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Correspondence between ULF activity, field-aligned currents, and dayside magnetospheric regions

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Abstract. We propose a technique for studying simultaneously observed ULF activity in the Pc5 frequency band, global patterns of field-aligned currents (FAC) derived from the IZMEM model driven by IMF, and maps of dayside magnetospheric regions obtained from DMSP charged particle flux measurements. This technique produces a sequence of two-dimensional "snap-shots" of the FAC distributions with overlapped DMSP satellites tracks along which we obtain a projection of magnetospheric regions onto the ionosphere. The 2-D distribution of the ULF spectral power is inferred from the worldwide array of geomagnetic stations. For most of the analyzed morning sector events the region of downward FAC maps together with the low latitude boundary layer (LLBL) projection to the polar ionosphere, whereas the upward FAC region coincides with the central plasma sheet (CPS) projection. Simultaneous occurrence of two source regions of the ULF activity is observed: one is located in the early morning/afternoon (magnetic local time) hours at latitudes 65°–70°, and the other is observed near noon at latitudes 75°–79°. The morning sector ULF intensity peaks equatorward of the R1 FAC. The near-noon Pc5 pulsation power peak coincides with the equatorward boundary of the LLBL, whereas a resonant maximum of Pc5 pulsations in the early morning hours corresponds to the CPS region.

1. Introduction

The interaction of solar wind plasma flow with the Earth's magnetosphere can be considered as a giant, natural magnetohydrodynamic (MHD) generator, which produces the large-scale, quasi-steady 3D current system at high latitudes. This system includes the field-aligned currents (FAC), or Birkeland currents, in the magnetosphere, coupled with the closure (horizontal) currents in the ionosphere. The intensity and spatial distributions of these current systems are controlled to a considerable extent by the interplanetary magnetic field (IMF). Much of the transfer of energy and momentum from the solar wind through the magnetosheath into the magnetosphere occurs at the dayside magnetospheric boundary layers. Mapping of magnetospheric boundary layers to low altitudes bears substantial uncertainty because of the uncertain topology of the entire magnetosphere, although it is clear that these spatially vast regions map into a very limited area around the low-altitude cusps. This mapping was studied by using advanced magnetic field models, low-altitude measurements of charged-particle precipitation, visible auroral emissions, radar observations, and other sources of information.

The global magnetosphere-ionosphere current system, as it is reconstructed from magnetic field measurements either on the ground or on low-altitude satellites, can be decom-

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posed into several subsystems. In the dawn/dusk sectors, the ionospheric DP1/2 (or field-aligned R1/R2) current system dominates. This current system consists of two longitudinally elongated current sheets with downward (upward) FAC in the poleward sheet (R1) and more wide upward (downward) FAC in the equatorward sheet (R2) at dawn (dusk). This system is intensified under conditions of southward IMF ($B_z < 0$).

In the dayside cusp/cleft region, the ionospheric disturbance polar driven by y component of IMF (DPY) current system is observed if the IMF has a substantial azimuthal component [*Troshichev et al.*, 1997]. In its simplest form, the DPY current system is an east-west oriented Hall current which is formed between the ionospheric ends of two FAC sheets. The equatorward sheet may be an extension of the R1 current, while the poleward sheet is located at higher latitudes, in the cusp/mantle region. It is often referred to as R0 FAC. Position and intensity of this current system are controlled by the IMF, predominantly by the azimuthal component, B_y, and to a lesser degree by the vertical component, B_z. Poleward of the cusp, the current system driven by northern B_z (NBZ) current system resides, most evident during periods of northward IMF, $B_z > 0$. The NBZ current system is located near noon at geomagnetic latitudes higher than 80°, with the upward prenoon FACs and downward postnoon FACs.

The energy transfer from the solar wind plasma into the magnetosphere and ionosphere has a turbulent character. Thus, it might be expected that in the key boundary regions, electromagnetic and magnetohydrodynamic noise can be generated. The occurrence of natural magnetospheric MHD waveguides and resonators may result in the noise's partial filtering producing quasiperiodic pulsations. Indeed, at high latitudes, intense quasiperiodic ULF (ultra-low-frequency) pulsations of the geomagnetic field in the Pc5 range (1–10 mHz) are commonly observed, but the exact physical mechanism for these ULF disturbances has not yet been established. The common view is that the main source of dayside Pc5 waves is the Kelvin-Helmholtz (K-H) instability at the flanks of the magnetosphere, excited by the solar wind flow. The velocity shear may exist at interfaces between other magnetospheric boundary regions, thus being the probable source of the K-H-generated disturbances.

Inside the magnetosphere, these disturbances are transformed into more regular, quasi-monochromatic Pc5 pulsations under the influence of magnetospheric resonance effects. The position of the resonance is determined by the match between the local Alfvén frequency and the frequency of an external source, irrespective of a particular source mechanism. According to this notion, the latitude of maximal ULF intensity is determined by the features of the magnetospheric plasma distribution.

An intriguing but still not resolved problem is the identification on the ground of specific ULF wave signatures of boundary phenomena. Early studies [*Olson*, 1986; *Rostoker et al.*, 1972; *Troitskaya and Bol'shakova*, 1977, 1988] suggested that a probable source of the dayside high-latitude long-period pulsations was related to the cusp, the region of direct penetration of turbulent magnetosheath plasma into the magnetosphere/ionosphere. The broadband disturbances in the period range of 3–15 min (named irregular pulsations at cusp latitudes (IPCL) [*Troitskaya*, 1985] or broadband Pc5 pulsations [*Clauer and Ridley*, 1995]; *Engebretson et al.*, 1995]) were also claimed to be typical features of the dayside cusp/cleft. Occurrence of ground-based pulsations has been suggested to be used for monitoring the dynamics of the cusp/cleft region [*Bolshakova et al.*, 1988; *Kleimenova et al.*, 1985; *McHenry et al.*, 1990]. Later, *McHarg et al.* [1995] and *Lanzerotti et al.* [1999] found that small-amplitude quasi-monochromatic Pc5 waves at the dayside might be a signature of near-cusp closed field lines and could be used as cusp discriminators. However, this goal can hardly be achieved by simple means. Observations at the MACCS (cusp-centered) array showed that the dayside broadband ULF activity is dominated by temporal variations across a large longitudinal extent [*Engebretson et al.*, 1995]. *Szuberla et al.* [2000] succeeded to identify a cusp signature in coherent Pc5 waves using polarization spectra.

Various hypotheses have been suggested for interpretation of the high-latitude ULF disturbances, including a fluctuating component of FACs or precipitating electrons [*Engebretson et al.*, 1991]; fluctuations of the cusp-related current system [*Olson*, 1986], and the K-H instability in the region of the convection reversal boundary [*Clauer et al.*, 1997] or in the inner part of the LLBL [*Lee et al.*, 1981].

The attempts to relate the location of ULF waves observed on the ground to magnetospheric boundary regions have been done so far either on a statistical basis, with all the inherent uncertainties of using average locations of boundaries, or on a very limited regional basis defined by a particular magnetometer array. To put ULF studies in a more global magnetosphere/ionosphere context, it is necessary to develop an approach that would enable one to study simultaneously the ULF global pattern together with some proxies of ionospheric electrodynamics and identification of ionospheric projections of dayside magnetospheric regions. A possible tool for these studies is suggested in this paper. We have combined observations from about 50 magnetometers in the northern high latitudes to produce an instantaneous (on the scale of the spectral window) global map of ULF wave power and have related this to magnetospheric regions defined either using DMSP particle data or a statistical FAC pattern that depends on the IMF measured at the time of the observation and propagated to the bow shock location. For the first time, this allows a view of the global distribution of ULF power and its relationship to magnetospheric regions. This tool has been applied to the problem of how the Pc5 ULF pulsations observed in the dayside polar region are related to the magnetospheric regions and global current systems (R1/R2, R0, and NBZ).

2. Empirical-Analytical Model of High-Latitude Global Electrodynamics

Long-term observations at high-latitude magnetic observatories established a reliable connection between the IMF

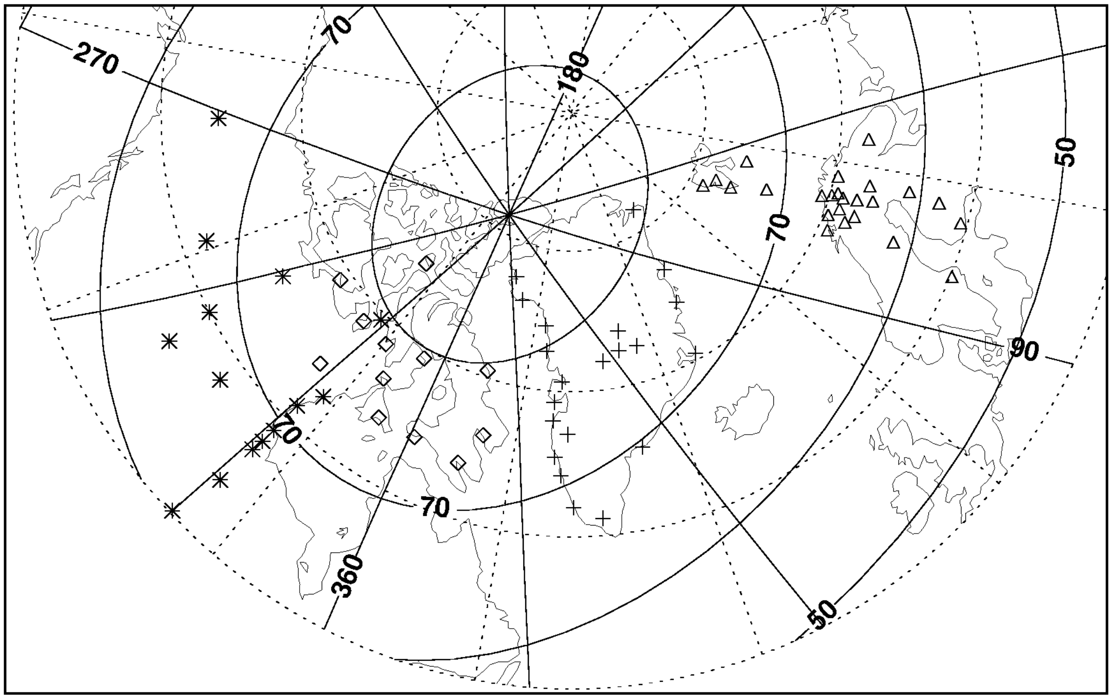

Figure 1. The magnetometer networks at high latitudes: CANOPUS (asterisks), MACCS (squares), Greenland array (crosses), and IMAGE (triangles).

and ionospheric current systems, which resulted in several empirical-analytical models. One of the approaches, the IZMIRAN Electrodynamics Model (IZMEM), developed at the Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation (IZMIRAN) [*Feldstein and Levitin*, 1986; *Papitashvili et al.*, 1994], utilizes a linear regression relationship between the IMF and ground-based geomagnetic disturbances at high latitudes. The IZMEM model has recently been recalibrated utilizing the DMSP electrostatic potentials [*Papitashvili et al.*, 1999]; the Web-based interface to the IZMEM model has been made available at http://www.sprl.umich.edu/MIST/limie.html. With the use of this model, the ionospheric electrodynamic pattern for a given IMF intensity and orientation can be calculated and mapped over both the northern and southern polar regions using a statistical model of ionospheric conductivity [e.g., *Robinson and Vondrak*, 1984; *Wallis and Budzinski*, 1981]. The algorithm incorporated in the model separates the ground magnetic variations into internal and external parts, restores electric potential and horizontal currents in the ionosphere, and finally determines the FACs in and out of the ionosphere. The IZMEM model does not require collection of in situ ground-based geomagnetic data for the event under investigation or selection of a magnetically quiet period to calculate geomagnetic disturbances. This distinguishes the IZMEM from other algorithms such as the "magnetogram inversion technique" [*Mishin et al.*, 1980], the KRM method [*Kamide et al.*, 1981], and the AMIE technique [*Richmond and Kamide*, 1988].

The IZMEM model allows the user to obtain instantaneous distributions of ionospheric electric potentials or FACs for a given IMF during the time interval under investigation. However, IZMEM is an empirical model, so physical mechanisms of predicted 3D systems and identification of the basic current elements within the magnetospheric regions have not been considered in this model.

3. Ground-Based Magnetometer Arrays

The existing global network of magnetic stations at high latitudes, shown in Figure 1, forms several latitudinal profiles: (1) CANOPUS (http://www.dan.sp-agency.ca/www/) is a network of 13 automatic stations deployed over west-central Canada with a sampling period of 5 s. (2) MACCS (http://space.augsburg.edu/space/) is a network with 12 identical fluxgate magnetometers with 0.5–1.0 s sampling deployed in the Canadian Arctic, which includes one station in the polar cap and longitudinal profiles along geomagnetic latitudes ∼79°N and ∼75°N. Together, MACCS and CANOPUS form three meridian profiles along corrected geomagnetic longitudes, ∼15°(MC-East), ∼335°(MC-Center),

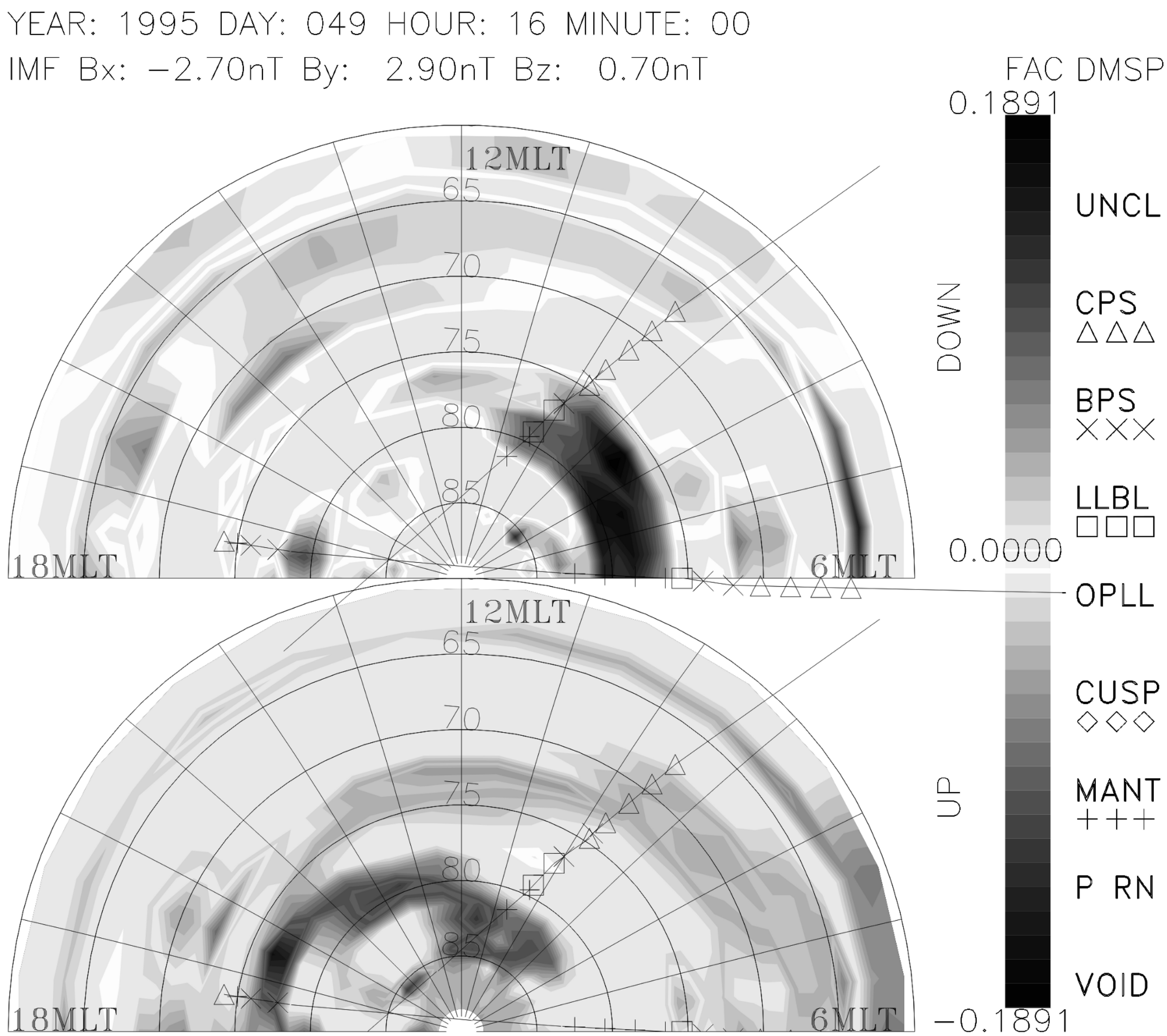

Figure 2. Comparison of the (top) downward and (bottom) upward FAC regions as derived from the IZMEM model with the magnetospheric boundary regions during the event 18 February 1995 (day 049) at 1600–1700 UT.

and ~315°(MC-West). (3) The Greenland coastal chain (http://www.dmi.dk/ projects/chain/)is an array of 17 magnetic stations with 20-s sampling rate, deployed along the west (~40°) and east (~95°) coasts of Greenland. It is augmented by MAGIC (http://www.sprl.umich.edu/MIST/), a magnetometer array on the Greenland ice cap (at ~60° magnetic longitude). (4) IMAGE (http://www.geo.fmi.fi/image), an auroral and sub-auroral network of 24 magnetometer stations with 10-s sampling rate, clustered along the Scandinavian meridian (~105° CGM longitude).

With these arrays, the spatial coverage of stations is dense enough to enable us to proceed from the analysis of 1D latitudinal profiles to the examination of 2D patterns. The pertinent technique is described further below.

4. Identification of Ionospheric Projections of Magnetospheric Regions From DMSP Data

Charged-particle precipitation characteristics seem to be the best low-altitude means to categorize the ionospheric projection of the magnetospheric boundary layers [*Newell and Meng*, 1988]. In this study observations from the Defense Meteorological Satellite Program (DMSP) satellites F10–F12 are used. The automated dayside region identification program distinguishes magnetospheric regions through the characteristics of precipitating electrons and ions (in the 30 eV to 30 keV range) at DMSP altitude (~800 km) [*Newell* *et al.*, 1991a, 1991b]. The classification scheme is described in Appendix A. The region identification database is given as a set of files with the Universal Time (UT) of the crossing of each boundary. The crossings are further tagged with the geomagnetic latitude and magnetic local time and with the geocentric coordinates.

5. Visualization and Mapping Technique

We develop a technique for simultaneous mapping (as a sequence of 2-D "snap-shots") of the ionospheric electrodynamic pattern, predicted by the IZMEM model, and of the ULF spectral power. We consider it as a first step toward performing a dynamical 2D analysis of ULF pulsations.

The program decimates the original geomagnetic time series to a common sampling period of 20 s. At each station, the H component is transformed into the frequency domain via an FFT over a gliding window, and the spectral power within a selected frequency band is estimated. These data are used to construct the 2D spatial distribution of ULF power (H component) for a particular time interval. For the gridding of irregularly spaced data the IDL routine CONTOUR has been used which handles this problem by constructing a Delaunay triangulation.

In subsequent analysis, a 1-hour window and the 2.0–8.0 mHz frequency band are used. The time interval on the plots is indicated by its onset, that is, "1000 UT" denotes "1000–1100 UT". The ULF power within each time interval is normalized with the maximum of the whole day. It is indicated on each plot and may be used as an indicator of ULF intensity in each snap-shot.

For the calculation of 2D spatial distributions of FACs over the high-latitude ionosphere as predicted by the IZMEM model, the necessary data are taken automatically from the OMNI database of 1-hour means of the IMF/solar wind parameters. Thus, the semiempirical model IZMEM driven by the IMF parameters produces snap-shots of 2D polar plots with the spatial structure of FACs throughout the dayside high-latitude ionosphere. The upward (negative) FACs are assumed to be transported by precipitating electrons whereas the downward (positive) FACs are carried by upward flow of ionospheric electrons.

To establish a correspondence between the spatial distribution of ULF intensity, FACs, and magnetospheric boundaries, we overlay on the plots available DMSP satellite tracks with the results of automated identification of magnetospheric boundaries. The ground track of each orbit is plotted in geomagnetic coordinates with the footpoints of the magnetospheric regions marked by diamonds (cusp), squares (LLBL), crosses (BPS), triangles (CPS) and pluses (mantle). Thus, this track clearly indicates the position of the ionospheric projection of each magnetospheric region.

6. Case Studies With New Mapping Technique

This technique is used to analyze the relationship between the large-scale current systems, the intensity of ULF waves and the relation of both parameters to the dayside magnetospheric boundaries. The suggested mapping technique can be an effective tool for the study of the following questions:

1. What is the correspondence between the basic FAC regions (e.g., predicted by the IZMEM model) and dayside magnetospheric regions?
2. What is the correspondence between the position of the spatial peak in the ULF Pc5 power distribution and FACs?
3. In which magnetospheric regions are the probable sources of ULF activity are located?

Special attention is paid to the noon and morning MLT sectors as these are the sectors of the most intense ULF activity in the Pc5 band. Hourly patterns for the following three days have been selected (rather arbitrarily) for analysis: (1) 26 November 1995 (day 360). The IMF B_z is slightly negative (~ -2 nT) during this day. Northward B_z excursions at $\sim$0400 UT and $\sim$1700 UT stimulated substorms observed at $\sim$0400 UT (GCA, MACCS, and CANOPUS), and at $\sim$1800 UT (IMAGE). (2) 18 February 1995 (day 049). At this day the IMF B_z was slightly northward and B_y varied from +5 nT to -4 nT at $\sim$0300–0400 UT, then remained near zero; and (3) 24 November 1995 (day 328). The OMNI IMF data indicate distinct periods with $B_y < 0$ (down to -5 nT) for different B_z conditions. Southward deviations of B_z cause substorms at $\sim$1545 UT (CPMN) and $\sim$1900 UT (IMAGE).

The IMF B_y changes during the latter two days should produce variations of the DPY current system; thus a possible coupling of dayside Pc5 activity and DPY current intensification could be examined.

6.1. Comparison of FAC Regions as Derived From the IZMEM Model With Magnetospheric Regions

Figure 2 shows the distribution of FAC in the dayside ionosphere with superposed tracks of DMSP satellites. This event, 18 February 1995, presents a typical pattern of FAC spatial structure as derived from the IZMEM model: the occurrence of the NBZ current system near noon at latitudes higher than 80° CGM latitude, with the upward prenoon and downward postnoon FACs, and below 80° a typical R1 structure with downward current on the dawnside and upward current on the duskside. At 1600 UT in the prenoon hours ($\sim$10 MLT), the upward R2 current coincides with the CPS projection, whereas the most intense part of the R1 downward FAC is mainly in the LLBL, with some admixture of the BPS projections. This correspondence is in accord with the common notion that LLBL is the source of the region 1 current system. The NBZ system is clearly seen because of IMF $B_z > 0$, and DMSP-derived projections show that the upward NBZ current is located in the mantle.

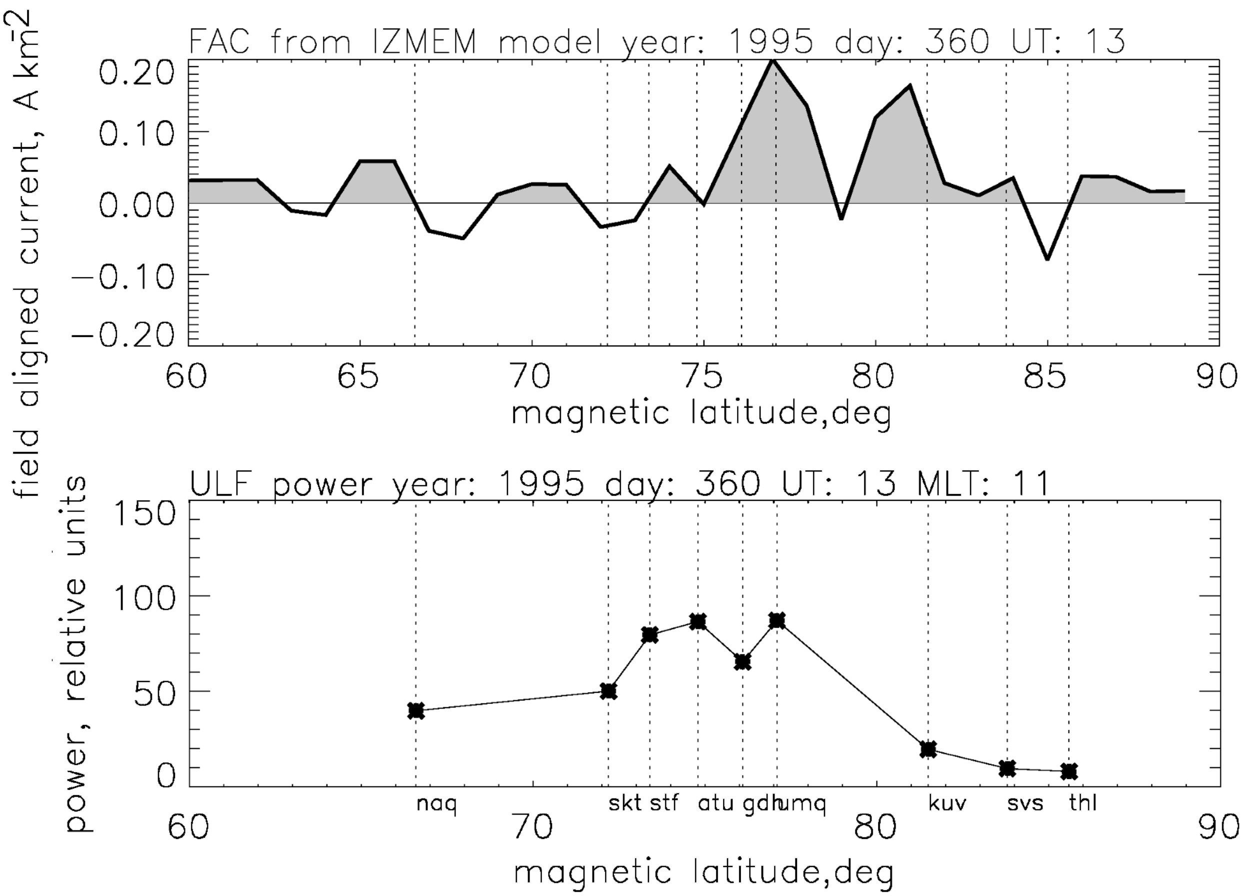

Figure 3. The latitudinal profile of (top) the IZMEM-derived FACs and (bottom) ULF wave power (H component) during 26 December 1995 (day 360) at 1300–1400 UT along the Greenland West Coast chain.

Similar observations have been made in a large number of events.

6.2. Correspondence Between ULF Activity and FAC

Many snap-shots show that at least two sources in the Pc5 band may operate simultaneously. One of them is located in the morning sector and generates quasi-monochromatic Pc5 pulsations as the examination of magnetograms (not shown) indicates. The other is located near noon. The magnetograms show that the Pc5 activity associated with the latter is characterized by longer periods and more irregular appearance compared to morning Pc5 activity. This second source of broadband Pc5 (IPCL) was often attributed to the ionospheric footpoint of the cusp.

The correspondence between the morning sector Pc5 wave power distribution along the Greenland West Coast array and the IZMEM-derived FAC can be seen in Figure 3 for the event of 26 December 1995 at 1300–1400 UT (no DMSP tracks for this interval). The paucity of magnetic stations prevents us from resolving the 2D wave power distribution for this event. Figure 3 shows that morning Pc5 are excited equatorward of the R1 current. Thus, the location of these pulsations may be related to the auroral electrojet flowing between the R1 and R2 current sheets.

After having analyzed all days we found no clear correspondence between the near-noon Pc5 peak and high-latitude current system features (such as DPY).

6.3. Identification of Source Regions of ULF Activity

Superposition of ULF power spatial distribution snapshots and DMSP tracks makes it possible to identify the probable source region of ULF activity. However, one should keep in mind that some peaks may not be directly related to a primary source but to the region of local resonant amplification of Pc5 waves. Thus, this region can be considered as a "secondary" source of these waves. Commonly, the waves in the resonant region are more intense and more monochromatic than those in the primary source. Some examples are given below.

On 26 December 1995, at 1800–1900 UT (Figure 4) two peaks of ULF wave power are observed: in the morning hours

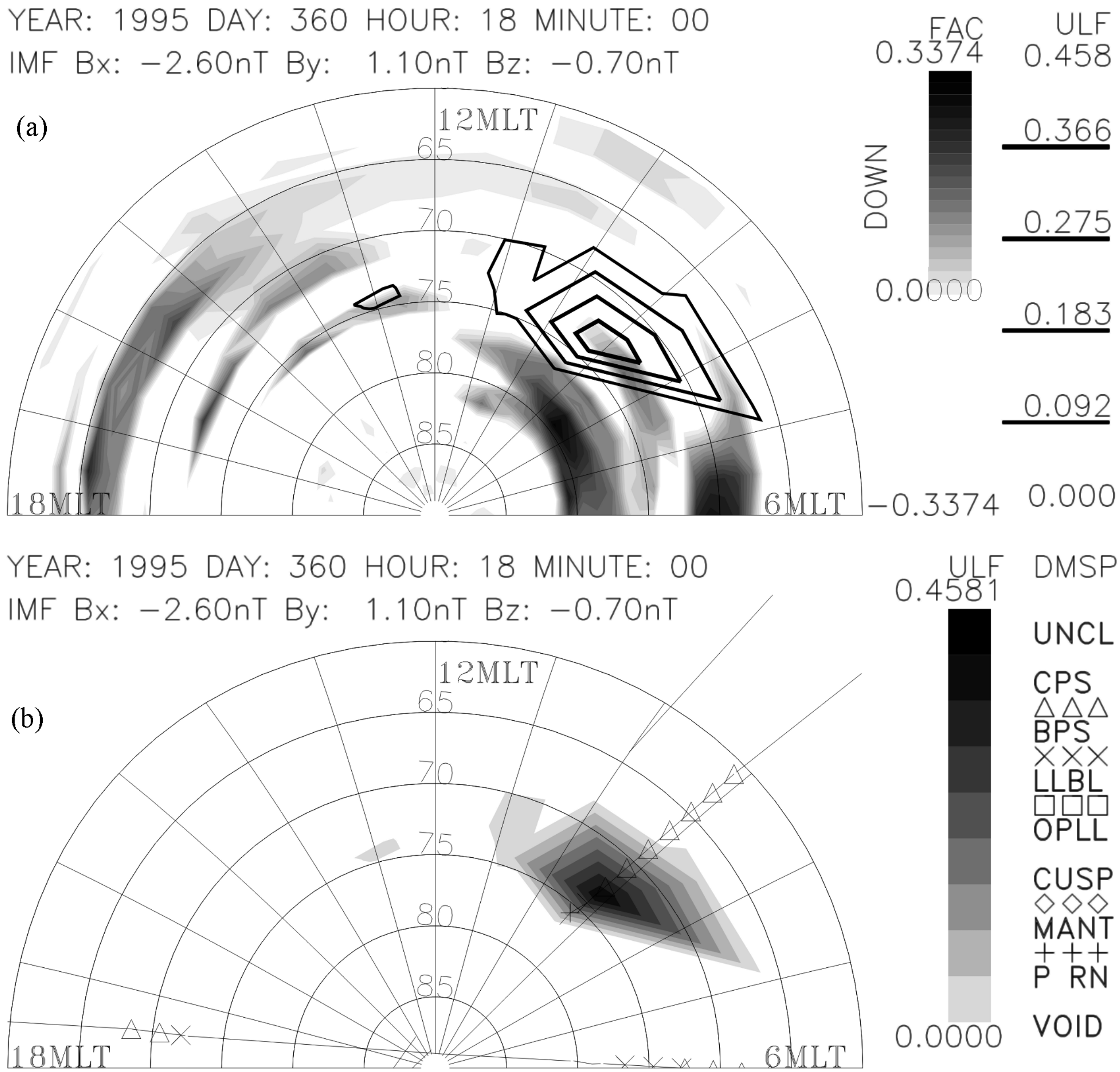

Figure 4. Identification of the peak of Pc5 wave intensity during 26 December 1995 (day 360) at 1800–1900 UT relative to the (a) downward FAC system and (b) boundary regions.

and near noon (especially evident in Figure 4b). The maximum of monochromatic Pc5 power (the region of resonant amplification) in the early morning hours at ∼72° is equatorward of the R1 current zone, as in the previous event, 26 December 1995. The DMSP magnetospheric region identification algorithm indicates that the center of morning Pc5 wave power is located inside the CPS region. At the same time, weaker near-noon and evening spatial maxima can be seen. However, there are no DMSP passes over these centers of the ULF activity to identify the magnetospheric region of their source.

For another event (26 December 1995, 1400–1500 UT), Figure 5 shows the ULF power density profile along the MC-Center stations with DMSP tracks overlaid. The morning Pc5 pulsation maximum is near the CPS/BPS boundary projection at ∼72°.

During the 24 November 1995, 1800–1900 UT event (Figure 6), DMSP passes through the near-noon maximum of ULF activity. The magnetograms (not shown) indicate that this ULF activity is broadband Pc5, commonly named cusp-related Pc5 or IPCL. The latitude of the power peak, 78°, is higher than the typical latitude of morning Pc5 waves. As DMSP data indicate, the source region of the near-noon, broadband Pc5 pulsations for this event are not located in the cusp but coincide with the equatorward boundary of the LLBL.

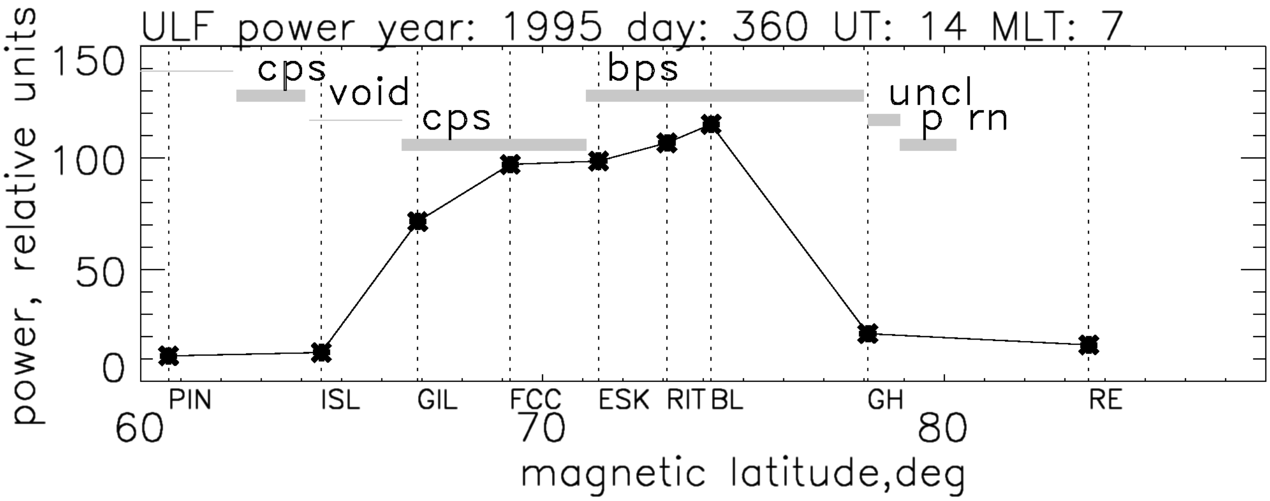

Figure 5. The profile of the morning Pc5 wave intensity along the MC-Center stations and DMSP-based ionospheric projections of boundary regions during 26 December 1995 (day 360) at 1400–1500 UT.

7. Discussion

Our study shows that the IZMEM-predicted location of R1 FACs coincides mostly with the LLBL. This result agrees well with the common view about the connection between R1 currents and the LLBL, namely, that the R1 FAC flows near or at the magnetosphere/LLBL interface, as has previously been suggested [e.g., *Hones,* 1983]. This correspondence gives additional support to the physical background of the IZMEM model. At the same time, R2 FAC in the morning sector are located mostly in the CPS region.

The relationship between large-scale FACs and ULF oscillations was studied by *Potemra et al.* [1988], who examined conjunctions between the polar orbiting Viking and AMPTE CCE in the equatorial orbit. The Viking particle observations confirmed that the R1/R2 interface mapped closely to the interface between the LLBL and CPS. Field line oscillations in the Pc5 band were detected on the same field lines that guide the R2 FACs (flowing away from the ionosphere) in the morning sector. They extended from the interface of the R1 and R2 current system, close to the LLBL/CPS interface, to the lowest L crossed by Viking. R1 currents were suggested to be associated with and possibly have their source in the LLBL, whereas the R2 currents should be associated with CPS.

In the morning sector, the peak of ULF resonant waves is commonly located at the equatorward boundary of the downward FAC (R1). This location may correspond to the R2 current system, in line with the observations of *Potemra et al.* [1988] or to the position of a westward auroral electrojet (Hall current), located between the R1 and R2 FACs. The accuracy of our ionospheric model is not sufficient to discriminate between these possibilities. In the morning/dayside sector, the latitude where the Pc5 wave power reaches peak amplitudes coincides with the latitude where the westward electrojet is most intense. This is in line with earlier observations of *Lam and Rostoker* [1978] and, more recently, *Pilipenko et al.* [2001]. This effect still lacks further observational confirmation and satisfactory interpretation.

The observed correspondence between the morning sector Pc5 wave power peak and the CPS projection may indicate where in the magnetosphere the region of resonant wave conversion is located. It is worth mentioning that *Yahnin and Moretto* [1996] found that centers of travelling convection vortices (TCV) in the ionosphere also mapped to the CPS. The preference of both wave and transient responses to the same region may evidence the occurrence of favourable conditions, e.g., density gradients, in this region.

Being a statistical model, the simple IZMEM technique can provide only a hint on the possible location of basic electrodynamic features for case studies. However, the technique enables us to substitute IZMEM with any other ionospheric model [e.g., *Weimer*, 1996]. For further case studies, we intend to incorporate the possibility to use results of the more advanced AMIE model or Ultraviolet Imagers in our mapping technique.

Early studies of dayside ULF activity at high latitudes gave support to the view that long-period irregular variations were closely associated with the cusp/polar cap interface and thus could be used as a simple indicator of dayside cusp position and polar cap boundary. However, further studies of high-latitude broadband wave activity on the dayside [*Engebretson et al.*, 1995] showed that ULF wave activity is not associated in a simple way with boundary layer or cusp. *Szuberla et al.* [2000] used polarization analysis and identified small-amplitude coherent Pc5 waves as cusp signature. Larger-amplitude pulsations bounding the former were representative of the boundary layers and showed correlated time dependence across several hours of local time. They obscure the cusp signature in ordinary power spectra analysis. A cause for these widespread temporal variations, as well as their source, has not yet been identified. The power spectra used in this study do not discriminate between po-

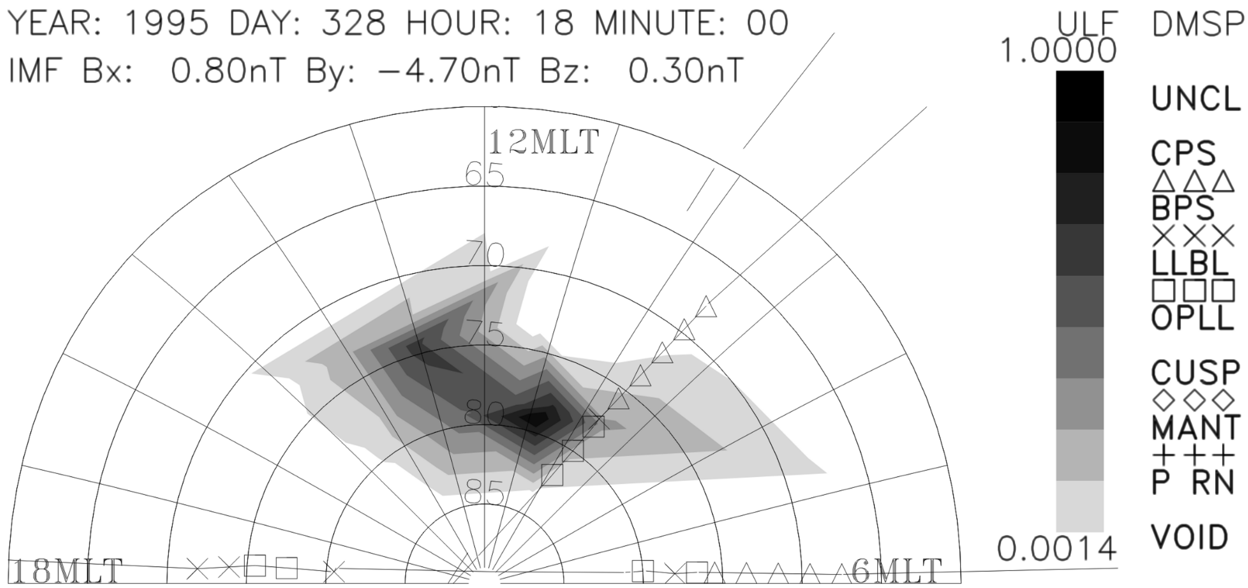

Figure 6. Mapping of the boundary regions identified from DMSP data onto the 2D distrubution of broadband ULF pulsation power near noon during the 24 November 1995 (day 328), 1800–1900 UT, event.

larized and nonpolarized pulsations, which may be a reason why we have not seen a correspondence between the proper cusp and ULF wave intensity.

In contrast to the approach in this paper, the search for specific ULF signatures of boundary phenomena was based on data from isolated stations with limited latitude/longitude coverage in most previous studies. At subauroral stations a persistent occurrence of quasi-monochromatic Pc5 pulsations are observed, mostly in the early morning hours during a substorm recovery phase. At higher latitudes, irregular long-period variations were observed at near-noon hours. However, some case studies with more extended arrays showed a regular transition from irregular broadband (IPCL) pulsations at high latitudes to more intense and monochromatic Pc5 pulsations at lower latitudes [*Clauer et al.*, 1997; *Pilipenko et al.*, 1998]. These events indicated that Pc5 and IPCL pulsations are not separate wave phenomena but are manifestations of the same wave process, whereas the difference in their appearance is related to the resonant amplification deeper in the magnetosphere, probably on closed dipole-like field lines. Thus, simultaneous occurrence of IPCL and Pc5 near noon may signify a situation where both the ULF driver and the resonant response are observed on the ground. However, *Kleimenova et al.* [1998] presented ULF events where IPCL and Pc5 were not related to each other. Therefore, the problem of the IPCL/Pc5 coupling needs further investigation. The region of the possible ULF driver is difficult to identify because the secondary maximum in a resonant region can be higher than the primary maximum in the source region.

Among all the considered events, we never observed a spatial correspondence between the cusp proper and the ULF activity peak. In the event shown here, we found that the peak of ULF activity near noon indeed mapped to the inner boundary of the LLBL. The occurrence of irregular magnetic variations with time scales 5–10 min inside the LLBL was detected in satellite data by *Takashashi et al.* [1991]. Coincidence of the probable source region of near-noon Pc5 pulsations with the LLBL projection agrees with an event with simultaneous radar and magnetometer observations studied by *Clauer et al.* [1997], who attributed the source of these pulsations to K-H instability excitation at field lines which map to the reversal boundary of ionospheric convection which is associated with the LLBL. Though a correspondence between ULF waves and LLBL needs further statistical investigation, it seems that the widely used term "cusp-related pulsations" is likely not adequate; probably, the term "boundary layer associated broadband ULF activity" would be more adequate.

Observations of morning and postnoon Pc5 led earlier workers to the conclusion that the K-H instability at the magnetopause or LLBL is a likely candidate for Pc5 drivers. Later, indications were found that impulsive variations of the dynamic pressure of the solar wind and FTE constitute another possible source of Pc5 wave packets in the magnetosphere. Thus, the intensity of Pc5 pulsations can be considered as an indicator of the level of turbulence in the boundary layers. Our analysis often revealed the simultaneous occurrence of three regions of ULF intensification: morning sector, near-noon, and postnoon hours. They may be hardly ascribed to the same driving mechanism, such as the K-H instability. Moreover, the assumption of the K-H instability as a universal driving source of geomagnetic pulsations meets some difficulties because the linear theory predicts the predominant growth of wave disturbances with small lateral scales.

The same K-H instability can be hardly applied to the near-noon broadband Pc5 because in this region the velocity of the magnetosheath plasma flow is low. The Pc5/IPCL activity at near-noon hours could be impulsively driven pulsations which occur in response to the magnetosheath plasma discontinuities and buffeting. In line with this idea, analysis of a series of IPCL bursts by *Kurazkovskaya and Klain* [2000] showed that these signals possess rather distinctive features, typical for a system near a critical transition to a chaotic regime. They suggested that IPCL series might be a manifestation of the dynamic turbulence of FACs which develops in the cusp region. The difference in source mechanisms of the noon and morning Pc5 should reveal itself in the spatial structure (e.g., azimuthal phase velocity) of pulsations, which is to be verified in further studies.

8. Conclusions

The paper is intended to demonstrate that the technique of 1D and 2D mapping of ground ULF wave activity together with field-aligned current distributions derived from an ionospheric model and projections of dayside boundary layers can be an effective tool for a deeper insight into several, still not resolved, problems of ULF physics. The preliminary analysis of several events has confirmed the relationships found in other studies by different techniques, though these examples have raised interesting questions:

In the morning sector, the region of downward FAC corresponds to the LLBL, whereas the upward FAC corresponds to the CPS. Thus, the LLBL is a driver of the R1 current system, at least in the morning sector.

Often, three regions of ULF excitation are simultaneously observed: during morning hours, near noon, and during afternoon hours. This may indicate the simultaneous occurrence of several drivers of ULF waves. In the morning sector, the peak of ULF intensity is commonly located equatorward of the downward R1 FACs, probably in the region of the auroral electrojet, or R2 FAC.

A resonant monochromatic response to Pc5 excitation is observed in the CPS or near the CPS/BPS interface. Broadband dayside high-latitude ULF pulsations in the Pc5 range are commonly referred to as “cusp-related pulsations”. However, the peak of their spatial intensity distribution coincides with the equatorward boundary of the LLBL.

Appendix A: Identifications of Dayside Magnetospheric Regions From DMSP Data

Regions are identified as one of the following, generally moving from higher to lower latitudes: prn, intense polar rain, the suprathermal component of solar wind electrons; mantle, de-energized magnetosheath ions observable poleward of the dayside oval; cusp, the projection of the magnetospheric exterior cusp, a region with full intensity magnetosheath ions and electrons; opll, clearly open LLBL, with low-energy ion cutoffs and magnetosheath electrons at reduced fluxes; llbl, closed LLBL with no low energy ion cutoffs, and spectra closely resembling high altitude LLBL; bps, boundary plasma sheet where precipitation closely resembles the poleward portion of the nightside auroral oval. The electrons have a typical energy of about 300 eV, somewhat higher than in the LLBL; ps, plasma sheet is the zone of hard electron precipitation with typical energies above 1 keV on the dayside; uncl, unclassified: when the flux levels are clearly above detector noise level but the precipitation did not fit any of the quantitative rules for other regions; void, fluxes are generally near or below noise levels.

A more detailed classification of the boundary regions is described on the Applied Physics Laboratory Web site http://sd-www.jhuapl.edu/Aurora/.

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References

Bolshakova, O. V., N. G. Kleimenova, and N. A. Kurazkovskaya, Dynamics of polar cap according to the observations of long period geomagnetic pulsations, *Geomagn. Aeron. (in Russian), 28,* 661, 1988.

Clauer, C. R., and A. J. Ridley, Ionospheric observations of magnetospheric boundary layer waves on August 4, 1991, *J. Geophys. Res., 100,* 21,873, 1995.

Clauer, C. R., A. J. Ridley, R. J. Sitar, H. Singer, A. S. Roger, E. Friis-Christensen, and V. O. Papitashvili, Field line resonant pulsations associated with a strong dayside ionospheric shear convection flow reversal, *J. Geophys. Res., 102,* 4585, 1997.

Engebretson, M. J., L. J. Cahill, R. L. Arnoldy, B. J. Anderson, T. J. Rosenberg, D. L. Carpenter, U. S. Inan, and R. H. Eather, The role of the ionosphere in coupling upstream ULF wave power into the dayside magnetosphere, *J. Geophys. Res. 86*, 1527, 1991.

Engebretson, M. J., W. J. Hughes, and J. L. Alford, Magnetometer array for cusp and cleft studies observations of the spatial extent of broadband ULF magnetic pulsations of cusp/cleft latitudes, *J. Geophys. Res., 100,* 19,371, 1995.

Feldstein, Ya. I., and A. E. Levitin, Solar wind control of electric fields and currents in the ionosphere, *J. Geomagn. Geoelectr., 38,* 1143, 1986.

Hones, E. W., Magnetic structure of the boundary layer, *Space Sci. Rev., 34,* 201, 1983.

Kamide, Y., A. D. Richmond, and S. Matsushita, Estimation of ionospheric electric fields, ionospheric currents and field-aligned currents from ground magnetic records, *J. Geophys. Res., 86,* 801, 1981.

Kleimenova, N. G., O. V. Bolshakova, V. A. Troitskaya, and E. Friis-Christensen, Two types of long period geomagnetic pulsations near equator border of dayside polar cusp, *Geomagn. Aeron. (in Russian), 25,* 163, 1985.

Kleimenova, N. G., O. V. Kozyreva, G. Bitterley, and G. Folk, Spectrum of long period geomagnetic pulsations (np) in the region of dayside polar cusp, *Geomagn. Aeron. (in Russian), 29,* 846, 1989.

Kleimenova, N. G., O. V. Kozyreva, J. Bitterli, and M. Bitterli, Long-period (T∼8–10 min) geomagnetic pulsations at high latitudes, *Geomagn. Aeron. (in Russian), 38,* 38, 1998.

Kurazkovskaya, N. A., and B. I. Klain, Peculiar features of burst series of long-period irregular IPCL-type geomagnetic pulsations in the vicinity of the dayside cusp, *Int. J. Geomag. and Aeronomy*, *2* (2), 129, 1990.

Lam, H. L., and G. Rostoker, The relationship of Pc5 micropulsation activity in the morning sector to the auroral westward electrojet, *Planet. Space Sci., 26,* 473, 1978.

Lanzerotti, L. J., A. Shono, H. Fukunishi, and C. G. Maclennan, Long-period hydromagnetic waves at very high geomagnetic latitudes, *J. Geophys. Res., 104,* 28,423, 1999.

Lee, L. C., R. K. Albano, and J. R. Kan, Kelvin-Helmholtz instability in the magnetopause-boundary layer region, *J. Geophys. Res., 86,* 54, 1981.

McHarg, M. G., J. V. Olson, and P. T. Newell, ULF cusp pulsations: diurnal variations and interplanetary magnetic field correlations with ground-based observations, *J. Geophys. Res., 100,* 19,729, 1995.

McHenry, M. A., C. R. Clauer, E. Friis-Christensen, P. T. Newell, and J. D. Kelly, Ground observations of magnetospheric boundary layer phenomena, *J. Geophys. Res., 95,* 14,995, 1990.

Mishin, V. M., A. D. Bazarzhapov, and G. B. Shpynev, Electric fields and currents in the Earth's magnetosphere, in *Dynamics of the Magnetosphere,* edited by. S.-I. Akasofu, p. 249, D. Reidel, Norwell, Mass., 1980.

Newell, P. T., and C.-I. Meng, The cusp and the cleft/boundary layer: low-altitude identifications and statistical local time variation, *J. Geophys. Res., 93,* 14,549, 1988.

Newell, P. T., W. J. Burke, C.-I. Meng, E. R. Sanchez, and M. E. Greenspan, Identification and observations of the plasma mantle at low altitudes, *J. Geophys. Res., 96,* 35, 1991a.

Newell, P. T., W. J. Burke, E. R. Sanchez, C.-I. Meng, M. E. Greenspan, and C. R. Clauer, The low latitude boundary layer and the boundary plasma sheet at low altitude: prenoon precipitation regions and convection reversal boundaries, *J. Geophys. Res., 96,* 21,013, 1991b.

Olson, J. V., ULF signatures of the polar cusp, *J. Geophys. Res., 91,* 10,055, 1986.

Papitashvili, V. O., B. A. Belov, D. S. Faermark, Ya. I. Feldstein, S. A. Golyshev, L. I. Gromova, and A. E. Levitin, Electric potential patterns in the Northern and Southern polar regions parameterized by the interplanetary magnetic field, *J. Geophys. Res., 99,* 13,251, 1994.

Papitashvili, V. O., F. J. Rich, M. A. Heinemann, and M. R. Hairston, Parameterization of the DMSP ionospheric electrostatic potentials by the interplanetary magnetic field strength and direction, *J. Geophys. Res., 104,* 177, 1999.

Pilipenko, V., O. Kozyreva, M. Engebretson, W. Hughes, S. Soloviyev and K. Yumoto, Coupling between substorms and ULF disturbances in the dayside cusp, in *Substorms 4*, edited by S. Kokubun and Y. Kamide, p. 573, Terra Sci., Publishing Company/Kluwer Academic Publishers, Tokyo, 1998.

Pilipenko, V., J. Watermann, V. Popov, and V. Papitashvili, Relationship between auroral electrojet and Pc5 ULF waves, *J. Atmos. Sol. Terr. Phys., 63,* 1545, 2001.

Potemra, T. A., L. J. Zanetti, P. F. Bythrow, R. E. Erlandson, R. Lundin, G. T. Marklund, L. P. Block, and P.-A. Lindquist, Resonant geomagnetic field oscillations and Birkeland currents in the morning sector, *J. Geophys. Res., 93,* 2661, 1988.

Richmond, A. D., and Y. Kamide, Mapping electrodynamic features of the high-latitude ionosphere from localized observations: Technique, *J. Geophys. Res., 93,* 5741, 1988.

Robinson, R. M., and R. R. Vondrak, Measurement of *E* region ionization and conductivity produced by solar illumination at high latitudes, *J. Geophys. Res., 89,* 3951, 1984.

Rostoker, G., J. C. Samson, and Y. Higuchi, Occurrence of Pc4,5 micropulsation activity at the polar cusp, *J. Geophys. Res., 77,* 4700, 1972.

Szuberla, C. A., J. V. Olson, M. J. Engebretson, M. G. McHarg, and W. J. Hughes, Spatiotemporal characteristics of cusp latitude spectra, *J. Geophys. Res., 105,* 7695, 2000.

Takahashi, K., D. G. Sibeck, P. T. Newell, and H. E. Spence, ULF waves in the low-latitude boundary layer and their relationship to magnetospheric pulsations: a multisatellite observation, *J. Geophys. Res., 96,* 9503, 1991.

Troitskaya, V. A. ULF wave investigations in the dayside cusp, *Adv. Space Res., 5,* 219, 1985.

Troitskaya, V. A., and O. V. Bolshakova, Diurnal latitude variation of the location of the dayside cusp, *Planet. Space Sci., 25,* 1167, 1977.

Troitskaya, V. A., and O. V. Bolshakova, Diagnostics of the magnetosphere using multipoint measurements of ULF waves, *Adv. Space Res., 8* (9–10), 413, 1988.

Troshichev, O. A. , A. L. Kotikov, E. M. Shishkina, V. O. Papitashvili, C. R. Clauer, E. Friis-Christensen, DPY currents in the cusp/cleft region: A crucial role of southward interplanetary magnetic field, *J. Geophys. Res., 102,* 4777, 1997.

Wallis, D. D., and E. E. Budzinski, Empirical models of height-integrated conductivities, *J. Geophys. Res., 86,* 125, 1981.

Weimer, D. R., A flexible IMF dependent of high-latitude electric potentials having "space weather" applications, *Geophys. Res. Lett., 23,* 2549, 1996.

Yahnin, A. G. and T. Moretto, Travelling convection vortices in the ionosphere map to the central plasma sheet, *Ann. Geophys., 14,* 1025, 1996.

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