

Auroral Poleward Boundary Intensifications and Tail Bursty Flows: A Manifestation of a Large-Scale ULF Oscillation?

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Abstract. Auroral zone observations often show significant ULF power. We have analyzed auroral and plasma-sheet observations during two prolonged periods of strongly southward and relatively steady IMF. We find evidence that auroral poleward boundary intensifications (PBIs), which have large intensity and occur repetitively throughout such periods, may be a manifestation of a large-scale ULF oscillation mode that strongly perturbs the plasma sheet and the auroral ionosphere. If this is correct, then ULF modes would be a major component of tail dynamics, of magnetosphere coupling to the ionosphere, and of auroral zone disturbances during periods of enhanced convection. They would simultaneously affect a large region of the nightside, extending along auroral-zone field lines from the ionosphere to the equatorial plasma sheet and extending from field lines that lie near the magnetic separatrix to, at times, as close to the Earth as synchronous orbit. They would also occasionally have amplitudes as large as the changes that occur in association with other auroral zone disturbances such as substorms. Here we have found peak-to-peak amplitudes as high as several hundred nT in ground X, an order of magnitude in synchronous energetic proton fluxes, ~20-40 nT in synchronous magnetic field components, ~20 nT in tail magnetic field components, ~1000 km/s in tail flow speeds, and ~400 m/s in ionospheric flow speed. We find evidence for significant power at 0.5-0.7 mHz (~25-30 min period), significant power at a possible second harmonic (~1.1-1.3 mHz), and power at frequencies that could be higher harmonics simultaneously within the auroral ionosphere and within the nightside plasma sheet.

1. Introduction

Auroral-zone magnetic field, plasma flow, and optical emissions often show significant ULF power and indicate that ULF pulsations may play an important role in magnetosphere-ionosphere coupling [e.g., Samson et al., 1991]. The power often shows spectral peaks at ~1.3, 1.9, 2.6, 3.4 mHz [e.g., Ruohoniemi et al., 1991; Samson et al. 1992a,b; Liu et al., 1995; Fenrich et al., 1995], the precise spectral peaks varying with time as geomagnetic conditions vary [Mathie et al., 1999]. It has been proposed that these spectral peaks are associated with global oscillatory modes of the magnetosphere that have been described as cavity modes [e.g. Kivelson et al., 1984; Samson et al., 1992b] or waveguide modes [Samson et al., 1992a; Samson and Rankin, 1994; Wright et al., 1999]. Sánchez et al. [1997] found that the same ULF pulsation frequencies seen in ground magnetometers were simultaneously seen in geosynchronous magnetic fields and in tail plasma and magnetic fields during a substorm period. Based on this observation, Sánchez et al. hypothesized that global nightside ULF modes significantly modulate particle and magnetic field transport in the magnetotail and also affect the auroral ionosphere.

Auroral enhancements that are now often referred to as “poleward boundary intensifications” or PBIs often occur repetitively and are associated with time variations of the ground magnetic field [de la Beaujardière et al, 1994; Kauristie et al., 1996; Yeoman and Lühr, 1997; Lyons et al., 1998]. They initiate near the poleward boundary of the auroral oval (which is typically near a geomagnetic latitude $\sim 73^\circ$), often extend equatorward from that boundary, and occasionally form north-south auroral structures [Rostoker et al., 1987; Nakamura et al., 1993]. PBIs are very much different from the auroral enhancements associated with substorms, which propagate poleward after initiating several degrees equatorward of the poleward boundary of the aurora. Auroral intensities and ground magnetic fields near the poleward boundary of the auroral zone have been found to have the ULF spectral power peaks typical of the auroral zone [Xu et al., 1993; Liu et al., 1995; Wright et al., 1999; Rostoker, 2000]. Thus if the ULF power is part of global ULF modes as suggested by Sánchez et al. [1997], then PBIs and their associated magnetic field variations would be an auroral manifestation of such global modes. Since PBIs are a major component of overall auroral-zone activity [Lyons et al., 1998], this would suggest that global ULF modes could often play an important role in auroral-zone activity.

It has recently become established that PBIs are an ionospheric signature of longitudinally localized earthward flow bursts [Henderson et al., 1998; Sergeev et al., 1999,

2000; Lyons et al., 1999; Kauristie et al., 2000; Zesta et al., 2000]. Such flow bursts are often observed within the tail plasma sheet and are an important component of tail plasma transport [e.g., Angelopoulos et al., 1992], and they have been observed to map from the plasma sheet to the auroral ionosphere [Sergeev et al., 1990]. Also, repetitive (~10-15 min period) PBIs during steady magnetospheric convection periods have been found to be associated with similarly repetitive flow bursts within the tail plasma sheet at $x \sim -25 R_E$ [Solovyev et al., 1999]. Flow bursts are expected to be related to PBIs because the localized enhanced electric fields that give rise to the flow bursts, when mapped to the auroral ionosphere, have a negative divergence along their western edge. Such a divergence drives upward field-aligned currents, which when sufficiently strong, are associated with downward electron acceleration and enhanced auroral emissions [e.g., Lyons 1992]. This expected spatial relation between PBIs and the ionospheric mapping of tail flow bursts has been observed within the auroral ionosphere [de la Beaujardière et al., 1994].

The connection between PBIs and tail flow bursts implies that if PBIs are a manifestation of global ULF waves, then tail flow bursts must also be a manifestation of these waves. If this wave mode covers a large portion of the nightside magnetosphere, and if tail flow bursts are narrow in longitude as has been inferred [Angelopoulos et al., 1994, 1996], then the flow bursts should often be repetitive in y over a substantial portion of the geomagnetic tail. Consistent with this possibility, global auroral images occasionally show a series of approximately parallel north-south auroral structures covering a large portion of the nightside auroral oval (see Figure 2 of Sergeev et al. [1999] and Plate 2 of Sergeev et al. [2001]). Evidence that ULF waves are important to tail dynamics includes the observation of significant ULF power (0.15-10 mHz) in plasma sheet magnetic fields [Bauer et al., 1995], the observation of discrete frequencies within the plasma sheet in the ~0.15 to 10 mHz frequency ranges [E. Neagu, personal communication, 2000], and the observation of ULF oscillations occurring simultaneously in the auroral electrojets, geosynchronous magnetic fields, and plasma sheet densities, velocities, and magnetic fields [Sánchez et al., 1997]. Also, the equatorward motion of PBIs has been suggested to be consistent with a coupling of the fast to the intermediate wave along outer field lines of the plasma sheet [Liu et al., 1995; Wright et al., 1999; Allan and Wright, 2000]. This would suggest that tail flow bursts are associated with fast mode oscillations of the nightside magnetosphere.

The above studies suggest that PBIs and tail flow bursts may both be components of global ULF waves on the night side. If this were the case, then global ULF modes would be critical to both tail dynamics and to magnetosphere-ionosphere coupling along auroral field lines. Here we investigate this possibility by examining observations from two periods of relatively steady, strongly southward interplanetary magnetic field (IMF). Each of these periods included extended time intervals of strong PBIs and a minimum of substorm activity. Ground based magnetometer and photometer data from the Canadian Auroral Network for the OPEN Program Unified Study (CANOPUS) ground array in central Canada, energetic particle data from the Los Alamos National Laboratories geosynchronous particle detectors, and geosynchronous magnetic field data are available for both periods. For one of the periods, there was also a good conjunction with the Geotail spacecraft in the tail plasma sheet, good SuperDARN measurements of ionospheric flows, and high-resolution POLAR images of the two-dimensional aurora. We find considerable evidence for the existence of large-amplitude ULF modes that give similar frequency peaks in our data for both periods. This is consistent with the possibility that PBIs and tail flow bursts are a manifestation of these modes.

2. Observations

2.1 IMF

The measured z -component (GSM coordinates) of the IMF, B_z , for the two periods of interest is shown in Figure 1. Both of the periods had extended intervals of strongly southward IMF and might be characterized as either strong steady magnetospheric convection (SMC)

periods or small magnetic storms. For the first period, January 10, 1997 (hereafter referred to as period 1), IMF measurements are shown from WIND located well in front, and to the dawn side, of the Earth and from Geotail, located within the magnetosheath just in front of the nose of the magnetosphere. The WIND measurements show that $B_z \sim -10$ to -15 nT impacted the magnetosphere after ~ 05 UT, and the Geotail measurements agree with the timing and the stability of the strongly negative B_z . A Dst minimum of -78 nT occurred at 10 UT. For the second period (hereafter referred to as period 2), WIND and IMP-8 measurements show a relatively steady IMF with $B_z \sim -5$ to -8 nT for many hours following ~ 2130 UT on January 29, 1998. During this interval, a Dst minimum of -55 nT occurred at 12-13 UT.

2.2 Optical

Auroral optical observations during both periods are shown in Plate 1. The top portion of the Plate shows 5577 \AA emissions from the CANOPUS meridian scanning photometers as a function of invariant latitude and UT. Intensities as a function of were obtained from emission measurements taken as a function of elevation angle along the magnetic meridian by assuming a fixed height of the auroral emissions. Observations are shown for both periods from a merging of data from the photometers at Gillam ($\lambda = 67^\circ$) and Rankin Inlet ($\lambda = 73^\circ$) along the same magnetic meridian. Observations from Fort Smith ($\lambda = 68^\circ$), ~ 1.5 hr in MLT to the west of Gillam, are also shown for period 1 (emissions at Fort Smith were obscured by clouds on January 30, 1998).

The CANOPUS photometer data for period 1 show only one substorm expansion phase, that being at Rankin Inlet-Gillam from 0635-0650 UT when the observations show a poleward moving region of active aurora initiating well equatorward of the poleward boundary of the auroral oval. At other times, the observed auroral activity was dominated by PBIs and, at 1050-1115 UT, by the response to a large interplanetary dynamic pressure pulse. There is no evidence for the equatorward auroral brightenings associated with substorm activity after 0650 UT. (See Lyons et al. [2000] for a discussion of the types of aurora-zone activity that occurred during this period). PBIs can be seen in the Rankin Inlet data from 0650-1110 UT, where they initiate at the poleward boundary of the auroral emissions. At Fort Smith, the poleward boundary of the auroral zone is only seen at ~ 0500 - 0540 UT and ~ 0905 - 0940 UT; however PBIs can be seen extending equatorward through much of the region of auroral precipitation from the plasma sheet from 0545 to 1110 UT. For period 2, PBIs can be seen in the Rankin Inlet-Gillam observations for most of the period shown (1-13 UT). There were also possible substorm onsets at ~ 0357 , and 0600, which show through the clouds at Gillam and in CANOPUS ground magnetic X and Pi2 pulsation observations. There were also brief auroral brightenings at ~ 0643 and 0928 UT that did not show the poleward expansion associated with substorms. Such brightenings are often classified as pseudo-breakups. Note the repetitive nature of the PBIs on both days, and that this repetition gives several separate intensifications per hour as would be expected if the PBIs were a manifestation of a ULF pulsation.

Sample two-dimensional images of nightside auroral 5577 \AA emissions during period 2 obtained by the high-spatial resolution camera (referred to as the "low resolution camera") of the POLAR Visible Imaging System are shown in the lower portion of Plate 1. These images show that the brightest auroral emissions occur within two zones, one along the poleward boundary of the auroral oval and one well equatorward of this boundary. Such a double aurora oval is typical of conditions of high magnetospheric convection. PBIs occur as bright emissions within the poleward emission region. The images indicate that, when viewed in two dimensions, the emissions within the poleward region have the appearance of waves extending along the poleward boundary of the auroral zone. These waves are observed over a large longitudinal range on the nightside, as expected from a mode covering a large portion of the nightside magnetotail. While emission intensities are not constant over the longitude extend of one wavelength, ~ 5 - 6 wavelengths can be discerned along the poleward boundary in each image of Plate 1. If these are indeed waves, their wavelength in the auroral ionosphere would be ~ 1000

km (based on 5 wavelengths spanning 8 hr of MLT at $\lambda = 70^\circ$). Sometimes these possible waves appear quite linear, such as in the three images between 0900 and 0925 UT. At the other times the waves appear to evolve non-linearly and wrap up into swirls, as appears to have occurred in the lower part of the three images between 1129 and 1142 UT. The aurora associated with swirls at times appears to extend equatorward through much of the auroral oval as approximately north-south oriented structures.

2.3 Ground magnetic field

Figure 2 shows magnetic X observations from representative CANOPUS ground stations for both periods. The stations Gillam, Ft. Smith, and Dawson are at about the same geomagnetic latitude, Dawson being ~ 2 hr of MLT west of Ft. Smith and Ft. Smith being ~ 2 hr in MLT west of Gillam. The other two stations in each panel are at different magnetic latitudes but very near the same longitude as Gillam. Figure 2 shows several hundred nT magnetic depressions associated with each of the substorm onsets. In addition, the figure shows large, approximately oscillatory magnetic perturbations during the time intervals of PBIs. For period 1 (January 10, 1997), these perturbations were often equal or larger than those associated with the substorms. For period 2 (January 30, 1998), the PBI-related perturbations typically ranged from ~ 50 to ~ 200 nT. (In addition, perturbations of ~ 400 nT were observed at Dawson from ~ 0925 -1000 UT during period 2, a period which includes the brief auroral brightening at 0928 UT and some relatively stable bright auroral features after that time which can be seen in VIS images for this time period.). Such approximately oscillatory magnetic perturbations are typically associated with PBIs, and they can reach hundreds of nT during SMCs [Lyons et al., 1998; 1999]. They often appear to be the dominant source of magnetic variation during periods of enhanced convection, including the two considered here. Magnetic perturbations during SMCs have previously been found to be transient (~ 15 min times scales), longitudinally localized (the same features not being simultaneously seen by stations separated by more than ~ 1 hr in MLT), and distinct from the signatures of substorms [Yahnin et al., 1994]. Note from Figure 2 that the identified substorms caused simultaneous X decreases at neighboring CANOPUS longitudes, whereas the PBI-associated oscillations did not. The longitudinal localization of the magnetic variations are consistent with the inference from the POLAR auroral images that PBIs have a longitudinal wavelength considerably smaller than the longitudinal extent of the nightside auroral oval.

2.4 Geosynchronous particles and magnetic fields

Figure 3 shows geosynchronous observations for period 1. Magnetic field observations are from GOES 9, which was located in the evening to post-midnight sector during the period of interest. Energetic protons are from LANL 1991-080 and 1994-084 located in the noon to afternoon sector and separated by ~ 2.25 hours in MLT. For comparison, the 5577 Å emissions from Fort Smith are also shown. The GOES 9 magnetic field shows significant oscillations soon after 0630 UT. The onset of these oscillations is at about the same time that the PBIs were first observed to extend equatorward to λ 's below $\sim 67^\circ$ and can thus be expected to have affected field lines near geosynchronous orbit. The oscillation at GOES 9 was particularly dramatic between 9 and 11:30 UT, when an ~ 30 min oscillation was observed with a peak-to-peak amplitude as large as 40 nT in the E (earthward directed) component and significant effects in the other components.

Substorm onsets, identified in Lyons et al. [2000], are indicated by vertical dashed lines in Figure 3. One of these (0427 UT onset) gave rise to an energy-dispersed flux enhancement, typical of substorm injections, that was observable at geosynchronous orbit. Then, starting at 0654 UT, there was a series of proton flux spikes at 1994-084 on the afternoon side that were also seen at 1991-080 after 0900 when that satellite reached 14 MLT. (Superposed on the spikes, the protons fluxes also show a more prolonged increase that initiated at ~ 1050 UT in response to the large pulse in solar wind dynamic pressure). Notice that several proton spikes were observed

per hour, which is comparable to the repetition rate of the PBIs during this period and unrelated to substorm activity. Also, allowing for a 15-min time delay from magnetic drift, the spikes initiate at the same time as when PBIs observed by the CANOPUS photometers at Fort Smith PBIs first extended to $< 67^\circ$. (15 min equals the time it would take a 200 keV proton to drift from midnight to 14 MLT in a dipole field, though the actual drift velocity and initial MLT of the particle injections are uncertain). The spikes seen on 1991-080 after 0900 have a one-to-one correspondence with those seen on 1994-084, but with a 5 min additional delay that is approximately consistent with magnetic drift between the longitudes of the two spacecraft. These data suggest that the extension of PBIs onto geosynchronous field lines is associated with the proton flux spikes. This is in agreement with Henderson et al. [1998] and Sergeev et al. [1999], who reported transient geosynchronous particle injections in association with north-south auroral structures that extended to near the equatorward boundary of the auroral oval.

The geosynchronous magnetic and energetic proton observations during period 1 in Figure 3 are consistent with the extension to synchronous orbit of a global ULF pulsation that modulates \mathbf{B} and energetic particle fluxes at times when the PBIs extend equatorward to synchronous orbit field lines. Geosynchronous magnetic and energetic proton observations from period 2 are shown in Figure 4 and compared with the photometer observations from Gillam and Rankin Inlet. The observations in Figure 4 are similar to those in Figure 3. PBIs are observed to have extended equatorward to geosynchronous field lines from 0905-1223 UT. This interval corresponds to an interval of proton flux spikes at geosynchronous orbit, with a 20 min time delay that should be related to magnetic drift. Magnetic variations were also observed by GOES 9 during this interval, though the variations were not as large or as distinct as were those during period 1.

2.5 Power spectra and tail plasma sheet particles and magnetic fields

Figures 5a and 5b show representative power spectra of the observations during period 1 for 07-09 UT and 09-1115 UT, respectively. The 07-1115 UT interval was selected because it corresponds to the period when evidence for ULF pulsations was seen in the geosynchronous data and because there is no evidence for substorms during this period. The period was divided in two because the repetition rate for the proton spikes on LANL 1994-084 (Figure 3) appears to have been slower from 07-09UT than from 09-1115 UT. Also the latitude of the poleward boundary of plasma sheet particle precipitation, as observed by the Rankin Inlet photometers (see Plate 1), decreased substantially near 09 UT, indicating that a possibly significant change in the magnetospheric configuration may have occurred at about this time. Such a change might be expected to affect the frequencies of global pulsations. To create the power spectra, the data were first high-pass filtered to remove frequencies lower than 0.417 mHz (periods greater than 40 min). The filtered data were then fast Fourier transformed using a Hanning window, and a three-point smoothing was applied to the resulting spectrum. Frequency resolution for each spectra before the three-point smoothing (equal to the inverse of the total length of each transformed data series) is 0.14 mHz for the 2 hour intervals selected, and the Nyquist frequency, $1/2 T$, is well above the frequencies of interest for all sampling intervals T of the data. Shading in Figure 5 identifies frequencies removed by filtering.

Spectra are shown in Figures 5a and 5b for the Goes 9 geosynchronous magnetic field, for 170-250 keV LANL proton fluxes from spacecraft that observed flux spikes, for the CANOPUS 5577 Å emissions from representative photometers and latitudes, and for the ground magnetic X component from several CANOPUS stations. A spectrum from the Gillam photometers is shown despite it being cloudy, because, as can be seen from Plate 1, temporally varying auroral brightenings showed clearly through the clouds. While scattering prevented latitudinal information from being obtained from Gillam, the scattered emissions received when looking overhead give an approximate average of the emission intensity over the latitudes within the field of view of the photometer.

Notice that during both intervals there was significant power at a frequency of ~ 0.6 mHz, (periods of ~ 25 - 30 min) in all the measurements as well as evidence for power near harmonics of this frequency. Spectral peaks are not at precisely the same frequencies in all the measurements within each time interval. Also, as discussed below, our identification of a spectral peak near 0.6 mHz has significant uncertainty due to filtering. However, the spectral peaks show enough similarities between the different measurements to be consistent with a common ULF pulsation being responsible for the spectral power in the measurements.

For period 1, ULF power is seen simultaneously within the auroral ionosphere and at synchronous orbit. For period 2, we also have Geotail particle and field data from within the nightside plasma sheet at $x \sim -30 R_E$ just to the dawn side of midnight. Geotail magnetic field plasma moment observations are shown in Figure 6 for the time period of the photometer observations in Plate 1. The bottom panel gives the total (magnetic plus ion) pressure P_{tot} and the ion pressure P_{ion} . The near equality of P_{tot} and P_{ion} shows that Geotail was well within the central plasma sheet for most of the 12-hr interval. Only from $\sim 6:30$ - $7:30$ UT and from $\sim 8:15$ - $8:45$ was the spacecraft in the lobes or plasma sheet boundary, as indicated by $P_{\text{tot}} \gg P_{\text{ion}}$. The x-component of plasma velocity V_x shows that flow bursts were present throughout most of the period when the spacecraft was within the central plasma sheet. This is expected from the known general association between flow bursts and PBIs, since PBIs were observed throughout most of the time interval. Vertical dashed lines in Figure 6 identify peaks of individual flow bursts observed by Geotail within the central plasma sheet. It can be seen that the bursts occur at a rate of ~ 4 - 5 per 2 hr period, which corresponds to a ~ 25 - 30 min period and thus approximately to the lower frequency seen in the power spectra for period 1. The Geotail data also show that the flow bursts were associated with significant variations in V_y , the three components of \mathbf{B} , and P_{ion} .

Power spectra for two intervals of relatively stable PBI activity in the photometer observations and during which Geotail was within the central plasma sheet, 04-06 UT and 09-1224 UT, are shown in Figures 5c and 5d, respectively. Both of these intervals were selected to avoid significant substorm activity. The second interval corresponds approximately to the time when flux spikes were observed at geosynchronous orbit. It was taken to be as long as possible, but does include the non-PBI related activity from 0925-1000 UT that affected the Dawson magnetic field (not included in our analysis) and perhaps the P-component of the GOES 9 magnetic field. The spectra shown for period 2 are from the same data sources as are the spectra shown for period 1, as well as from the geosynchronous magnetic field measured by Goes 8, located ~ 4 hours in MLT east of Goes 9 (not available for period 1), and the x and y components of velocity and magnetic field measured by Geotail.

There were strong PBIs near $\sim 72^\circ$ during the 04-06 UT interval. Most of the power spectra in Figure 5c for this interval show significant power at ~ 0.6 mHz (~ 28 min period). Significant power is also seen near twice this frequency ~ 1.2 mHz (~ 14 min period), giving evidence for a harmonic structure to the ULF pulsations. For the 09-1224 UT interval, when PBIs extended equatorward to $\sim 67^\circ$, all the spectra shown have significant power at ~ 0.53 mHz (~ 31 min period) and evidence for power at a second and possibly a third harmonic with periods of ~ 16 min (~ 1.1 mHz) and ~ 10 min (~ 1.6 mHz). Most importantly, for both intervals significant power is seen simultaneously at Geotail at approximately the same frequencies as seen at synchronous orbit and within the auroral ionosphere. This would be expected if the oscillations in the auroral ionosphere, synchronous orbit, and tail plasma sheet are all components of a large-scale, nightside ULF oscillation.

The spectral peaks obtained in previous studies (see Introduction) correspond reasonably well to the second harmonic (~ 1.1 - 1.3 mHz) that is seen in most of our measurements and to the higher harmonics seen in some of our measurements. Most previous studies have reported only the second and higher harmonic frequencies (Fenrich et al. [1995] found a few examples where power at 0.8 mHz was observed). However, these studies have been unable to see a possible

lower harmonic because of filtering of frequencies below 1 mHz. We have used two to three hour data windows because of the relative stability of the magnetosphere-ionosphere system during SMCs, and thus been able to apply a lower frequency filter than is typically feasible. However, even with a two to three hour window, frequency resolution is poor below several tenths of a mHz and we have filtered out frequencies ≤ 0.4 mHz. Thus our identification of the frequency of a spectral peak below 1 mHz is not precise, and our filtering may give false peaks at frequencies near 0.4 mHz. However, some of our data show clear oscillations with an ~ 30 min period (e.g., the GOES magnetic field during period 1 after 0630 UT and the energetic protons from spacecraft 1997A during period 2 after 0930 UT) lending credibility to the existence of such a peak. Also, the 0.5-0.7 mHz frequency peak that we have found is appropriate for being the fundamental of the harmonics ($\sim 1.3, 1.9, 2.6, 3.4$ mHz) observed previously for ULF pulsations and field-line resonances.

The ULF pulsations in the data we have analyzed show very large amplitude, the amplitude of the oscillations being as large as other major dynamical features of the magnetosphere-ionosphere system. This large amplitude of the pulsations is illustrated in Figure 7, which shows examples of our filtered data for 6-12 UT during period 1. For example, peak-to-peak variations in the ~ 30 min oscillation are often ~ 10 -25 nT in the filtered geosynchronous magnetic-field components and ~ 200 -600 nT in the filtered ground magnetic X-component.

2.6 Ionospheric plasma flow

If these large-amplitude oscillations are indeed a component of a global ULF pulsation, then these pulsations must be an extremely significant component of the dynamics of the magnetosphere-ionosphere system. The connection between the magnetosphere and the ionosphere should be seen as a mapping to the ionosphere of the localized enhanced magnetospheric electric fields that give rise to the tail flow bursts. We are fortunate that some measurements of ionospheric flows are available from the SuperDARN radars during period 2. Most of the usable nightside radar echoes are from the radar at Saskatoon, located ~ 1 hr in MLT west of Gillam. In addition, some useable echoes obtained by another of the SuperDARN radars are available from a region about 110° east of the Saskatoon echoes.

Examples of line-of-sight ionospheric flow vectors from the Saskatoon radar are shown in Figure 8. In each panel, dots give the locations where radar echoes were measured the two-minute radar scan that began at the time indicated. Lines with one end at the measurement locations extend away from each dot in the direction of the measured line-of-sight flow, the length of each line being proportional to the flow speed. The top two panels show Saskatoon observations from two radar scans, separated by 10 min, during the interval for which power spectra are shown in Figure 5c. At this time Saskatoon was near 22 MLT. The bottom two panels show observations from two radar scans, separated by 6 min, during the interval for which power spectra are shown in Figure 5d and when Saskatoon was near 3 MLT. The 0513 and 1007 UT panels of Figure 8 show regions of large flows that do not extent longitudinally across the entire radar field of the radar, and both pairs of measurements show large flow changes at several measurement locations during the 6-10 min interval between measurements. This is what is expected from a mapping of the tail flow bursts to the ionosphere. Also, the wavelength of PBIs estimated from the VIS images in Plate 1 is $\sim 25^\circ$ in longitude. If this wavelength applies to the flow bursts, it would give longitudinal variations in the flows similar to those seen by the radar at 0513 and 1007 UT.

Figure 9a and b shows time sequences of line-of-sight velocities when good sequences are available for the 4-6 UT and 9-12.4 UT time intervals, respectively, of period 2. Each of the four groups of panels in the figure gives time sequences of measurements at a fixed magnetic latitude and for adjacent magnetic longitudes. Within each panel group, longitudes are arranged with the westernmost on the top and the easternmost on the bottom. In Figure 9a, three sets of measurement are shown from Saskatoon (pre-midnight) and one set is shown on the morning

side from the radar with useable echoes located east of Saskatoon. In Figure 9b, two sets of measurements are shown from Saskatoon on the morning side. Positive velocities indicated flow away from the observing radar.

Figure 9 shows that ionospheric flows often varied considerably with longitude and with time during both intervals. Individual flow enhancements were large, many reaching several hundred m/s. Most of the flow enhancements had a line-of-sight component directed towards the observing radar at pre-midnight MLTs and directed away from the observing radar at post-midnight MLTs. Continuous time series of radar data were not long enough to perform the spectral analysis as we have done for other data. However, on a number of occasions, the flow sequences appear approximately sinusoidal (e.g., at 70.5° latitude and -43.5° and -46.5° longitude in Figure 9a, and after 11UT in the top five panels in Figure 9b). These oscillations of the flow are about a significant mean speed, so that the line of sight flows stay mostly in the same direction. Occasionally, however, the flow oscillations reverse the direction of the flows, though the flow speeds during the reversals remain small (e.g., fourth and fifth panels of Figure 9b). During these periods, 2-4 peaks in flow speed were observed per hour, indicating possible power at the fundamental and second harmonic frequencies seen in the power spectra of the other data. Dashed lines in Figure 9 connect individual peaks in the magnitude of the flow when it appears that the same flow speed peak was observed at two or more adjacent longitudes (Thinner dashed lines are used for the two cases that are based primarily on data series that terminate near the time of an apparent flow peak.). All these lines (except the one in Figure 9b at 9.64 UT) are tilted from the vertical indicating azimuthal propagation of the flow peaks. This direction is westward for all measurements taken before midnight and eastward for all measurements after midnight. This indicates an azimuthal component of phase velocity for the flow peaks that is directed away from the region near magnetic midnight. The speed of the propagation is ~500-20000 m/s. The same directions and magnitudes for azimuthal propagation of non-substorm auroral current and flow disturbances were found by Wild and Yeoman [2000].

3. Conclusions and Discussion

Observations have been examined during two prolonged periods of strongly southward and relatively steady IMF. We find evidence that auroral PBIs, which occur repetitively throughout such periods, may be a manifestation of a strong ULF oscillation mode that strongly perturbs the plasma sheet and the auroral ionosphere. Evidence within the auroral ionosphere is seen in ground optical and magnetic observations during both periods. Evidence that this mode affects the nightside plasma sheet is seen at synchronous orbit during time intervals when PBIs were observed to extend equatorward to synchronous field lines. Evidence for effects within the plasma sheet is also seen in data from the Geotail spacecraft, which was located within the tail plasma sheet at $X \sim -30 R_E$ during one of our periods. The Geotail data show repetitive flow bursts and associated magnetic variations, consistent with the known association between tail flow bursts and PBIs. These Geotail observations have spectral power peaks at approximately the same frequencies as seen simultaneously within the auroral ionosphere and at synchronous orbit, consistent with the tail flow bursts being a manifestation of the same ULF oscillation as the PBIs and the oscillations seen at synchronous orbit.

The connection between the tail flow bursts and the PBIs is expected to result from a mapping to the ionosphere of the localized enhanced magnetospheric electric fields that give rise to the tail flow bursts. SuperDARN observations of nightside ionospheric flows show large flow variations while repetitive flow bursts are seen at Geotail, as expected from the mapping to the ionosphere of the longitudinally localized enhanced plasma sheet electric fields associated with the tail flow bursts. Note that the flow variations in the ionosphere and the y-component of plasma flow at Geotail are far more sinusoidal than the x-component of plasma flow at Geotail. However, it must be remembered that the relation $\mathbf{V} = (\mathbf{E} \times \mathbf{B})/B^2$ is not valid in the tail plasma sheet where there are large spatial variations in \mathbf{B} over the scale of a proton gyroradius. Thus

the bursty nature of the earthward flows may result from a combination of electric and magnetic field variations.

If the implications from the present study are correct, then ULF modes are a major component of tail dynamics, of magnetosphere coupling to the ionosphere, and of auroral zone disturbances during periods of enhanced convection, consistent with the suggestion of Sánchez et al. [1997]. They would simultaneously affect a large region of the nightside, extending along auroral-zone field lines from the ionosphere to the equatorial plasma sheet and extending from field lines that lie near the magnetic separatrix to, at times, as close to the Earth as synchronous orbit. They also can have large amplitudes, being as large as changes that occur in association with other auroral zone disturbances such as substorms. Here we have found peak-to-peak amplitudes as high as several hundred nT in ground X, approximately an order of magnitude in synchronous energetic proton fluxes, ~ 20 - 40 nT in synchronous magnetic field components, ~ 20 nT in tail magnetic field components, ~ 1000 km/s in tail V_x , and ~ 400 m/s in ionospheric flow speed. The oscillations in flows in the tail and in the ionosphere are generally about a significant mean, so that net transport of the plasma is primary in one direction. However, the oscillations do result in flow reversals with small magnitudes. The large amplitude of the ULF oscillations would be expected to give rise to non-linearities, and possible evidence for non-linearities is seen in the POLAR spacecraft images of the aurora.

Power spectra of the observations within the auroral ionosphere and the nightside plasma sheet show significant power at 0.5-0.7 mHz (~ 25 - 30 min period), significant power at a possible second harmonic (~ 1.1 - 1.3 mHz), and evidence for power at frequencies that could be higher harmonics. We do not see precisely the same frequencies in all our simultaneous observations, nor do we see precise harmonic structure. This could be associated with the non-linearity of the pulsations. The second and higher harmonics that we have found have often been seen before on the nightside. However, the fundamental frequency that we have possibly identified has not been generally seen in the past. This may be because we have used 2-3 hr of data for our power spectra. Such a long period of relative stability of the magnetosphere-ionosphere system is not common, so that most previous analysis have had to filter away power at frequencies below ~ 1 mHz. Even with the length of our data series, our precision in identifying the frequency of this <1 mHz oscillation is not particularly good and our filtering of frequencies below 0.42 mHz adds uncertainty to our identification of the low frequency peak. Analysis of data from even longer intervals of steady solar wind forcing of the magnetosphere may be needed if these uncertainties are to be decreased. That several of our observations show a visually identifiable ~ 30 -min period oscillation lends credibility to the possibility that such a low frequency oscillation indeed does exist and is important.

We have also found evidence that the flow oscillations associated with PBIs have an azimuthal wave phase velocity that is directed away from midnight with a speed of order 500-2000 m/s, in agreement with Wild and Yeoman [2000], and that the azimuthal wavelength of PBI auroral brightening is of order 1000 km in the auroral ionosphere. The azimuthal phase speeds are greater than typical flow speeds, implying that the oscillations are not simply being carried by the plasma flow. If the PBIs correspond to a series of flow bursts distributed longitudinally across the tail, then the spacing between the center of flow bursts would be $\sim 5 R_E$ (based on 5 wavelengths spanning $25 R_E$ across the tail). This corresponds quite well to the inferred scale-size of plasma sheet flow bursts [Angelopoulos et al., 1994, 1996]. Note that the above rough estimates of wavelengths and azimuthal phase speed gives frequency estimates of ~ 0.5 - 2 mHz, consistent with the frequencies we have observed.

It is interesting that the frequencies we have found in association with PBIs are similar to those that have been found in association with morning-side auroral omega bands and Ps6 magnetic pulsations [e.g., Buchert et al., 1990]. Also omega bands and Ps6 pulsations have been seen simultaneously with PBIs during SMCs [Solov'ev et al., 1999]. This suggests that there may be an association between auroral omega bands and the oscillations associated with PBIs

and tail flow bursts. An examination of whether or not there is such an association may be worth further pursuit.

Our analysis has been limited to two periods of enhanced convection. The extent to which our results apply to periods of enhanced convection in general and to other conditions remains to be determined. Also, while we have identified some important properties of the possible large-scale ULF mode of the magnetosphere, determination of many other important properties will require further analyses. Finally, our analysis has not considered possible energy sources or causes for the large-scale, large-amplitude ULF oscillations. Proposed sources for ULF pulsations at the frequencies we have seen include external solar wind dynamic pressure impulses [Mann et al., 1998; Mathie et al., 1999], a Kelvin-Helmholtz instability at magnetopause [Mann et al., 1999; Mathie et al., 1999], substorm associated compressional (fast mode) disturbances [Liu et al., 1995; Wright et al., 1999; Allan and Wright, 2000], and magnetosheath turbulence [J. Borovsky, private communication, 2001]. Of these, only the Kelvin-Helmholtz instability and magnetosheath turbulence could account for pulsations continuing for many hours during prolonged periods of enhanced convection irrespective of substorms and dynamic pressure impulses.

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Figures

Plate 1. Top: 5577 Å emissions from the CANOPUS meridian scanning photometers as a function of λ and UT. Observations are shown from a merging of data from Gillam and Rankin Inlet for both periods and from Fort Smith for January 10, 1997. Bottom: sample two-dimensional images of nightside auroral 5577Å emissions on January 30, 1998 obtained by the “low resolution camera” of the POLAR Visible Imaging System.

Figure 1. Top: IMF B_z for January 10, 1997 measured by WIND within the solar wind and by Geotail located within the magnetosheath just in front of the nose of the magnetosphere. Times from WIND have been adjusted for propagation to the location of Geotail. Bottom: IMF B_z for January 30, 1998 measured by WIND and IMP-8 within the solar wind. Times from WIND have been adjusted to the location of IMP-8. Spacecraft locations in Cartesian GSM coordinates are given. Time intervals are indicated for which representative power spectra of magnetospheric observations are shown in Figure 5.

Figure 2. X component from auroral-zone ground magnetometers for the time periods of the meridian-scanning photometer data in Plate 1. For each station, solid triangles identify the UT of magnetic midnight, and magnetic latitude is given along the right-hand edge of the figure.

Figure 3. Geosynchronous magnetic field and energetic proton observations for 3-12 UT on January 10, 1997. The total magnetic field B_{tot} and the components of the field in local spacecraft coordinates are shown (P directed parallel to the magnetic dipole axis and positive northward, N directed eastward from the plane containing the point of observation and the magnetic dipole, and E directed from the point of observation toward the dipole axis and perpendicular to P). The 5577 Å emissions from Fort Smith are shown at the bottom of the figure.

Figure 4. Same as Figure 3, except for the period 1-13 UT on January 30, 1998. Also, the 5577 Å emissions are from Gillam and Rankin Inlet.

Figure 5. Representative power spectra of observations during the four time intervals indicated in Figure 1. Shading identifies frequencies removed by filtering.

Figure 6 Geotail magnetic field and plasma moment observations for the time period of the photometer observations in Plate 1. $V_{x,\text{perp}}$ is the x component of the velocity component perpendicular to the measured magnetic field

Figure 7 Examples of high-pass filtered data used to make the power spectra in Figure 5 for 6-12 UT during period 1. The filter had a low frequency limit of 0.417 mHz (40-min period).

Figure 8. Examples of line-of-sight ionospheric flow vectors from the Saskatoon radar. In each panel, dots give the locations where radar echoes were measured during the two-minute radar scan that began at the time indicated. Lines extending out from the measurement locations point in the direction of the line-of-sight component of plasma flow. The heavy dot in each panel labeled Sa gives the location of the radar.

Figure 9a Time sequences of line-of-sight velocities when good sequences are available for the 4-6 UT time interval of period 2. Magnetic latitude and longitude, respectively, are indicated in each panel.

Figure 9b Same as Figure 9a, except for the 9-12.4 UT time interval of period 2