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Birkeland Currents and Charged Particles in the High-Latitude Prenoon Region: A New Interpretation

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Simultaneous, conjugate measurements of magnetic fields and charged particles at low altitude in the high-latitude prenoon sector and the magnetosheath were made with the DMSP F7, HILAT, and Active Magnetospheric Particle Tracer Explorers (AMPTE) CCE satellites on November 1, 1984. These data show that the low-latitude portion of the traditional "cusp" particle signature is coincident with the prenoon region 1 current system in both hemispheres and for both northward and southward interplanetary magnetic fields (IMF). The traditional "cusp" Birkeland currents are associated with the dispersion region of cusp ions when the IMF is directed southward and with electron fluxes that are slightly enhanced over polar rain intensities. Finally, electron spectra measured by AMPTE CCE in the magnetosheath near 1000 MLT are similar in shape and energy to those acquired at low altitude by both DMSP F7 and HILAT. These observations indicate that for both northward and southward IMF, the traditional "cusp particle" signature is coincident with the region 1 Birkeland current system and maps to low altitude along field lines that thread the dayside boundary layer. The traditional "cusp" Birkeland current system flows along field lines that lie poleward of the region of cusp particles and the region 1 current system. These field lines thread the plasma mantle. Thus, we suggest that the traditional "cusp" current system might be appropriately renamed the "mantle" Birkeland current system.

INTRODUCTION

The magnetospheric cusps (clefts) are neutral points (lines) on the dayside magnetopause that divide lines of magnetic field that drape the dayside magnetopause from those that thread the magnetotail lobes and mantle [see *Crooker*, 1977*b*, Figures 1 and 3]. The magnetospheric cusps derive from the deformation of the geomagnetic dipole by its interaction with the solar wind and are apparent even in the earliest models of the magnetosphere [*Spreiter and Briggs*, 1962; *Midgeley and Davis*, 1963]. The solar wind interaction with the geomagnetic field results in the generation of a large-scale surface current, "the Chapman Ferraro current," flowing along the magnetopause surface normal to the solar wind velocity vector [*Chapman and Ferraro*, 1933]. The polar cusp has been associated with the diversion of a portion of this current along magnetic field lines and through the dayside high-latitude ionosphere [*Eastman et al.*, 1976; *Iijima and Potemra*, 1976]. How these currents may be related to the entry of solar wind particles into the magnetosphere is as yet an unanswered question.

Over the past two decades the cusp/cleft has been identified by the presence of magnetosheath-like plasma in the low-altitude, high-latitude, dayside ionosphere. The charged particle detectors on IMP 5 observed magnetosheath-like plasma in the dayside magnetosphere at high latitudes from about 4 to 7 R_E [*Frank*, 1971]. Frank concluded that this plasma had entered the magnetosphere via the magnetospheric cusp. *Heikkila and Winningham* [1971] first defined the cusp at low altitude using data acquired at about 2000 km from the ISIS 1 SPS (soft particle spectrometer). They noted that intense low-energy electron and proton precipitation had spectra of energy versus number flux that were nearly identical to those of magnetosheath particles, i.e., Maxwellian with electron average energy of ~100 eV and ion average energy of ~1 keV. The region of intense precipitation was located between about 74° and 80° ILAT (invariant latitude) and extended from about 0800 to 1500 MLT (magnetic local time). Thus, they inferred that this plasma had unimpeded entry to the magnetosphere along field lines that thread the magnetospheric cusps. The broad range in MLT and ILAT over which these particles were observed was attributed to the extension of the axially symmetric cusp into a cleft and to the porosity of the cusp magnetic bottle [*Heikkila and Winningham*, 1971, and references therein].

Large-scale Birkeland currents detected by the TRIAD satellite at high latitudes on the dayside were associated with the polar cusp by *Iijima and Potemra* [1976]. These currents were found in roughly the same region where magnetosheathlike particles had been statistically observed. Aptly named cusp currents, they lie poleward of and adjacent to the region 1 current system, and their flow is directed opposite that of region 1 at all local times between about 0900 and 1500 MLT. Since TRIAD did not carry a charged particle detector, this study was unable to evaluate the relationship between "cusp currents" and "cusp particles." *Potemra et al* [1977] examined data from the low-energy electron detector (200–25 eV) and photoelectron spectrometer (0–500 eV) on board the AE-C and AE-D satellites in the low-altitude cusp. From these data they concluded that two populations of electrons were present at high latitudes on the dayside, a higher-energy population at low auroral zone latitudes and a lower-energy population at higher latitudes. Based on the statistical pattern of large-scale Birkeland currents they suggested that the higher-energy population was associated with the region 1 currents and the lower-energy population was associated with the cusp currents. The first simultaneous measurements of Birkeland currents and charged particles were made with ISIS 2 in the early afternoon sector [*Burrows et al.*, 1976]. In a case study they showed that in this local time sector an upward directed Birkeland current was associated with cusp particle precipitation. A later study of the magnetic field and charged particle data from ISIS 2 by *McDiarmid et al.* [1979] indicated that "cleft

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electrons" overlapped the east-west reversal of the magnetic field perturbation.

In a recent statistical study of ion and electron precipitation using data from the Defense Meteorological Satellite Program (DMSP) F2, DMSP F4, and the P78-1 satellites, *Hardy et al.* [1985] determined that a crescent-shaped region of low-energy electrons with magnetosheath-like properties extends several degrees in ILAT and several hours in MLT either side of noon. This crescent of low-energy electron precipitation gradually blends into BPS (boundary plasma sheet) electron precipitation in the dawn and dusk sectors. At the poleward edge of the crescent near noon, Hardy et al. detected a localized region of minimum average energy. They identify this confined region of minimum average energy as the low-altitude signature of the "polar cusp" or "entry layer" [*Paschmann et al.*, 1976]. The crescent-shaped region was suggested to be the low-altitude projection of the dayside LLBL (low-latitude boundary layer). The LLBL is likely to be one source of the dayside region 1 current system [*Eastman et al.*, 1976; *Sonnerup*, 1980; *Bythrow et al.*, 1981]. Analysis of data acquired with the magnetometer, ion drift meter, and low-energy electron experiment on Atmosphere Explorer C showed that the region 1 current system in the dawn and dusk sectors spans the ion convection reversal and is colocated with a low-energy electron population identified as having characteristics of boundary plasma sheet electrons [*Bythrow et al.*, 1981]. Due to the inclination of the AE-C orbit, the satellite's trajectory crossed the auroral oval at an oblique angle and, at best, skimmed the noon sector at high latitudes. For this reason the study did not attempt to address the cusp currents or to differentiate between "cusp" and BPS particles. Birkeland currents and charged particles have been examined separately and simultaneously in the dayside ionosphere, but the question still remains as to what high-latitude current systems are most intimately linked with magnetosheathlike particle populations.

In this paper we offer to answer this question by way of a set of case studies made on November 1, 1984, with the DMSP F7, HILAT, and Active Magnetospheric Particle Tracer Explorers (AMPTE) CCE satellites. On this day the magnetosphere was severely compressed to the extent that the bow shock was observed within 8 R_E with the AMPTE CCE. We survey simultaneous, conjugate hemisphere measurements of magnetic fields and charged particles from the low-altitude prenoon sector and the magnetosheath and examine consecutive passes of DMSP F7 through the prenoon sector in the northern hemisphere. Our results demonstrate that in both hemispheres and for both northward and southward orientations of the interplanetary magnetic field (IMF) the lowest-latitude portion of the traditional "cusp particle" signature is coincident with the prenoon region 1 current system. The traditional cusp currents are associated with electron fluxes only slightly enhanced over polar rain intensities, and electron spectra measured in the 1000 MLT magnetosheath are similar in shape and energy to those acquired simultaneously at low altitude in both hemispheres. The implications of these observations are discussed in the context of a consistent model of the dayside magnetosphere.

OBSERVATIONS

The magnetic field and charged particle data used in this study were acquired from four spacecraft, IMP 8, AMPTE CCE, DMSP F7, and HILAT, with IMP 8 located in the solar wind, CCE in the magnetosheath, and both DMSP and HILAT in the low-altitude ionosphere. AMPTE CCE was launched on August 16, 1984, into an equatorial elliptical orbit with apogee of 8.8 R_E and perigee of 1.1 R_E. Charged particle data in the magnetosheath were acquired from the HPCE (hot plasma composition experiment) which provides ion composition measurements from very low energies, 0 eV/*e* (limited by spacecraft potential) to 17 keV/*e*, and electron measurements from 50 eV to 25 keV [*Shelley et al.*, 1985]. The DMSP F7 and HILAT satellites are both in low-altitude (~800 km) circular polar orbits and both carry similar magnetic field and charged particle experiments. The magnetic field experiments sample the ambient vector magnetic field at a rate of 20 samples/s using 13-bit analog to digital converters. Thus, a spatial resolution of ~400 m and an amplitude resolution of ~12 nT is provided. For further information on the magnetic field experiments, see *Potemra et al.* [1984] and *Rich et al.* [1985]. The charged particle experiments on board DMSP F7 and HILAT are also of similar design. The DMSP F7 ion and electron spectrometers measure the precipitating flux of electrons and ions from the zenith direction in 20 energy channels from 30 eV to 30 keV. Thus a 20-point ion and electron spectrum is completed in 1 s. HILAT is equipped with three electron spectrometers oriented at the zenith, nadir, and 45° from zenith look angles. These spectrometers measure the flux of electrons in 16 energy channels from 20 eV to 20 keV and can provide four 16-point spectra each second from each of three separate spectrometers. For further information on the charged particle spectrometers, see *Hardy et al.* [1984*a*,*b*].

On November 1, 1984, the dayside magnetosphere was compressed, and the bow shock was located unusually close (earthward of AMPTE CCE) to the Earth due to the high solar wind dynamic pressure. Data for this study were acquired between the hours of 0700 and 1000 UT. IMF data from IMP 8 located 25 R_E upstream in the solar wind during this period are shown in Figure 1. Fifteen-second averages are used in this plot of B_x, B_y, and B_z in GSM coordinates. The shaded portions of the plot at A, B, and D denote low-altitude crossings of the prenoon sectors by the DMSP F7 and HILAT satellites. Times are corrected for IMP 8's position in the solar wind. A 6-min time delay is appropriate for the solar wind velocity of 450 km/s present at the time of these measurements. The shaded region at C indicates the time when AMPTE CCE electron data are examined. Consecutive DMSP F7 crossings of the northern prenoon sector occurred when the IMF was directed southward (A and D). The DMSP F7 prenoon crossing denoted by B occurred in the southern hemisphere when the IMF had been directed northward for over 50 min. The HILAT satellite crossed the northern prenoon sector at a location nearly conjugate to DMSP F7 in the south during period B.

Case A ($B_z < 0$)

Data depicted in Plate 1 were collected by the DMSP F7 satellite as it traversed the northern hemisphere at latitudes greater than 50° MLAT (magnetic latitude). As shown in Figure 1, the IMF *Z* component during this crossing was directed southward, and the *Y* component was positive (east). The top panel of Plate 1 is a plot of the transverse magnetic field perturbation vectors measured along the orbit track. The satellite was traveling from south to north along its orbit, and the vectors are plotted on a MLAT/MLT (magnetic local time) polar dial. The next two panels display the transverse components of the perturbation magnetic field in spacecraft coordinates for the prenoon sector portion of the orbit highlighted in the polar dial. B_z in spacecraft coordinates is directed perpendicular to the orbit plane, which is essentially an east-west geographic orientation, while B_y is in the plane of the orbit transverse to the main field, i.e., a north-south geographic orientation. Charged particle data, measured simultaneously with

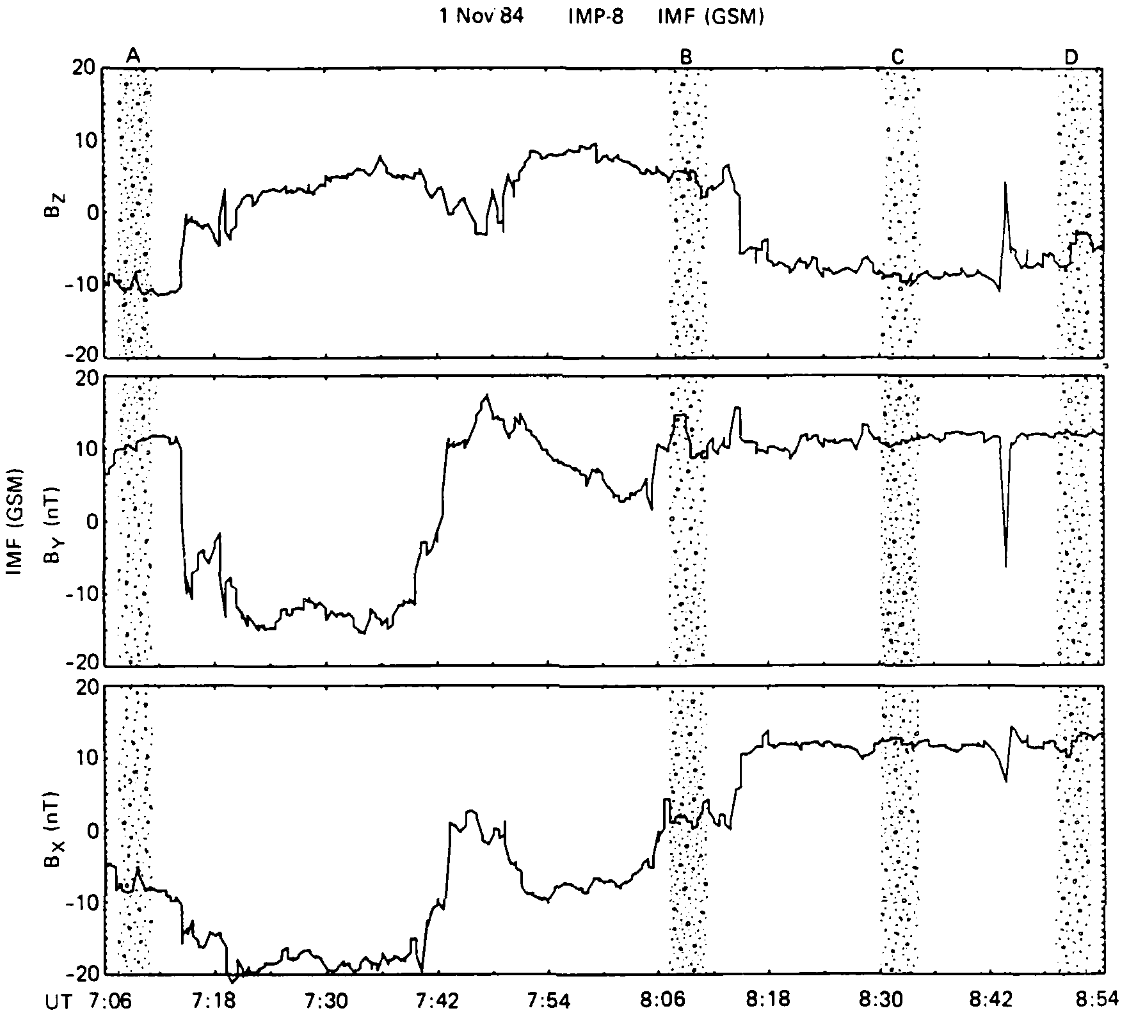
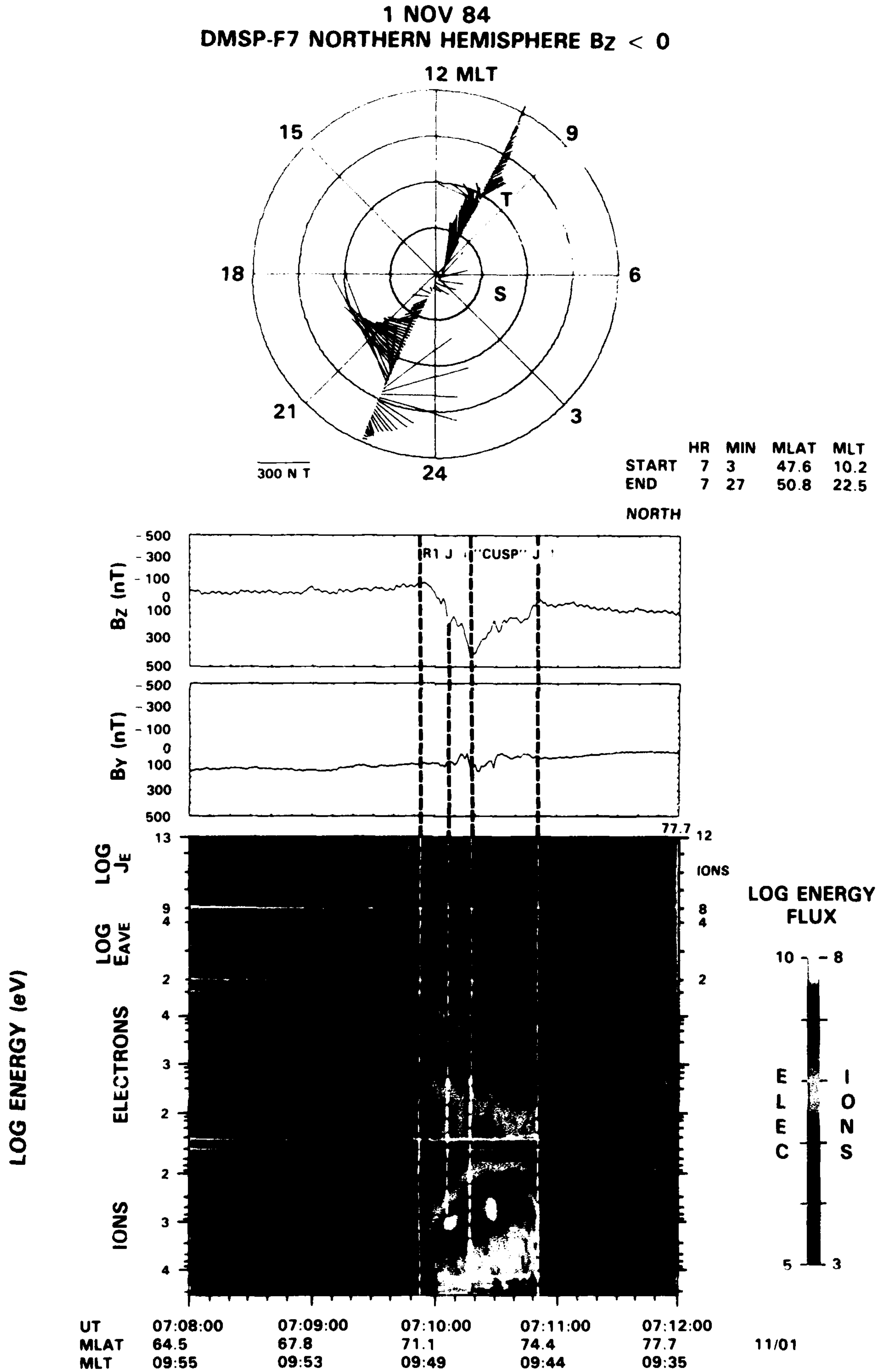


Fig. 1. Interplanetary magnetic field data from IMP 8 for the period of interest. Each highlighted segment represents a period when low-altitude data were available.

the magnetic field, are displayed in the lower four panels. The upper two of these panels are plots of electron (white) and ion (orange) energy flux and average energy. The lower two panels are electron (top) and ion (bottom) spectrograms of energy flux versus time versus energy for precipitating ions and electrons.

At about 0947 MLT and about 71° MLAT the transverse perturbation magnetic field vector, plotted on the MLAT/MLT dial, rotates from a predominantly southwest direction through east and back to a southeast direction. Rotation of the magnetic field in this sense indicates the presence of an earthward flowing Birkeland current that spans the field reversal. A reversal of the magnetic field perturbation vector can, within some uncertainty due to the baseline, be considered to coincide with a reversal of ion drift [*McDiarmid et al.*, 1978]. In this case the ion drift reversed from eastward (sunward) to westward (antisunward) flow. B_z, the east-west component of the perturbation field, is plotted in the next lower panel (note the inverted scale). The magnetic field in the east-west direction exhibits an average gradient of ~30 nT/s between 0709:57 and 0710:17 UT. For a low-altitude satellite such as DMSP this gradient corresponds to a current density of about 3 $\mu A/m^2$ with flow directed into the ionosphere [*Potemra et al.*, 1984]. We identify this earthward directed Birkeland current as the prenoon region 1 current system. The gradient in the magnetic field equatorward of the region 1 current is indicative of a very weak (<0.05 $\mu A/m^2$) region 2 current in this MLT sector. Embedded within the region 1 current at about 0710:05 UT there is an enhancement of the current density paired with a narrow upward directed Birkeland current with density of about 2 $\mu A/m^2$. Immediately poleward of the region 1 current, the gradient in B_z reverses sign and remains relatively constant from 0710:17 to 0710:52 UT. This gradient corresponds to an outward directed Birkeland current with density of about 1.2 $\mu A/m^2$. Because of its location relative to the region 1 current system this current can be identified against a background of statistical Birkeland current patterns as the traditional "cusp current" first described by *Iijima and Potemra* [1976].

In the first panel of charged particle data displayed in Plate 1 the electron and ion energy flux between 0709:57 and 0710:53 UT increased by at least an order of magnitude over the background flux observed at higher and lower latitudes. During the same interval, the electron average energy in the next panel shows a sharp decrease to approximately 100 eV. Ion average energy exhibits a negative slope from about 0709:58 to about 0710:25. The slope of ion average energy remains nearly constant from this point to 0710:50 UT. The observed increase in electron and ion energy flux coincident with a marked decrease in electron average energy when observed in this local time sector has been considered as a low-altitude signature of the "polar cusp" or "cleft" [*Meng*, 1981].



1 NOV 84
DMSP-F7 NORTHERN HEMISPHERE Bz < 0
12 MLT
15
9
18
6
21
3
24
T
S
300 N T
HR MIN MLAT MLT
START 7 3 47.6 10.2
END 7 27 50.8 22.5
NORTH
Bz (nT)
By (nT)
R1 J
"CUSP" J
LOG JE
LOG EAVE
ELECTRONS
IONS
LOG ENERGY (eV)
LOG ENERGY FLUX
ELEC
IONS
UT 07:08:00 07:09:00 07:10:00 07:11:00 07:12:00
MLAT 64.5 67.8 71.1 74.4 77.7 11/01
MLT 09:55 09:53 09:49 09:44 09:35

Between 0709:57 and 0710:17 UT, the ion spectrogram shows that precipitating ions exhibit a steeply sloped energy versus latitude dispersion. The ion energy flux peaks near 1 keV at lower latitudes and decreases toward higher latitudes. This dispersion signature has been cited by *Reiff et al.* [1977, 1980] as evidence for particle injection resulting from dayside merging in the "polar cusp" when the IMF has a southward component. *Heikkila* [1978] disputed this interpretation and suggested that the same dispersion signature can result from plasma entry processes occurring on closed geomagnetic field lines. Recent MHD simulations by *Galvez* [1987] have shown that polarization of streaming plasma and the ensuing shear instability of the polarization charge layer can provide plasma with nondiffusive access to closed field lines.

The region of maximum ion energy dispersion is colocated with a Birkeland current directed into the ionosphere that is identified as the region 1 current system, while at higher latitude the traditional "cusp" current is associated with a less intense flux of ions that exhibits a less steeply sloped dispersion signature. The electron flux within the region of traditional cusp current gradually decreases with increasing latitude. Polar rain electrons are encountered at the equatorward edge of the "cusp current" and superimposed on this low-energy electron precipitation.

The ions display a narrow maximum in flux located in the center of the sharply sloped energy latitude dispersion. This flux maximum is colocated with a spatially limited pair of upward directed and enhanced earthward directed currents embedded within the region 1 current system. The 1-keV energy of this maximum is comparable to the energy of a proton flowing with a typical boundary layer bulk velocity of ~300 km/sec [*Eastman and Hones*, 1979]. A similar maximum in ion flux at about 0.7 keV is colocated with a narrow earthward flowing current embedded within the traditional cusp current at 0710:30 UT.

Case B (B_z >0) DMSP F7

Here we examine simultaneous and conjugate measurements acquired from both the northern (HILAT) and southern (DMSP F7) low-altitude ionospheres and from the 1000 MLT magnetosheath at about 8 R_E (AMPTE CCE). These data were acquired about 50 min after those data examined in case A. As shown in Figure 1, the IMF had a northward component for about 50 min prior to the DMSP and HILAT crossings of the prenoon sector. The IMF Z component turned southward at about 0811 UT. Therefore, during the period when AMPTE CCE data were collected the IMF has been directed southward for about 20 min.

In Plate 2 the magnetic field and charged particle data from DMSP F7 have the same format as in Plate 1. At about 0900 MLT and 73° MLAT the perturbation magnetic field vector plotted on the MLT MLAT polar dial rotates from an easterly to westerly orientation corresponding to an earthward directed Birkeland current and an inferred reversal of **E** × **B** ion drift from a southeasterly to southwesterly flow. In this case there is a significant poleward directed component of the perturbation field both prior to and after the rotation. Three large-scale gradients in the Z component of the perturbation field indicate the three large-scale Birkeland currents involved in the rotation of the magnetic field. The first of these, located at the highest latitude, extends from 0808:40 to 0809:23 UT and is directed out of the ionosphere. The second extends from 0809:23 to 0809:55 UT and results from an earthward directed region 1 current with a density of 2.5 $\mu A/m^2$. Adjacent to the region 1 current a weak region 2 current extends toward lower latitudes. As observed in case A for southward IMF there is a narrow upward directed current embedded in the region 1 system at 0809:38 UT.

Charged particle data show a traditional cusp signature between 0809:18 and 0809:55 UT. At 0809:18 UT about 74° MLAT the electron and ion energy flux exhibit a marked increase. The electron average energy is about 150 eV until 0809:55 UT and 72° MLAT where the average energy increases to about 1 keV. Although the IMF had a northward component, the region 1 Birkeland current remained colocated with the cusp particle population as we observed in the previous case for southward IMF. The traditional cusp current extends poleward of region 1 up to about 76° MLAT. The transition from an earthward directed region 1 current to an upward flowing current at higher latitude is marked by a sharp (< 50 km and 2 orders of magnitude) decrease in the energy flux of low-energy electrons, while the electron average energy remained relatively constant at about 200 eV. At this transition the ion average energy and energy flux fell by 1 and 2 orders of magnitude, respectively. The transition to the region 2 current at the equatorward edge of the region 1 current is similarly marked by boundaries in the electron and ion populations. At latitudes lower than the juncture between region 1 and region 2, the electron average energy and energy flux both increase by an order of magnitude, while the ion energy flux and average energy undergo a gradual decrease. These low-latitude plasma sheet-like ion and electron populations were undetectable in the previous case for southward IMF although the magnetic local time was less than 1 hour later.

In the interval between 0809:18 UT and 0809:55 UT an energy versus latitude dispersion of the ions cannot be discerned in the ion spectrogram. This observation is consistent with the predictions made by *Reiff et al.* [1980] for ion energy dispersion during periods of northward IMF, i.e., a diffusion signature. The energy flux of earthward directed ions and electrons in the region of the most intense flux is essentially the same for this case of northward IMF as it was for the previous case when the IMF was directed southward. In the center of the most intense flux of low-energy electrons about 0809:38 UT, the ion energy flux exhibits a maximum in the energy range between 0.7 and 2 keV. As before, this enhanced flux corresponds to the upward directed current embedded within the region 1 current system.

Case B (B_z > 0) HILAT

Magnetic field and charged particle data acquired from the HILAT satellite between 0807:00 and 0811:00 UT on November 1, 1984, are shown in Plate 3. The HILAT data were collected in the northern hemisphere at nearly the same MLAT, MLT, and UT as those data obtained from DMSP F7 in the southern hemisphere and displayed in Plate 2. The plots of HILAT magnetic field data display the transverse components of the perturbation magnetic field in spacecraft coordinates. The X component is oriented in the east-west direction. The three gradients in the east-west component of the perturbation magnetic field as measured by HILAT are almost identical in slope and latitudinal extent to those measured simultaneously by DMSP F7. Thus, the triplet of Birkeland currents in the southern hemisphere measured by DMSP

Plate 1. (Opposite) The first of three consecutive crossings of the prenoon auroral zone by DMSP F7. This pass is from the northern hemisphere when the IMF had a southward component. In the top panel magnetic field vectors along the orbit track are plotted on a MLAT/MLT polar dial. The highlighted portion of the orbit is displayed in detail below. The next two panels display the transverse components of the perturbation magnetic field. The next two panels are line plots of electron (white) and ion (orange) energy flux and average energy. The bottom two panels are spectrograms of electron (top) and ion (bottom) energy flux versus energy and time.

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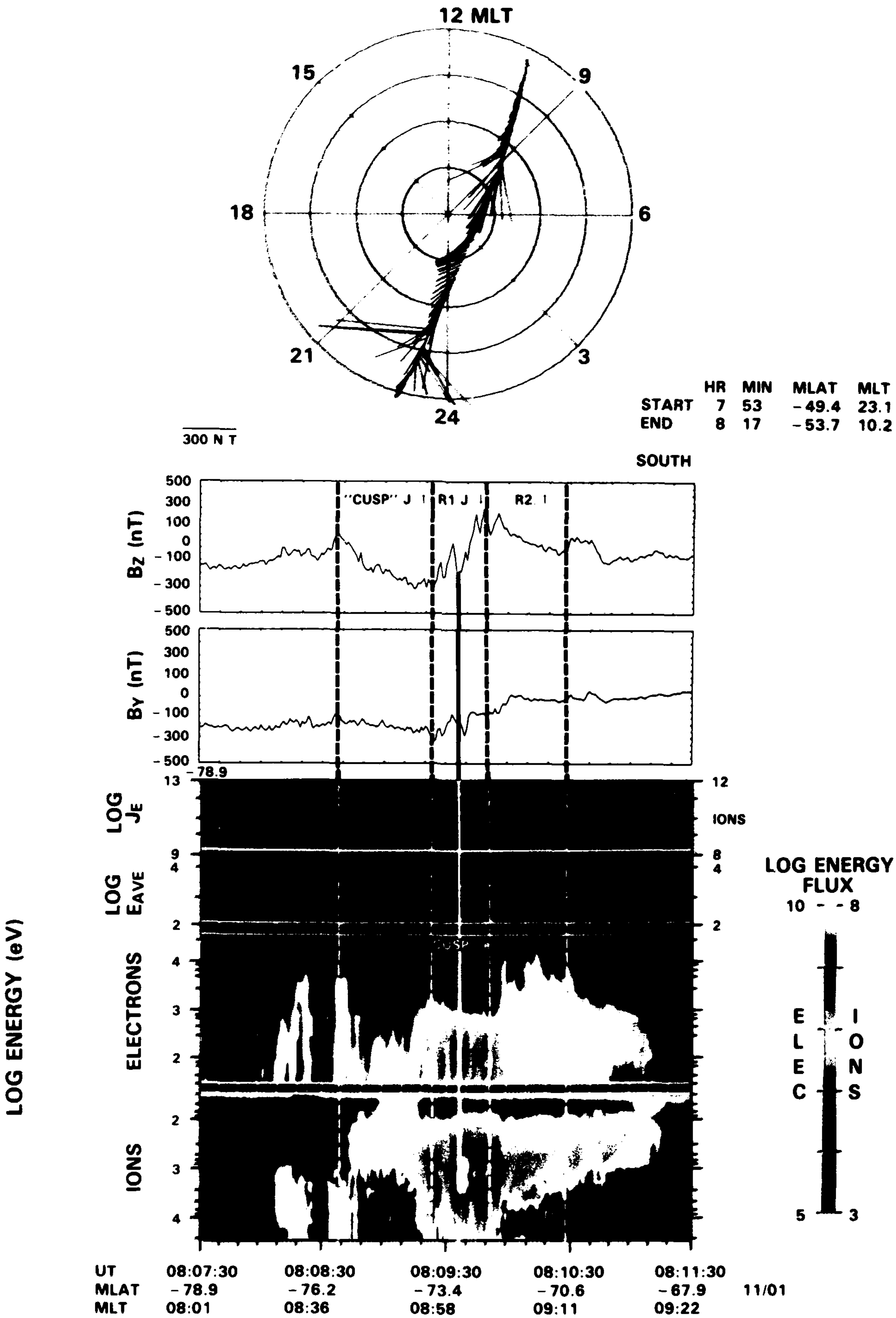
DMSP F7 SOUTHERN HEMISPHERE $B_Z > 0$



F7 have almost identical counterparts in the conjugate northern hemisphere. Of the three gradients in B_x the one associated with the region 1 current between 0808:40 and 0809:26 UT is most nearly conjugate with its southern hemisphere counterpart.

Charged particle data from HILAT are limited to electrons only, but unlike DMSP F7, pitch angle information is available. Pitch angle information was provided by sampling the electron flux with three fixed detectors at different orientations to the magnetic field. The three spectrograms of number flux versus time versus energy are from the zenith, 40°, and nadir pitch angles. Between 0808:40 and 0809:30 UT there is an enhanced flux of low-energy electrons measured by the zenith and nadir detectors that can be associated with the traditional cusp, but as was observed by DMSP in the southern hemisphere, these electrons are colocated not with the cusp current but with the region 1 current. The most intense flux of low-energy electrons at 0808:55 UT is colocated with a plateau or slightly reversed gradient in the magnetic field embedded within the region 1 current. This feature is very similar to the one observed simultaneously by DMSP in the conjugate hemisphere. The traditional cusp current observed between 0809:30 and 0810:26 UT extends to higher latitudes than region 1 and is associated with a less intense flux of electrons. At the interface between region 1 and cusp currents (0809:30 UT), the electron pitch angle distribution transitions from relatively isotropic to field aligned, suggesting a change in magnetic field topology from dayside to tail lobe or plasma mantle field lines. The region 2 current between 0807:55 and 0808:40 UT is associated with a plasma sheet-like population of electrons that extend from about 68° MLAT up to the region 1/region 2 interface at about 72.5° MLAT.

Case C Spectra

Figure 2 shows three typical electron spectra: one obtained from HILAT in the northern hemisphere at 0808:55 UT, another from DMSP F7 in the southern hemisphere at 0809:38 UT, and a third from AMPTE CCE when the spacecraft was in the 1000 MLT magnetosheath. The data are plotted as log differential number flux versus log energy. The three spectra are nearly identical in shape, peak flux, and average energy. The similarity between these three spectra confirms that even during periods of northward IMF, magnetosheath particles are relatively unimpeded as they penetrate into the magnetosphere and along magnetic field lines into the dayside auroral zone. *Candidi and Meng* [1984] have shown that near-conjugate measurement of precipitating electrons in the prenoon sector yields nearly identical spectra. Our observations show that during a period of northward IMF, conjugate ionospheric spectra are essentially indistinguishable from nearly simultaneously measured magnetosheath spectra. Thus, an efficient plasma entry mechanism other than dayside merging may be operative when the IMF is directed northward.

Case D ($B_z < 0$)

DMSP F7 next crossed the prenoon sector in the northern hemisphere when the IMF had once again acquired a southward component. The magnetic field and charged particle data collected during this traversal are displayed in Plate 4. The display format is the same as for Plates 1 and 2. Data from the orbit segment highlighted in the MLT/MLAT dial are reproduced in detail in the lower five panels. In the center of the highlight, the perturbation magnetic field vector undergoes a shearlike reversal from a southwesterly orientation to an almost due easterly direction over less than 0.5° of magnetic latitude. At latitudes greater than about 73° MLAT the vector rotates gradually to the southeast. The shear reversal in the magnetic field vector indicates the presence of an intense region 1 current flowing into the ionosphere, while the gradual rotation at higher latitude is associated with the outward directed "cusp" current. As mentioned previously, the nominal direction and velocity of ion drift can be inferred from the magnetic field vectors and an ionospheric conductivity model. Thus, the ion drift undergoes a shear reversal from a dominantly sunward to antisunward flow, the shear reversal being centered within the region 1 Birkeland current. *Heelis et al.* [1976] have shown that these reversals occur within a region of "cleft particle" precipitation.

The gradient in B_z between 0850:35 and 0851:00 UT, seen in the top line plot, is about 20 nT/s. From this we derive a region 1 current density of 2 $\mu A/m^2$ with flow directed into the ionosphere. This case shows very clearly that the equatorward edge of the region 1 current is precisely colocated with the onset of low-energy electron precipitation that has generally been associated with the polar "cusp/cleft." The high-energy tail of the cusp electrons clearly visible in the spectrogram is bounded by the limits of the region 1 current system, while a classic polar rain electron signature with essentially no flux of electrons at energies above 1 keV has its onset at the poleward edge of the region 1 current. The onset of polar rain is colocated with a reversal in the magnetic field gradient signifying an outward directed cusp Birkeland current with a density of about 0.6 $\mu A/m^2$. Ions associated with the region 1 current display a steeply sloped energy versus latitude dispersion signature with a maximum flux at about 1 keV. The total energy flux of ions is of the same order of magnitude as is the energy flux of electrons within the region 1 current. Ions associated with the cusp current appear to have convected poleward from lower latitudes and exhibit a shallower sloped energy versus latitude dispersion signature. We find as in case A that for southward IMF, within the limits of the DMSP F7 instrumentation, there is no discernable indication of a region 2 current or of plasma sheet-like electron precipitation equatorward of the region 1 current. This is consistent with a dayside gap in the region 2 current system [*Iijima and Potemra,* 1978] and in the diffuse visible wavelength aurora [*Meng,* 1981 and references therein].

DISCUSSION

The relationship between Birkeland currents and charged particles in the ionosphere at low altitude is not well understood for the late morning through early afternoon hours, yet this relationship has significant bearing on the generation of large-scale Birkeland current systems and on mechanisms of charged particle entry into the dayside magnetosphere. Statistically, the region 1 Birkeland current system is a persistent feature of the dayside ionosphere at all magnetic local times and generally has current flow directed into the ionosphere in the morning hours and out of the ionosphere in the afternoon hours. A recent study by Erlandson et al. (IMF B_y dependence of region 1 Birkeland currents near noon, this issue 1988), using magnetic field and charged particle data from the Viking spacecraft, has revealed that near noon the region 1 current flow direction is strongly dependent on the *Y* component of the IMF. The so-called "cusp Birkeland currents" lie adjacent to region 1 at higher latitude and are somewhat more limited in local time [*Iijima and Potemra,* 1976].

Plate 2. (Opposite) The same as Plate 1 but in the southern hemisphere about 45 min later with a northward component of the IMF. The data presented in this plate are simultaneous with and conjugate to those presented in Plate 3.

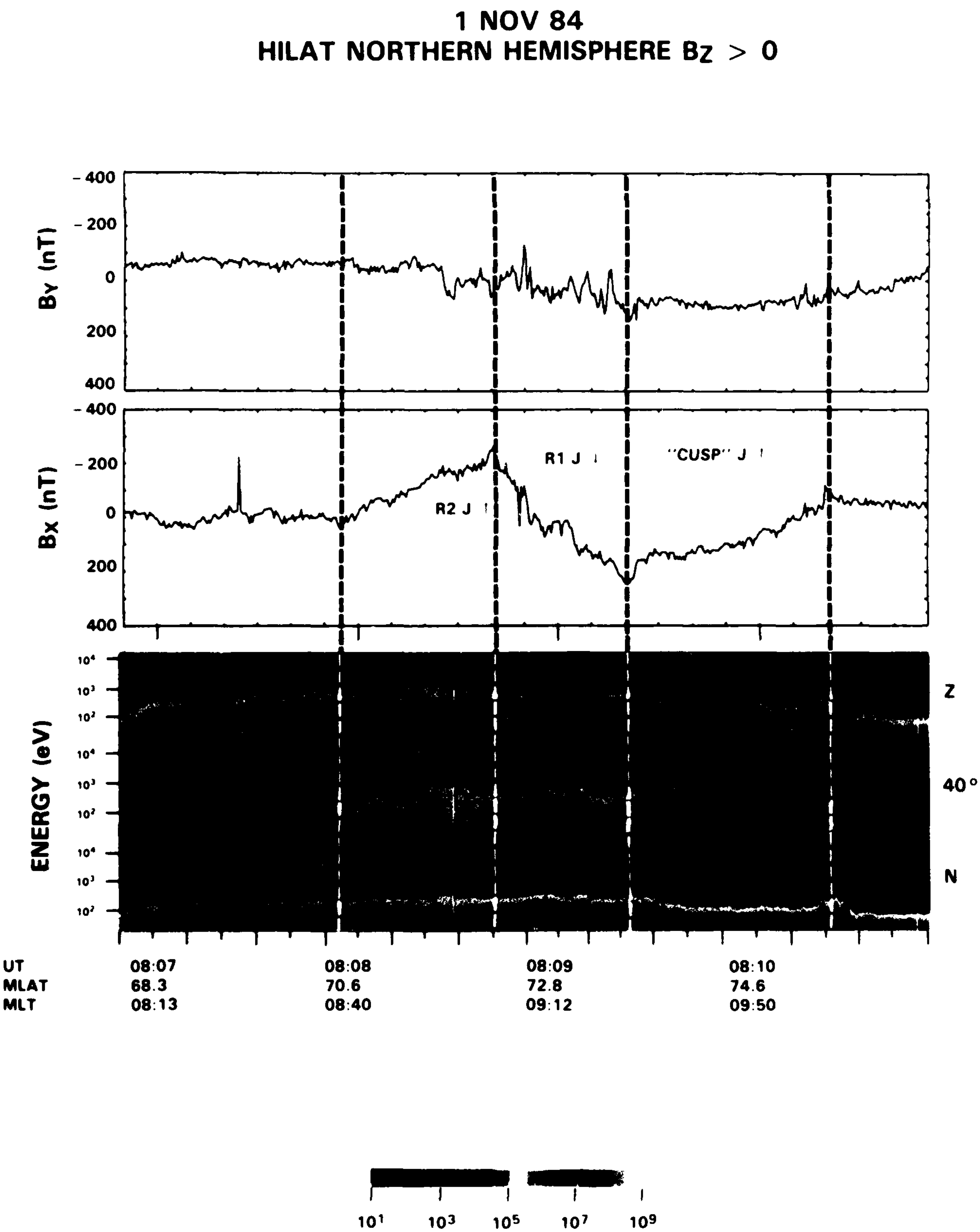


Plate 3. Magnetic field and electron data collected with the HILAT satellite in the northern hemisphere simultaneously with those data presented in Plate 2. The upper two panels are the transverse components of the perturbation magnetic field. The lower three panels are electron spectrograms from the zenith, 40°, and nadir look angles.

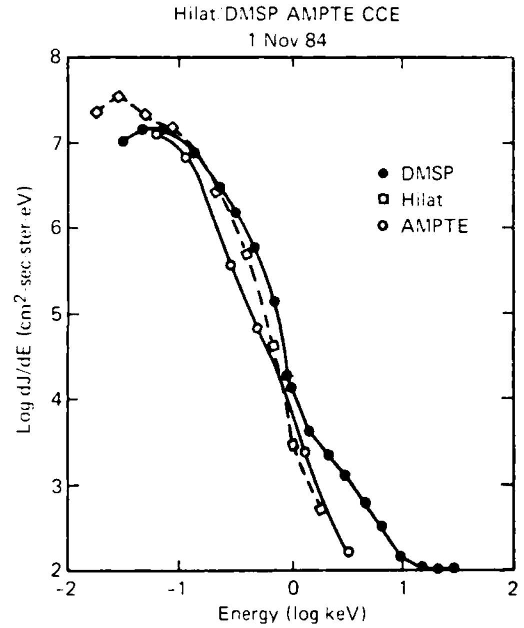


Fig. 2. Three near-simultaneous electron spectra taken from HILAT in the northern hemisphere, DMSP F7 in the southern hemisphere, and AMPTE/CCE in the 1000 MLT equatorial magnetosheath at 8 Earth radii.

Region 1 Currents and "Cusp" Particles

The data presented in Plates 1 through 4 provide evidence that the region 1 current system in the prenoon sector is colocated with low-energy electrons and ions apparently of magnetosheath origin. This is in agreement with Erlandson et al.'s recent results from Viking. Moreover, in each case the equatorward edge of the region 1 current is very nearly coincident with the lower-latitude boundary of these particle fluxes. In Plates 2 and 3 the equatorward edge of the region 1 current in both the northern and southern hemispheres coincides with the poleward edge of the region 2 currents. Electrons associated with region 2 have hotter non-Maxwellian spectra than those associated with region 1 and are likely to originate in the dayside extension of the plasma sheet.

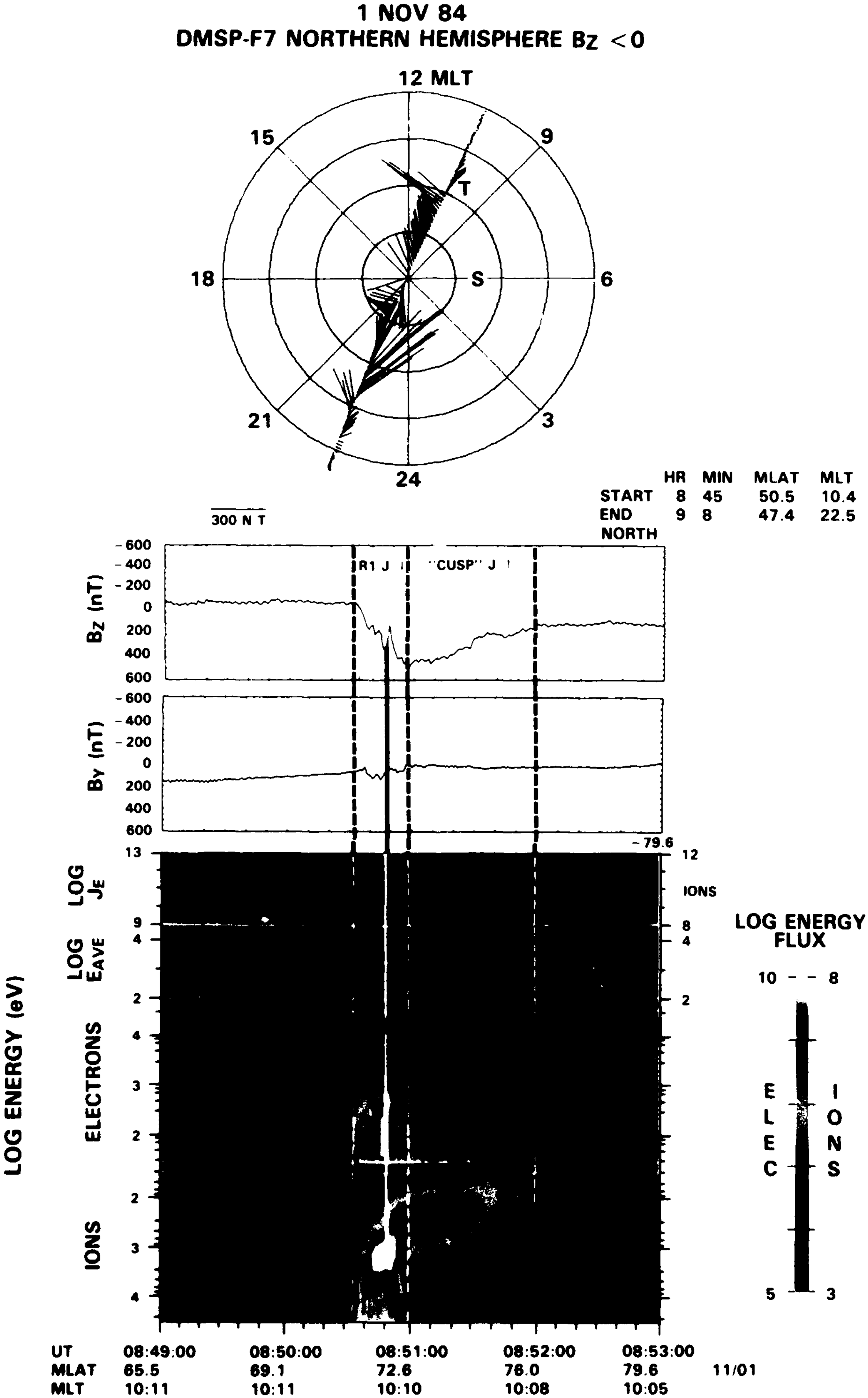
There is mounting evidence that the dayside region 1 currents are generated as a direct result of the solar wind/magnetospheric interaction and that they couple the electrodynamic processes between the solar wind, magnetosphere and the ionosphere. If magnetosheathlike particles in the dayside ionosphere are colocated with the region 1 Birkeland currents as these data show, then it is unlikely that this plasma originates in a stagnant region of the magnetosheath. On the contrary, an MHD generator that is the source of the dayside region 1 currents is best suited to regions of high-velocity shears associated with "viscous" flow in the low-latitude boundary layer [*Eastman et al.*, 1976; *Bythrow et al.*, 1981; *Lundin and Dubinin*, 1984]. In this view the region 1 current and the cusp particles both originate in the boundary plasma which extends over the entire dayside, i.e., a dayside boundary layer. In this context we define the "dayside boundary layer" as the magnetospheric plasma regime associated with those field lines whose ionospheric foot points lie in the region of cusp particle precipitation, although their equatorial crossing points may lie tailward of the dawn-dusk meridian. (See, for example, Figure 1 of *Vasyliunas* [1979].)

Charged particles with magnetosheathlike characteristics are observed at low altitude over a broad range of magnetic local times and over a few degrees in invariant latitude in the dayside ionosphere [*Hardy et al.*, 1985 and references therein]. *Vasyliunas* [1979] suggested that only a spatially limited region located near noon and embedded within the larger region of magnetosheath-like particles was indeed associated with the magnetospheric cusp. He hypothesized that the region of low-energy charged particle precipitation that is distributed over a broad range of local times is the low-altitude signature of the low-latitude boundary layer. Observations of plasmas and magnetic field made by the HEOS 2 satellite confirm the entry of magnetosheath plasma into the magnetosphere at high latitude via the entry layer [*Paschmann et al.*, 1976]. *Crooker* [1977*a*], using high-latitude charged particle and magnetic field data from the Explorer 33 spacecraft, extended the interpretation of the entry layer to include high-latitude dipolar field lines that may extend as far as 8 R_E down the tail. These results are consistent with our definition of the dayside boundary layer. The IMP 6 spacecraft made measurements of plasmas and magnetic fields in the LLBL (low-latitude boundary layer) near noon which show that ions and electrons that are in the boundary layer near the inner edge of the magnetopause appear to be on closed field lines and are virtually indistinguishable from adjacent magnetosheath particles [*Eastman and Hones,* 1979]. Thus, dayside magnetosheath plasma has relatively unimpeded entry to the magnetosphere at low as well as high latitudes. This plasma has a significant component of flow directed across the magnetic field and is therefore a likely source of the region 1 currents.

Conjugate Measurements

The similarity between the simultaneous, conjugate measurements of magnetic fields and charged particles displayed in Plates 2 and 3 indicates that for conditions of northward IMF either dayside merging can proceed in a hemispherically symmetric manner or the region of Birkeland currents and magnetosheathlike particles can reside on closed field lines or both. Owing to the large positive B_y component of the IMF it is unlikely that a dayside merging process would produce hemispherically symmetric results. Therefore, under these conditions the boundary layer is likely to consist of magnetosheath particles that reside primarily on closed field lines. A comparison by *McDiarmid et al.* [1976] between low-energy particles measured with the SPS and more energetic particles measured with the EPD (energetic particle detector) on ISIS 2 revealed that a significant fraction of the low-altitude cusp particles do in fact reside on closed field lines. From this observation they concluded that diffusion of magnetosheath plasma onto closed field lines could be one source of cusp particles. Evidence for both merging and diffusive entry processes was given by *Reiff et al.* [1977]. They observed energy versus latitude dispersion signatures in the ion spectrograms acquired from the AE-C and deduced that an inverse latitude versus energy relationship indicated merging and that a V-shaped signature was indicative of diffusion. It was determined that the merging signature dominated when the IMF had a southward component [*Reiff et al.*, 1980]. In case B the DMSP F7 spectrogram of ion energy flux versus energy and time shows no evidence of an energy versus latitude dispersion, which supports the conclusion that the dayside boundary layer and thus the sheathlike particles reside on closed field lines for $B_z > 0$.

Candidi and Meng [1984] used electron flux data from the DMSP F2 and DMSP F4 satellites and solar wind data from ISEE 3 and IMP 8 to examine the relationship between sheathlike electron fluxes in the dayside ionosphere and solar wind parameters. They found that the density of the solar wind was well correlated with the intensity of low-altitude electron flux, while the orienta-



1 NOV 84
DMSP-F7 NORTHERN HEMISPHERE Bz <0
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15
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START 8 45 50.5 10.4
END 9 8 47.4 22.5
NORTHERN
300 N T
R1 J
"CUSP" J
Bz (nT)
By (nT)
-600
-400
-200
0
200
400
600
-79.6
LOG JE
LOG EAVE
LOG ENERGY (eV)
ELECTRONS
IONS
LOG ENERGY FLUX
10 - - 8
ELEC
IONS
5
3
UT 08:49:00 08:50:00 08:51:00 08:52:00 08:53:00
MLAT 65.5 69.1 72.6 76.0 79.6 11/01
MLT 10:11 10:11 10:10 10:08 10:05

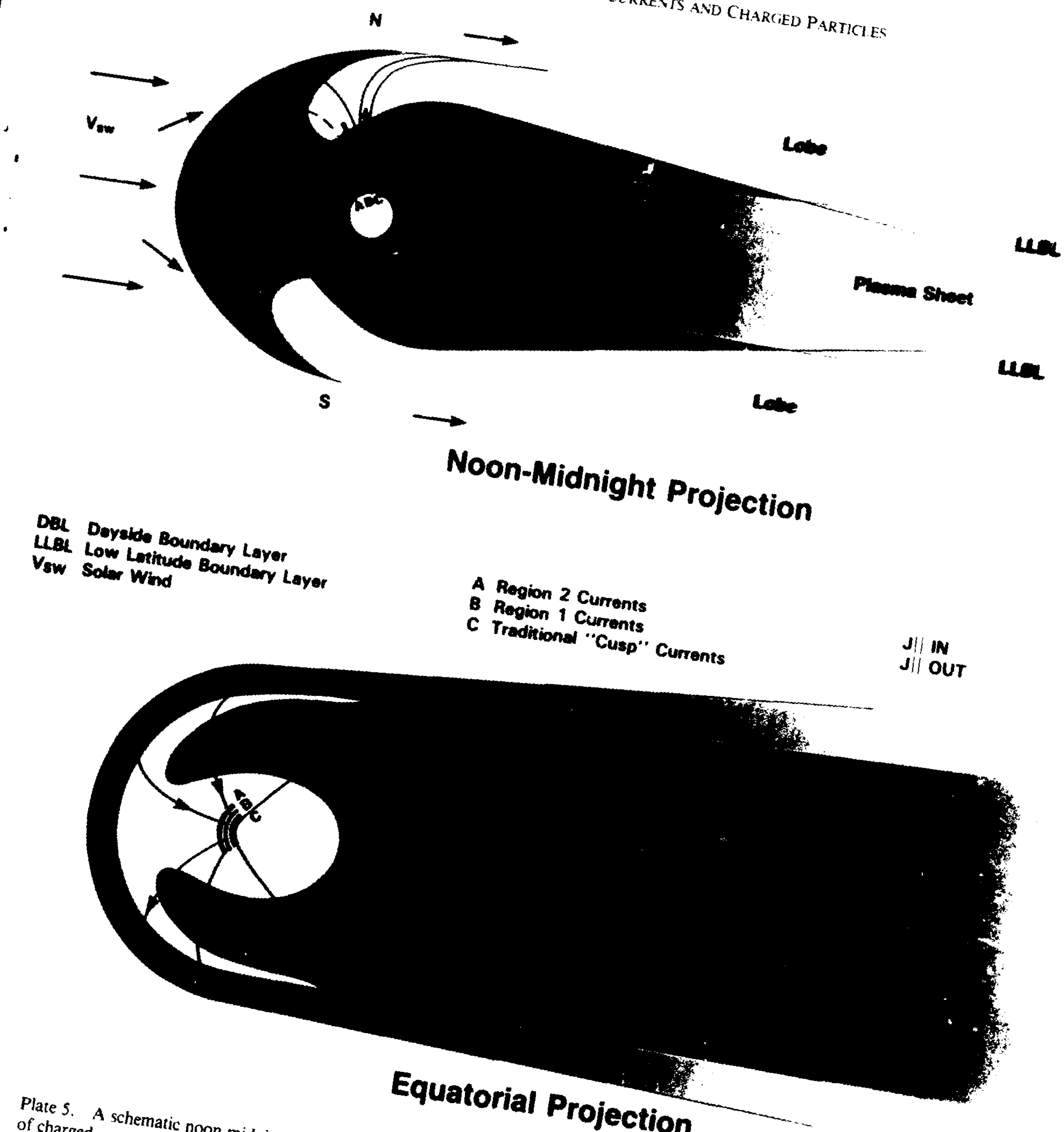

Plate 5. A schematic noon-midnight projection (top) and equatorial projection (bottom) of the magnetosphere show mapping of charged particle populations and dayside Birkeland currents to regions of the magnetosphere. The region 2 currents are represented as currents A. Currents B are the region 1 system, and the "mantle currents" are represented as C. In the noon-midnight projection, only the prenoon currents are shown.

tion of the IMF appeared at best to have a much smaller effect [see *Candidi and Meng*, 1984, Figures 10–12]. In Plates 1, 2, and 4 we show that the total energy flux J_E for ions and electrons is nearly equal for both strongly northward (Plate 2) and strongly southward (Plates 1 and 4) conditions of IMF. In agreement with Candidi and Meng, we conclude that dayside merging is likely to be a secondary consideration regarding the processes that lead to the penetration of magnetosheath particles into the magnetosphere.

Plate 4. The same as for Plate 1 but about 90 min later.

Mantle Currents

The outer layer of tail lobe field lines at high latitude is populated by plasma that is of magnetosheath origin. This tail lobe boundary layer has been designated the plasma mantle [*Rosenbauer et al.*, 1975]. Figure 3 of *Crooker* [1977*b*] is a schematic representation of this topology. As best demonstrated in Plate 4 of the DMSP F7 data, the flux of low-energy electrons experiences a sharp decrease at the poleward edge of the region 1 current. The high-latitude tail of the ion energy versus latitude dispersion extends well poleward of the region 1 system into the region of electron polar rain. At the high-latitude edge of the region 1 current, "polar rain" electron fluxes dominate the electron spectrum, and the high-energy components of the sheathlike precipitation disappear. *Gussenhoven et al.* [1984] using electron data from the DMSP F2 satellite concluded that polar rain electrons originate in the plasma mantle. Thus, the onset of polar rain electrons on the dayside may be identified as the low-latitude boundary of the plasma mantle. Plasma mantle ions are excluded from the tail lobes due to their low thermal pressure [*Gussenhoven et al.*, 1984]. Thus, in the ionosphere the poleward limit of tailward convecting sheathlike ions represents the high-latitude limit to the plasma mantle. In each case we have examined, the highest-latitude Birkeland current is associated with this poleward extension of magnetosheathlike ions and therefore flows along field lines that thread the plasma mantle.

The electric field gradients required by these currents imply a divergent flow of ionospheric plasma at high latitude on the dayside.

CONCLUSIONS

The relationship of the large-scale Birkeland currents to magnetospheric boundaries and plasma regimes as we perceive them is shown in Plate 5. This is a grossly simplified schematic that shows the projection of ionospheric Birkeland currents and charged particles onto the noon-midnight meridian and equatorial plane.

The following list summarizes our results and conclusions concerning the relationship between dayside Birkeland currents and charged particles. These conclusions have been drawn from a limited set of low-altitude observations and from comparison with previous studies, but we propose that they are generally applicable.

1. For periods when the IMF has either positive or negative Z components, the prenoon region 1 currents are colocated with charged particles that have characteristics similar to those found in the magnetosheath. Although these particles have been traditionally associated with the polar cusp, the region 1 currents flow along field lines that thread the dayside boundary layer. Thus, this region is likely to be the source of the sheathlike particles.

2. Ions that are colocated with the region 1 current system have essentially the same energy flux for both northward and southward IMF. When the IMF is directed southward, these ions exhibit an energy versus latitude energy dispersion. For northward IMF this dispersion signature is absent. Therefore, we conclude that for northward IMF, particle access to the dayside boundary layer is unimpeded, but the mechanism of entry may differ from when the IMF is directed southward.

3. The traditional "cusp Birkeland currents" lie poleward of the most intense sheathlike particle precipitation. Hence, it is likely that these currents map to the plasma mantle and are associated with divergent flow of ionospheric plasma near noon.

4. The region 1 currents flow along field lines that map to the "dayside boundary layer" while the "cusp currents" flow on those field lines that map tailward into the plasma mantle. Thus, we suggest that the low-altitude representation of the magnetospheric cleft might be best identified as the interface between the region 1 and higher-latitude currents. We also suggest that a more appropriate name for this high-latitude current system is the "mantle" current.

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