* and *AO* indices for all six cases are shown in Fig. 1, with the times of the DE-1 passes indicated by horizontal bars. In the presentation of data, we will identify the following boundaries to be traced with the magnetic field models: the polar cap boundary, labeled “PC”; the polewardmost boundary of the discrete aurora and Region 1 current, labeled “R1”; the boundary between discrete and diffuse aurora, labeled “CPS”; and the equatorward edge of the diffuse aurora, labeled “IB”, for inner boundary (of the plasma sheet). An additional boundary, “RC” for ring current, will be noted in the high-altitude data.

2.1 Passes occurring during southward IMF

The three southward IMF passes occurred on September 22, September 26, and October 6, 1981, referred to as days 81265, 81269, and 81279, respectively. Figure 2 shows the low-altitude (LAPI, top) and high-altitude (HAPI, bottom) plasma data for day 81265. This pass occurred during a substorm recovery phase with *AE* = 250 nT, a three-hour *Kp* index of 3+, and a *Dst* index of -14 nT. The top panel of the LAPI display shows the precipitating ($0^\circ \leq \alpha \leq 45^\circ$) electron energy flux in the energy range 0–30 keV, followed by line plots of precipitating (0°) and trapped (90°) electrons with energies greater than 35 keV. The third and fourth panels show precipitating and mirroring 0–30 keV ions, respectively.

The polar cap boundary occurs at 21:31:25 UT, at an invariant latitude of 67.2° . The precipitation poleward of this boundary is characterized by soft, polar rain (WINNINGHAM *et al.*, 1975). The poleward edge of the discrete aurora (defined as that latitude where electrons are observed to undergo an acceleration of at least 500 eV) occurs at approximately 21:31:37 UT (66.5° IL); this boundary is labeled R1 since the Region 1 current is co-located with the field-aligned electron acceleration characteristic of the discrete aurora (LU *et al.*, 1991). Between the PC and R1 boundaries lie a region characterized at low-altitudes by low-density electron precipitation and velocity-dispersed ion (VDI's) signatures. This region was termed (on the basis of low-altitude data) the polar diffuse aurora (PDA) by FELDSTEIN and GALPERIN (1985) and (on the basis of tail data) the low-energy electron layer (LEL) by PARKS *et al.* (1992). DEEHR *et al.* (1976) demonstrated that the BPS discrete aurora is embedded in a diffuse background Maxwellian population on both the equatorward and poleward sides. The VDI's are evident in the panels 3 and 4 between ~21:31:33 UT and ~21:31:42 UT. These ions, which precipitate with the highest energies at the highest latitudes, are believed to be the low-altitude signature of the tail plasma sheet boundary layer (PSBL) (ZELENY *et al.*, 1990). The equatorward edge of the discrete aurora (BPS-CPS boundary) occurs at 21:32:05, at 65.5° IL; note that the BPS region extends from the CPS boundary to the PC boundary and includes the VDI's (PSBL) and PDA. The diffuse aurora occurs between 21:32:05 and 21:32:50 UT. The 35 keV trapping boundary (where the 90° electrons drop out, at 21:32 UT in panel 2) is nearly colocated with

Fig. 1. The AE and AO indices for the six DE passes used in this study. Passes on days 81265, 81269, and 81279 occurred during southward IMF while those on days 81263, 81268, and 81275 occurred during northward IMF. The times of the HAPI passes are indicated by horizontal bars.

Fig. 2. Energy-time electron and ion spectrograms for the low-altitude plasma instrument (LAPI, top) and high-altitude plasma instrument (HAPI, bottom). The pitch angle range of the data is given at the top right of each panel. The second panel of the LAPI display shows trapped and precipitating >35 keV electrons measured by the Geiger-Muller tube (GMT). The arrows designate the poleward boundary of the polar diffuse aurora and VDI signature ("PC", for polar cap boundary); the poleward boundary of the discrete aurora and Region I current ("R1"); the discrete-diffuse auroral boundary ("CPS"); the boundary where the ring current merges with the plasma sheet ("RC"); and the equatorward boundary of the diffuse aurora ("IB", for inner boundary of the plasma sheet).

Fig. 3. DE-1 electron distribution functions from three sensors (labeled A, B, and C) at 21:32:05 UT (66° IL) for pitch angle ranges (a) 0°-20°, and (b) 65°-90°. The smooth line corresponds to the distribution function for one count.

Fig. 4. Scatter diagrams of the relationship between ion and electron temperature in the (a) inner and (b) outer central plasma sheet, and (c) ion versus electron density in the central plasma sheet (lower right) and plasma sheet boundary layer (upper left) as measured by the 3D plasma instrument on AMPTE/IRM (from BAUMJOHANN *et al.*, 1988, 1989).

Fig. 5. LAPI (top) and HAPI (bottom) plasma data for day 81279 (same format at Fig. 2).

Fig. 6. LAPI (top) and HAPI (bottom) plasma data for day 81263 (same format as Fig. 2).

the BPS-CPS boundary and, although not shown here, the Region 1–Region 2 current transition occurs at this same location. The trapping boundary indicates the transition from dipolar to tail-like field lines. The equatorward edge of the diffuse aurora appears as a decreasing ramp in energy between 21:32:40 and 21:32:50 UT; the lower latitude is the inner boundary of the plasma sheet. Equatorward of the IB boundary the plasma is very cool (<20 eV), and merges smoothly into the plasmasphere.

The same boundaries are evident in the DE-1 pass, which was separated by about one hour in magnetic local time from DE-2. The upper two panels of the HAPI display, shown in Fig. 2, show the downcoming ($0^\circ \leq \alpha \leq 20^\circ$) and mirroring ($80^\circ \leq \alpha \leq 110^\circ$) electron energy fluxes, while the lower three panels show the downcoming, mirroring, and upflowing ($160^\circ \leq \alpha \leq 180^\circ$) ion populations, in that order. The polar cap boundary is evident at 21:28:30 UT ($\sim 67.2^\circ$ IL), the poleward edge of the discrete aurora at 21:29:50 UT (66.8° IL), the boundary between discrete and diffuse aurora at 21:34:40 UT (65° IL), and the equatorward boundary of the diffuse aurora at 21:41:30 UT. An additional feature which appears only in the high-altitude trapped electrons (panel 2) is a high-energy (≥ 5 keV) population overlapping the equatorward edge of the diffuse aurora. These electrons are associated with the outermost extent of the outer Van Allen belt (WINNINGHAM *et al.*, 1975) and, since they are also colocated with a population of trapped, high energy ions (panel 4), are interpreted as the signature of the ring current. These electrons are highly anisotropic with a pancake distribution and stably trapped. The boundary where the high-energy, trapped ring current population becomes distinct from the lower energy, nearly isotropic plasma sheet population is referred to as “RC”, for ring current. The decreasing energy of the plasma sheet particles between RC and IB is a convection feature, caused by the sum of the gradient and $E \times B$ drifts allowing deeper penetration of low energy plasma near midnight (HAREL *et al.*, 1981). The ions in this region are believed to have an ionospheric or boundary layer source since their energies would be greater (comparable to the ring current population) if they had been convected in from the magnetotail (G. Erickson, personal communication, 1992).

Since the plasma sheet ion fluxes at DE-1 were rather weak, the magnetotail ion densities and temperatures were inferred from the electron densities and temperatures measured at DE-1 using the linear relationships determined by BAUMJOHANN *et al.* (1988, 1989). Examination of the HAPI ion fluxes confirms that the T_i/T_e ratio of ~ 7.5 is in fact reasonable. Values of N_e and T_e were determined from the distribution functions at the boundaries noted above as well as at 1° intervals from PC to IB. The isotropy of the plasma distribution at DE-1 was tested by examining, whenever possible, the 0° – 20° , 20° – 45° , and 65° – 90° pitch angle populations for any large deviations in number density and temperatures. The perpendicular distribution was used to estimate the average temperature in the magnetotail. At these altitudes (12000–18000 km) a 90° pitch angle particle corresponds to a $\sim 8^\circ$ pitch angle particle in the magnetotail. By comparison, a 90° pitch angle particle at DE-2 altitudes corresponds to only a 1° pitch angle particle in the tail. We note, however, that most of the plasma sheet distributions were nearly isotropic at DE-1, with the exception being the overlapping ring current electrons noted above.

Electron distribution functions from three sensors (labelled A, B, and C for sensors 0, 2 and 4, respectively) sampling the 0° – 20° and 65° – 90° pitch angle ranges at 66° IL are shown in Figs. 3(a) and (b), respectively. Values of temperature (slope = $[kT]^{-1}$) and density ($N_e = f(0)[2\pi kT/m]^{-3/2}$) are noted on each plot and the one count level is denoted by a solid curve. Sensor 0 (A) is in the spacecraft equatorial plane, and 2 (B) and 4 (C) just above and below it. The values of $N_{e(\perp)} = 0.75 \text{ cm}^{-3}$ and $kT_{e(\perp)} = 498 \text{ eV} = 5.8 \times 10^6 \text{ K}$ were used to infer the

corresponding ion densities and temperatures of $N_i = 0.75 \text{ cm}^{-3}$ and $kT_i = 43 \times 10^6 \text{ K} = 3735 \text{ eV}$ from the linear relationships shown in Fig. 4 (BAUMJOHANN *et al.*, 1988, 1989). We note that the electron temperatures were used to infer the ion temperatures only when the two populations were judged to be in correspondence; for instance, no ion temperatures were inferred from electron temperatures poleward of the R1 boundary, and in cases where both a hot and cold (suprathermal burst) electron population existed, only the hotter temperature was used. Field lines from the DE-1 boundaries (PC, BPS, CPS, RC, and IB) and at 1° intervals from PC to IB were traced using both magnetic field models and statistics kept on the z -value vs. ion density and temperature of each line if it crossed $x = -15 R_E$.

The southward IMF pass on day 81279 also occurred during a substorm recovery phase, with $AE = 100 \text{ nT}$, $Kp = 2$, and $Dst = -14 \text{ nT}$. The low- and high-altitude plasma data for this day are shown in Fig. 5, in the same format as Fig. 2. In the LAPI data, the polar cap boundary occurs at 21:29:30 UT (70.7° IL), the poleward boundary of the discrete aurora at 21:29:50 UT (69.7° IL), the BPS-CPS boundary at 21:31:10 UT (65.5° IL), and the equatorward boundary of the diffuse aurora at 21:31:40 UT (63.8° IL). In the HAPI spectrograms, the PC boundary is identified at 20:53:30 UT (72.3° IL). A discrete auroral zone is evident between 21:00:30 (70° IL) and 21:05 UT (68.5° IL), followed by a region of sporadic, suprathermal precipitation between 21:05 and 21:11:50 UT (65.6° IL) (JOHNSTONE and WINNINGHAM, 1982). Although it may seem initially difficult to tell from the electron spectrograms whether the discrete-diffuse (BPS-CPS) auroral boundary occurs at 21:05 UT at the equatorward edge of the inverted-V precipitation (68.4° IL) or equatorward of the sporadic precipitation at 21:11:50 UT (65.6° IL), the presence of upflowing ion beams between 65.6° and 70° (HAPI, panel 4) and the location of both the 35 keV trapping boundary (LAPI, panel 2) and the Region 1–Region 2 current transition (not shown) at $\sim 65.6^\circ$ argue in favor of the lower latitude boundary. We therefore establish the BPS-CPS boundary at 65.6° (but will suggest an improved nomenclature for the BPS region in Subsection 4.1). The RC and IB boundaries are evident in the HAPI data at 21:11:50 UT and 21:14:30 UT, respectively; note that on this day, the only diffuse aurora occurs between these boundaries. Very clear signatures of velocity-dispersed ions (VDI's) are evident in the HAPI precipitating and mirroring ion spectrograms between 70° – 71.5° .

2.2 Passes occurring during northward IMF

The northward IMF passes used in this study occurred on September 20, September 25, and October 2, 1981, referred to as days 81263, 81268, and 81275, respectively. Figure 6 shows the LAPI (top) and HAPI (bottom) plasma data for the pass on day 81263, which occurred during quiet conditions (see Fig. 1) with $AE = 100 \text{ nT}$, $Kp = 2-$, and $Dst = -28 \text{ nT}$. The poleward edge of the discrete aurora as observed by LAPI is believed to occur at 07:45:30 UT (76.8° IL), based on the ion and ($\geq 500 \text{ eV}$) electron precipitation boundaries at this location. Considerable structure, in the form of polar cap arcs, occurs poleward of this boundary in a region termed the “web” by HONES *et al.* (1989); the “web” is likely an extended PDA region. One would not expect, and indeed does not see in the spectrograms, a strong VDI signature during northward IMF. The discrete-diffuse (BPS-CPS) boundary occurs at 07:47:40 UT (69.6° IL), at the same boundary where the trapped, high-energy electron flux falls to $\leq 10^4 \text{ cm}^{-2} \text{ s}^{-1}$ and the transition from Region-1 to Region-2 currents (not shown) occurs. The equatorward diffuse boundary occurs at 07:48:30 (65.7°). Note the positive gradient in the plasma sheet ion temperature as the satellite moves equatorward from the polar cap to the RC boundary, encountering plasma which has been heated by beta- and cyclotron acceleration as it is convected earthward. The

Fig. 7. HAPI electron and ion spectrograms for day 81268 (same format as Fig. 2). No low-altitude (LAPI) data is available for this day.

high-altitude R1, CPS, RC and IB boundaries occur at 07:37 UT (73.8° IL), 07:52 UT (68.7° IL), 07:57 UT (66.7° IL), and 07:58:40 UT (66° IL), respectively. No poleward boundary of the web region (PC boundary) can be discerned on this day. As before, field lines originating from these boundaries and from 1° IL intervals were traced using both magnetic field models.

The HAPI plasma data for a second northward IMF pass, day 81268, is shown in Fig. 7. The IMF B_z component was predominantly southward for the eight hours prior to the pass, with the two large substorms (Fig. 1) triggered by small northward excursions. The pass occurred during the recovery phase of the latter substorm, with $AE = 200$, $Kp = 4-$, and $Dst = -16$. Unlike day 81263, in which B_z had been northward for over 5 hours, the polar cap is remarkably empty of structured precipitation and the polar cap boundary is clearly discernible at 17:26 UT (73.2° IL). Moreover, VDI signatures are evident between 17:31 UT–17:36 UT, indicating that the conversion of open to closed magnetic flux is still occurring in the tail. The BPS-CPS boundary occurs at 17:46 UT (68.5° IL), at the equatorward boundary of the upflowing ion beam, and the RC and IB boundaries occur at 1800 UT (64.1° IL) and 18:07 UT (61.4° IL), respectively.

3. Magnetic Field Models

Two different magnetic field models, Hilmer-Voigt '91 (HILMER and VOIGT, 1992) and Tsyganenko '89 (TSYGANENKO, 1989), were used to trace selected field lines into the tail. Although both models use an internal dipole field coupled with analytic representations of the different magnetospheric current systems, the internal parameters used to specify the currents

depend on different input parameters. The Hilmer-Voigt (HV) model depends on four input quantities: (1) the dipole tilt angle, (2) the magnetopause stand-off distance (derived using solar wind velocity and density measurements from the IMP-8 spacecraft), (3) the equatorward boundary of the diffuse aurora at midnight (with corrections for observations more than one hour away from midnight made using the relationships of GUSSENHOVEN *et al.* (1983)) and (4) the geomagnetic index Dst . In contrast, the Tsyganenko (T89) model depends on only two inputs: (1) the dipole tilt angle and (2) the activity index Kp .

In the HV model the tilt angle and stand-off distance are used to determine the magnetopause currents which shield the dipole magnetic field within a defined magnetosphere geometry (VOIGT, 1981), while a tilt-dependent flexing of the current sheet in the near tail allows the shape and position of the neutral sheet to change in a manner consistent with observations. Ring and cross-tail current distributions are introduced sequentially to gradually stretch the nightside field until the equatorward boundary of the diffuse aurora in the ionosphere maps magnetically to the plasma sheet inner edge at midnight and the resulting ΔB patterns are consistent with Dst .

In the T89 model, the analytic representations of current systems are adjusted by numerical fits using IMP and HEOS spacecraft data sorted by six different Kp bins. The Kp index allows average magnetic field configurations appropriate for different magnetic activity levels to be chosen and a dipole tilt-dependent function is used to position the nightside current to form a warped plasma sheet. The T89 model uses two planar current sheets parallel to and $30 R_E$ away from the GSM equatorial plane to simulate some of the effects of true magnetopause return currents, as well as a set of expressions to help represent magnetic field contributions from currents not explicitly modeled, e.g., Chapman-Ferraro and field-aligned currents.

4. Results and Discussion

4.1 Boundary magnetic field line mapping

The T89 and HV boundary field line (PC, R1, CPS, RC, and IB) neutral sheet crossing distances for the six case studies are listed in Tables 1 and 2, for southward and northward IMF conditions, respectively. The distances are in units of R_E ($-x$). Examples of the boundary field line mappings for the southward IMF passes 81265 and 81279 are displayed in Fig. 8, and the northward IMF passes 81263 and 81268 in Fig. 9. A comparison of the T89 and HV mappings reveals similar neutral sheet crossing distances for the IB and RC boundaries, but some significant differences exist in the mapping distances for the inner ("CPS") and outer ("R1") boundaries of the discrete aurora. In general, the HV model is more stretched than the T89 model, with one exception (day 81263). In the T89 model, the discrete aurora generally maps to equatorial crossing distances between 7 and $40 R_E$ for southward IMF cases, and 15 and $60 R_E$ for northward cases. The equatorial thickness varies from $11 R_E$ to $35 R_E$. In the HV model, on the other hand, the inner and outer equatorial boundaries of the discrete auroral region exit the simulation box ($-50 R_E$) before crossing the neutral sheet in half of the cases (see Tables 1 and 2); in the other three cases, the discrete aurora maps between 8 and $44 R_E$.

The T89 model may be less stretched than the HV model on 81263 due to the input value of $Kp = 2$, when in fact the pass occurs during quiet magnetospheric conditions. To examine this possibility and to illustrate the sensitivity of the models to input activity indices, the PC, R1, CPS, RC and IB boundary field lines were traced for day 81263 using the T89 model with $\Delta Kp = \pm 1$ from the nominal value of 2, and with the HV model with the equivalent effect of

Table 1. Neutral sheet crossing distances, IMF $B_z < 0$.

	Polar Diffuse Aurora		Discrete Aurora		Diffuse Aurora			
	'PC'		Outer Boundary 'R1'		Discrete - Diffuse 'CPS'		Inner Boundary 'RC'; 'IB'	
Day	T89	HV	T89	HV	T89	HV	T89	HV
81265	27.4	33.8	21.7	32	7.5	19.8	5.5 ; 5.1	5.6 ; 5.2
81269	48	> 50	41.2	> 50	14.5	> 50	4.5 ; 3.3	4.2 ; 3.2
81279	58.3	> 50	36.2	43.5	7.1	7.6	7.1 ; 5.9	7.6 ; 5.9

Neutral sheet crossing distances, in units of R_E ($-x$), of field lines defining the polar cap boundary (PC), the poleward boundary of the Region 1 currents and the discrete aurora (R1), the discrete-diffuse auroral boundary (CPS) and the ring current overlap (RC) and inner boundary of the plasma sheet (IB) for cases occurring during southward IMF conditions. Values are given for both the Tsyganenko '89 (T89) and Hilmer-Voigt '91 (HV) models.

Table 2. Neutral sheet crossing distances, IMF $B_z > 0$.

	Polar Diffuse Aurora		Discrete Aurora		Diffuse Aurora			
	'PC'		Outer Boundary 'R1'		Discrete - Diffuse 'CPS'		Inner Boundary 'RC'; 'IB'	
Day	T89	HV	T89	HV	T89	HV	T89	HV
81263	?	?	49.8	35.4	14.5	9.1	7.5 ; 6.6	6.8 ; 6.2
81268	63	> 50	47	> 50	35.6	> 50	7.2 ; 4.8	7.5 ; 4.7
81275	> 70	> 50	57.3	> 50	22.3	> 50	5.4 ; 4.7	5.6 ; 4.8

Neutral sheet crossing distances, in units of R_E ($-x$), of field lines defining the polar cap boundary (PC), the poleward boundary of the Region 1 current and discrete aurora (R1), the discrete-diffuse auroral boundary (CPS) and the ring current overlap (RC) and inner boundary of the plasma sheet (IB) for cases occurring during northward IMF conditions. Values are given for both the Tsyganenko '89 (T89) and Hilmer-Voigt '91 (HV) models.

$\Delta Kp = \pm 1$ on its most sensitive parameter, the equatorward boundary of the diffuse aurora (roughly 2° IL in equatorward shift for 1 Kp increase). The results of this effort are shown in Fig. 10. As expected, the $\Delta Kp = \pm 1$ mappings “frame” the original mappings created with $Kp = 2$, shown in Fig. 9. In the T89 model, for instance, the CPS boundary field line, which originally crossed the neutral sheet at $-15 R_E$, ranges from $-12 R_E$ ($\Delta Kp = -1$) to $-21 R_E$ ($\Delta Kp = +1$); in the HV model, the original CPS boundary field line crossing of $-9 R_E$ ranges from $-8 R_E$ to $-50 R_E$. We stress that since Kp is not an explicit input parameter of the HV model, the actual mapping uncertainty of the HV model is not as large as is implied in Fig. 10(a), since an uncertainty of 2° IL in the location of the inner boundary (IB) is not consistent with the LAPI data (Fig. 6). To the extent that Kp can be a poor predictor of the instantaneous magnetospheric

Fig. 8. A comparison of the Hilmer-Voigt (HV) and Tsyganenko '89 (T89) boundary magnetic field line maps (noon-midnight plane) for the southward IMF passes on (a) 81265 and (b) 81279.

Fig. 9. A comparison of the HV and T89 boundary magnetic field line maps for the northward IMF passes on (a) 81263 and (b) 81268.

Fig. 10. a) HV and b) T89 boundary magnetic field line maps for day 81263 showing the effect of $\Delta Kp = \pm 1$ from the originally used value of $Kp = 2$ (see Fig. 9). In the case of the HV model, the effect of $\Delta Kp = \pm 1$ was translated to the equivalent effect, $\pm 2^\circ$, on the equatorward boundary of the diffuse aurora, its most sensitive input parameter. We stress that, however, the inner edge of the diffuse aurora used in the Hilmer-Voigt model is taken from the actual LAPI data and that such a large spread of IB latitude is inconsistent with the LAPI data (see Fig. 6). Thus the actual HV mapping uncertainty is considerably smaller than the uncertainty implied by the two panels of (a).

configuration, the results of this paper (and all results based on statistically average magnetospheric models) must be weighed by the choice of the input activity index.

Despite differences in their absolute mapping distances, the T89 and HV magnetic field models clearly indicate that the discrete aurora maps to an extended region (usually $>20 R_E$ in width) of the main portion of the plasma sheet outside the dipolar, inner magnetosphere, in agreement with the recent results of SERGEEV (1992) and ZWOLAKOWSKA and POPIELAWSKA (1992). Because of the past confusion regarding the projection of the low-altitude “BPS” into the magnetosphere, and because the discrete aurora has been shown to map to such a large portion of the plasma sheet, we suggest that the region previously called the “BPS” in the magnetosphere be broken into two parts: the thin ($\sim 1 R_E$), anisotropic “PSBL”, and the vast, isotropic plasma sheet on tail-like field lines, or “IPS”. Figure 11 shows a schematic, noon-midnight, diagram of the magnetosphere which clearly distinguishes these different plasma regimes. We feel that the term IPS is more descriptive of the plasma in this region, as it should be, rather than of the position of the region at the outer “boundary” of the central plasma sheet. Moreover, the use of the term IPS certainly differentiates it from the PSBL, which contains highly anisotropic ion distributions and counterstreaming ion beams, and from the CPS which, although also generally isotropic, corresponds to the region of stably trapped particles and drift shells. Finally, we present Table 3 which shows the detailed correspondence of plasma regimes identified at low altitudes with those identified in the magnetotail.

4.2 Statistical analysis

Results of the statistical analysis using the T89 and HV magnetic field models are displayed in Figs. 12 and 13, which show ion density and temperature, respectively, as a function of z at a distance of $-15 R_E$ downtail. The histograms (solid black lines) represent averaged observations presented by HUANG and FRANK (1986) for ISEE crossings between

Fig. 11. Schematic noon-midnight diagram of the earth's magnetotail showing the primary plasma regimes, including the Isotropic Boundary Plasma Sheet (IPS). (Adapted from HILL and DESSLER, 1991).

Table 3. Correspondence of plasma regimes at low altitudes and in the magnetotail.

Line label	Low-Altitude Region	Characteristics near Earth	Magnetotail Region	Characteristics in Tail
'PC'	Polar Cap	polar rain electron fluxes; essentially no ions	magnetotail lobes	weak cool electrons; mantle ions flowing antisunward
	Polar Diffuse Aurora [Feldstein & Galperin; 1985]	low density electrons; evidence of weak trapped electrons	LEL (Low-Energy electron Layer) [Parks et al, 1992]	cool electrons just outside PSBL
	VDIS [Zeleny et al, 1990]	velocity-dispersed ions ($\partial E/\partial \lambda > 0$)	PSBL [Eastman et al., 1984]	outermost ions flowing sunward, inner region flowing antisunward
'R1'	Discrete Aurora	field-aligned accelerations, region 1 currents	Isotropic [Boundary] Plasma Sheet	nearly isotropic at all energies
	Suprathermal bursts [Johnstone and Winningham, 1982]	sporadic, <1 keV precipitation along with plasma sheet electrons		transition between tail-like fields and dipole-like fields
'CPS'	Diffuse Aurora	unstructured energetic plasma sheet hotter at lower latitudes ($\partial T/\partial \lambda < 0$)	Anisotropic [Central] Plasma Sheet	>35 keV electrons durably trapped; hot plasma sheet precipitates
'RC'	Ring Current / Diffuse Aurora overlap region	hot, very anisotropic (trapped) plasma ($\partial T_h/\partial \lambda < 0$) simultaneously with fresh, cool plasma ($\partial T_p/\partial \lambda > 0$)	Outer Van Allen Belt and innermost plasma sheet	>8 keV electrons highly anisotropic (trapped); cooler electrons and (ionospheric?) ions
'IB'				

Plasma distribution functions are used to map low-altitude precipitation regions to magnetotail plasma regimes. Here T is defined as the (Maxwellian) temperature, E the characteristic energy of the dispersing ions, and λ the invariant latitude.

10–25 R_E with $AE < 200$ nT. The scattered data points represent the mapped magnetotail plasma densities and temperatures, as determined from the HAPI spectra at 1° IL intervals for the six passes. Averages of the mapped densities and temperatures for 2 R_E bins in z are shown as open circles, with error bars denoting the standard deviations of the data in each bin. A statistically significant correspondence exists between the HV mapped densities and temperatures and the average of the ISEE observations, with reduced $\chi^2 = 0.45$ and 0.47, respectively (i.e., on average, the difference between the HV bin-averaged values and the ISEE data is 0.7σ); the densities and temperatures mapped with T89 yield an even better correspondence, with reduced $\chi^2 = 0.27$ and 0.19, respectively (roughly 0.5σ). The fact that the mean of the ion densities and temperatures mapped with the HV and T89 models falls so close to the average of the ISEE measurements suggests that both models successfully reproduce the average magnetospheric configuration at this distance, with the Tsyganenko model being slightly better.

The mean of the ion temperatures mapped with the HV model are slightly greater than the average of the ISEE observations, indicating that this version of the HV model may be

Fig. 12. Scatter plot of ion densities at $-15 R_E$ mapped with the (a) Hilmer-Voigt and (b) Tsyanenko '89 magnetic field models, with bin averages shown as circles with error bars. The histogram corresponds to the averaged ISEE measurements.

Fig. 13. Scatter plot of ion temperatures at $-15 R_E$ mapped with the (a) Hilmer-Voigt and (b) Tsyganenko '89 magnetic field models, with bin averages shown as circles with error bars. The histogram corresponds to the averaged ISEE measurements.

somewhat too stretched. Densities and temperatures mapped with the Hilmer-Voigt model also fall at greater z -distances (at $-15 R_E$), indicative of the fact that the HV model is more inflated in the z -direction than the T89 model. This is understandable since the HV model is essentially "open"; the magnetosphere is unshielded and the model does not create an artificial magnetopause as the T89 model does. Recently improved ring current calibration methods have produced less inflated HV tail configurations, however. Additional improvements in this respect are expected when the HV model is coupled to the Toffoletto-Hill magnetic field model (TOFFOLETTO and HILL, 1989) which shields the magnetosphere using Chapman-Ferraro currents. We will report on this improvement in a follow-up paper. Another frequently used magnetic field model is the Tsyganenko '87 model (TSYGANENKO, 1987); similar mapping studies (e.g. STASIEWICZ, 1991), show that, for example, a line across the tail at $x = -30 R_E$ maps to 68° IL at midnight for the T89 ($Kp = 3$) model but to 70° IL for the T87 ($Kp = 3$) model. Thus it is likely that mapping using that the less-stretched T87 will yield average temperatures which are lower than the ISEE measurements, but that will be investigated in a later paper.

It is important to note that the T89 and HV models rely on statistical inputs and thus predict an averaged magnetospheric configurations which can differ significantly from the actual configuration; for this reason the application of these models to specific case studies must be approached cautiously. Recently, the T89 model has been successfully modified for case-specific use by using local measurements of the near-tail magnetic field to carefully model the magnetic field and current structure in the vicinity of the spacecraft (PULKKINEN *et al.*, 1991). Other factors which should be taken into account when evaluating the results of this study include the fact that the two data sets (ISEE and DE) were compared on the basis of AE (not always a reliable indicator of magnetotail configuration), and that the DE densities and temperatures mapped to $-15 R_E$ are compared to ISEE values averaged over 10 – $25 R_E$.

This work was supported at Rice University by the National Science Foundation under grant ATM91-03440, by Air Force Contracts F19628-91-K-0025 and F19628-90-K-0012, and by NASA under grants NAGW-1655 and NAG5-775, and at Southwest Research Institute under grant NAS5-33031. The authors would like to thank N. A. Tsyganenko for providing a Fortran code of his model, G.-H. Voigt for his useful comments, and B. D. Moore and R. Frahm for data analysis support.

REFERENCES

- BAUMJOHANN, W., G. PASCHMANN, N. SCKOPKE, C. A. CATTELL, and C. W. CARLSON, Average ion moments in the plasma sheet boundary layer, *J. Geophys. Res.*, **93**, 11507, 1988.
- BAUMJOHANN, W., G. PASCHMANN, and C. A. CATTELL, Average plasma properties in the central plasma sheet, *J. Geophys. Res.*, **94**, 6597, 1989.
- BURCH, J. L., J. D. WINNINGHAM, V. A. BLEVINS, N. EAKER, W. C. GIBSON, and R. A. HOFFMAN, High-altitude plasma instrument for Dynamics Explorer-A, *Space Sci. Instrum.*, **5**, 455, 1981.
- DEEHR, C. S., J. D. WINNINGHAM, F. YASUHARA, and S.-I. AKASOFU, Simultaneous observations of discrete and diffuse auroras by the Isis-2 satellite and airborne instruments, *J. Geophys. Res.*, **81**, 5527, 1976.
- EASTMAN, T. E., L. A. FRANK, W. K. PETERSON, and W. LENNARTSSON, The plasma sheet boundary layer, *J. Geophys. Res.*, **89**, 1553, 1984.
- EASTMAN, T. E., L. A. FRANK, and C. Y. HUANG, The boundary layers as the primary transport regions of the Earth's magnetotail, *J. Geophys. Res.*, **90**, 9541, 1985.
- ELPHINSTONE, R. D., D. HEARN, J. S. MURPHREE, and L. L. COGGER, Mapping using the Tsyganenko long magnetospheric model and its relationship to Viking auroral images, *J. Geophys. Res.*, **96**, 1467, 1991.
- FELDSTEIN, Y. I. and Y. I. GALPERIN, The auroral luminosity structure in the high-latitude upper atmosphere: its dynamics and relationship to the large-scale structure of the Earth's magnetosphere, *Rev. Geophys.*, **23**, 5217,

1985.

- FRIIS-CHRISTENSEN, E. and K. LASSEN, Large-scale distribution of discrete auroras and field-aligned currents, in *Proceedings of the International Conference on Auroral Physics*, edited by C.-I. Meng, p. 339, Cambridge University Press, Cambridge, U.K., 1989.
- GALPERIN, Y. I. and Y. I. FELDSTEIN, Auroral luminosity and its relationship to magnetospheric plasma domains, in *Auroral Physics*, edited by C.-I. Meng, M. J. Rycroft, and L. A. Frank, p. 208, Cambridge University Press, Cambridge, U.K., 1991.
- GUSSENHOVEN, M. S., D. A. HARDY, and N. HEINEMANN, Systematics of the equatorial diffuse auroral boundary, *J. Geophys. Res.*, **88**, 5692, 1983.
- HAREL, M., R. A. WOLF, R. W. SPIRO, P. H. REIFF, C.-K. CHEN, W. J. BURKE, F. J. RICH, and M. SMIDDY, Quantitative simulation of a magnetospheric substorm 2: comparison with observations, *J. Geophys. Res.*, **86**, 2242, 1981.
- HILL, T. W. and A. J. DESSLER, Plasma motions in planetary magnetospheres, *Science*, **252**, 410, 1991.
- HILMER, R. V. and G.-H. VOIGT, A magnetospheric magnetic field model with flexible current systems driven by independent physical parameters, *J. Geophys. Res.*, **97**, 1992 (to be submitted).
- HOFFMAN, R. A. and E. R. SCHMERLING, Dynamics Explorer program: An overview, *Space Sci. Instrum.*, **5**, 345, 1981.
- HONES, E. W., Jr., J. D. CRAVEN, L. A. FRANK, D. S. EVANS, and P. T. NEWELL, The horse-collar aurora: a frequent pattern of the aurora in quiet times, *Geophys. Res. Lett.*, **16**, 37, 1989.
- HUANG, C. Y. and L. A. FRANK, A statistical study of the central plasma sheet: implications for substorm models, *Geophys. Res. Lett.*, **13**, 652, 1986.
- JOHNSTONE and WINNINGHAM, Satellite observations of suprathermal electron bursts, *J. Geophys. Res.*, **87**, 2321, 1982.
- LU, G., R. H. REIFF, J. L. BURCH, and J. D. WINNINGHAM, On the auroral current—voltage relationship, *J. Geophys. Res.*, **96**, 3523, 1991.
- LUI, A. T. Y., D. VENKATESAN, C. D. ANGER, S.-I. AKASOFU, W. J. HEIKKILA, J. D. WINNINGHAM, and F. R. BURROWS, Simultaneous observations of particle precipitations and auroral emissions by the ISIS-2 satellite, *J. Geophys. Res.*, **82**, 2210, 1977.
- PARKS, G. K., R. FITZENREITER, K. W. OGILVIE, C. HUANG, K. A. ANDERSON, J. DANDOURAS, L. FRANK, R. P. LIN, M. MCCARTHY, H. REME, J. A. SAUVAUD, and S. WERDEN, Low-energy particle layer outside of the plasma sheet boundary, *J. Geophys. Res.*, **97**, 2943, 1992.
- PULKKINEN, T. I., D. N. BAKER, D. H. FAIRFIELD, R. J. PELLINEN, J. S. MURPHREE, R. D. ELPHINSTONE, R. L. MCPHERRON, J. F. FENNEL, R. E. LOPEZ, and T. NAGAI, Modeling the growth phase of a substorm using the Tsyganenko model and multi-spacecraft observations: CDAW-9, *Geophys. Res. Lett.*, **18**, 1963, 1991.
- REIFF, P. H., H. L. COLLIN, E. G. SHELLEY, J. L. BURCH, and J. P. WINNINGHAM, Heating of upflowing ionospheric ions on auroral field lines, in *Ion Acceleration in the Magnetosphere and Ionosphere*, *Geophys. Monogr. Ser.*, **38**, edited by T. Chang, pp. 83–91, AGU Press, Washington, D.C., 1986.
- REIFF, P. H., H. L. COLLIN, J. D. CRAVEN, J. L. BURCH, J. D. WINNINGHAM, E. G. SHELLEY, L. A. FRANK, and M. A. FRIEDMAN, Determination of auroral electrostatic potentials using high- and low-altitude particle distributions, *J. Geophys. Res.*, **93**, 7441, 1988.
- SANDHAHL, I., L. ELIASSON, A. PELLINEN-WANNBERG, G. ROSTOKER, L. P. BLOCK, R. E. ERLANDSON, E. FRIIS-CHRISTENSEN, B. JOCOBSEN, H. LUHR, and J. S. MURPHREE, Distribution of auroral precipitation at midnight during a magnetic storm, *J. Geophys. Res.*, **95**, 60511, 1990.
- SERGEEV, V. A., Tail-aurora direct relationship, *Proceedings of the International Substorm Conference*, Kiruna, Sweden, March, 1992 (in press, ESA publications).
- STASIEWICZ, K., Polar cusp topology and position as a function of interplanetary magnetic field and magnetic activity: comparison of a model with Viking and other observation, *J. Geophys. Res.*, **96**, 15789, 1991.
- TOFFOLETTO, F. R. and T. W. HILL, Mapping of the solar wind electric field to the Earth's polar caps, *J. Geophys. Res.*, **94**, 329, 1989.
- TSYGANENKO, N. A., Global quantitative models of the geomagnetic field in the cislunar magnetosphere for different disturbance levels, *Planet. Space Sci.*, **35**, 1347, 1987.
- TSYGANENKO, N. A., A magnetospheric magnetic field model with a warped tail current sheet, *Planet. Space Sci.*, **37**, 5, 1989.
- VOIGT, G.-H., A mathematical magnetospheric field model with independent physical parameters, *Planet. Space Sci.*, **29**, 1, 1981.
- WINNINGHAM, J. D., The morphology of the nightside magnetosphere and its polar projection: the BPS/CPS

- revisited (abstract), *EOS, Trans. AGU*, **73**, 269, 1992.
- WINNINGHAM, J. D., F. YASUHARA, S.-I. AKASOFU, and W. J. HEIKKILA, The latitudinal morphology of 10-eV to 10-deV electron fluxes during magnetically quiet and disturbed times in the 2100 = 0300 MLT sector, *J. Geophys. Res.*, **80**, 3148, 1975.
- WINNINGHAM, J. D., J. L. BURCH, N. EAKER, V. A. BLEVINS, and R. A. HOFFMAN, The low altitude plasma instrument (LAPI), *Space Sci. Instrum.*, **5**, 465, 1981.
- ZELENYI, L. M., R. A. KOVRAZHIN, and J. M. BOSQUED, Velocity-dispersed ion beams in the nightside auroral zone: AUREOL 3 observation, *J. Geophys. Res.*, **95**, 12119, 1990.
- ZWOLAKOWSKA, D. and B. POPIELAWSKA, Tail plasma domains and the auroral oval—results of mapping based on the Tsyanenko 1989 magnetospheric model, Polish Academy of Sciences Preprint #12, 1991 (to be submitted, Planetary and Space Sciences).