Polar observations of transverse magnetic pulsations initiated at substorm onset in the high-latitude plasma sheet

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[1] This paper presents simultaneous observations of 6-MHz magnetic pulsations in the nightside high-latitude plasma sheet, inner plasma sheet at the geosynchronous distance, and auroral region on the ground in association with substorm onset. We study an isolated substorm (ΔE ~ 300 nT) onset on 19 October 1999 at ~0145 UT. The Polar spacecraft was located in the plasma sheet near the plasma sheet boundary and was magnetically conjugate with the Greenland west coast magnetometer chain. Polar measured large-amplitude transverse magnetic (10 nT; toroidal) and electric (20 mV m−1) field oscillations (~6 MHz) during the early development of the negative bay (300 nT) in Greenland. On the ground, pulsations (50 nT) with the same frequency were superimposed on the negative bay. The geostationary GOES 8 spacecraft was located 2 hours west of Greenland. It observed compressional magnetic field oscillations (1 nT and ~6 mHz). At Polar the pulsations were initiated ~3 min before the first outward propagating substorm signature, as abrupt enhancement of the plasma sheet electron fluxes. Such a rich data set allows us to study in detail the spatial origin of the pulsations, their timing with respect to the negative bay onset, and their role in initiation of the substorm current wedge. It is concluded that the pulsations were initiated between the plasma sheet boundary and the tailward expanding region of the enhanced plasma sheet electron fluxes. The pulsations were then later observed on the ground and at GOES 8. It can also be argued that the pulsations were an integral part of the formation of the substorm current wedge. Finally, we suggest that the pulsations were generated by periodic variations in the rate of the current diversion from the braking region of the earthward flows generated by reconnection at the near-earth neutral line. In situ measurements of magnetic and electric field oscillations are needed for understanding this process.

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1. Introduction

[2] The substorm current wedge is a key element in the coupling between the geomagnetic tail and the ionosphere during magnetospheric substorms [McPherron et al., 1973]. The current wedge is thought to be formed at substorm onset as a partial diversion of the cross-tail current into field-aligned currents that close through the ionosphere. The ionospheric part of the substorm current wedge forms the auroral electrojet, which is responsible for magnetic disturbances such as negative bays observed by ground-based magnetometers. Several mechanisms for the initiation of substorm current wedge have been assumed by substorm onset models such as the near-earth neutral line (NEQL) model [e.g., Baker et al., 1996] and the current disruption model [e.g., Lui, 1996]. Thus observations of the formation of the substorm current wedge are important for understanding the physics of substorms and future development of the substorm models.

[3] Magnetic pulsations are a typical ground signature of substorm onset in a wide range of geomagnetic latitudes and longitudes. A class of these pulsations defined as P2 pulsations occurs in the period range from 40 to 150 s. These are closely correlated with other onset phenomena, including brightening of auroral arcs and electrojet intensi-
fications. Thus the Pi2 band has been used extensively in substorm studies, for example, to determine the onset time or location of the initial brightening. In space according to statistical results of Saito and McPherron [1983], magnetic pulsations during substorm activity at geographically distances can be classified primarily by two types of pulsations: (1) an irregular wave with a significant compressional component and (2) a more quasi-uniform transverse wave in the azimuthal component (toroidal). Saito and McPherron [1983] concluded that the pure transverse waves are quite rare when during almost every substorm. According to the statistical study of Saito et al. [1996] ~30% of the Pi2 events on the ground are accompanied by high-frequency turbulent pulsations in the frequency range of Pc3–Pc5.

On the basis of theoretical considerations MHD transients are expected to be excited by any change in magnetospheric convection or configuration during substorms [Southwood and Stuart, 1980]. High-latitude and midlatitude Pc2 pulsations are thought to be caused by the sudden generation of field-aligned currents in association with the disruption of cross-tail currents in the plasma sheet [e.g., Olson, 1999]. Also, the flow channel of enhanced plasma flows generated by magnetic reconnection near the Earth–neutral line is expected to excite Pi2 pulsations: the dawn-to-dusk electric field associated with the flow channel is propagated to the ionosphere as an Alfven wave, and the field-aligned current associated with the wave initiates the substorm current wedge [e.g., Baker et al., 1994]. Low-latitude Pi2s are thought to be a response of the inner magnetosphere to compressional waves generated at the substorm onset [e.g., Olson, 1999]. In contrast to the extensively studied Pi2 pulsations little attention has been paid to the transient toroidal pulsations observed at midlatitudes. Considering the wave parameters and ambiguities in the magnetizing mechanisms of the pulsations in the overlapping frequency ranges of Pi2s and Pc5s and the extent of use of this frequency range in the substorm activity studies, it is important to understand any processes generating the Pi2 frequency range to establish their role in substorm activity.

[5] An important way to consider the effects of various field variations in space on the substorm physics is the magnetic field-aligned Pi2 flux associated with the variations. Recently, there have been several studies of large parallel Pi2 flux on auroral magnetic field lines during substorm activity. Toivanen et al. [2001b] presented observed large Pi2 flux associated with magnetic field and plasma flow variations obtained by the UVI spacecraft in the high-latitude plasma sheet. Timing of these observations corresponded to the Pi2 and Pi4 auroral onsets at magnetically conjugate ground stations [Toivanen et al., 2000a]. Similar field variations occurring near or at the plasma sheet boundary during substorm activity have also been studied by Keelings et al. [2000]. According to Wygant et al. [2000], these variations and Pi2 flux occur on auroral field lines conjugate to Pi4 auroral activity in the UVI image (albeit the Pi2 auroral image is however not clearly visible). Parallel Pi2 onset has also been reported by Ericson et al. [2000] in the CRRES spacecraft data set.

According to these authors, there is another source region of large parallel Pi2 flux located in the near-Earth plasma sheet, and this region is associated with the near-geostationary onset (NGO) mechanism. As there seem to be two spatial sources of large parallel Pi2 flux, it is important to present detailed multipoint observations of electromagnetic field pulsations and associated Pi2 flows in order to address the spatial origin, the timing with respect to various ground signatures, and the role of the pulsations in the initiation of the substorm current wedge and in the physics of substorms.

2. Observations

2.1. Ground Activity

[6] On 19 October 1999 an isolated substorm occurred with AL reaching ~300 nT. It was first observed shortly before 0745 UT by the southernmost of the Greenland magnetometers in Nanarsaarq (NAQ; 66.31 CGM latitude, 43.91 CGM longitude). Figure 1 shows the northward (Figure 1a), eastward (Figure 1b), and vertical (Figure 1c) components as functions of time at the Greenland west coast stations (Figure 2). The vertical line at 0144-23 UT marks the initiation of the substorm-related signatures at Polar as defined in section 2.5. The northward component shows a very weak deflection (~7 nT) at NAQ beginning at ~0142 UT, but the actual northward expansion of the negative deflections took place after 0145 UT. The latitude of the auroral electrojet can be identified as the boundary between positive and negative deflections of the vertical component (Figure 1c). At ~0147 UT, the electrojet was located at NAQ and was moving northward. The positive deflection from 0145 UT to 0147 UT at NAQ, FHB, and GHB implies that the electrojet enhancement initiated south of NAQ. Prior to 0145 UT, only a weak deflection of the vertical component can be identified, and no substorm signatures were observed. The increase of the west coast chain. The key features of this event are the large-magnitude magnetic pulsations in a timescale of a few minutes, the positive deflection at the auroral electrojet, and its northward migration.

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Figure 1. Detections of the horizontal (a) north-south and (b) east-west, and (c) vertical magnetic field CGM components in functions of CGM latitude and time (CGM, Corrected Geomagnetic). The magnitudes were interpolated in the latitude range of the Greenland west coast stations. At 0144:23 (vertical line), Polar observed the first dynamical signatures (defined in Figure 8c) associated with the ground onset. See color version of this figure at back of this issue.

of SAMNET (D. K. Milling, private communication 2002). Figure 4 shows midlatitude magnetic field perturbations west of Greenland in Ottawa (OTT), 56.7°CGM latitude, 21.1°CGM longitude) and St. John’s (STJ; 54.6°CGM latitude, 13.2°CGM longitude). During the early expansion phase, the positive deviation of the X component at STJ (and OTT) suggests that the center of the substorm current wedge was located west of STJ. On the other hand, the positive X component at STJ indicates that the center of the upward FAC current was located west of STJ. The small deviations of the X component from the baseline at OTT indicate that OTT was located near the reversal of the positive and negative deviations of X associated with the upward FAC of the substorm current wedge. The positive deviations of the X component after ~0200 UT at OTT, can then be considered as a signature of the approach of the upward FAC to OTT. On the basis of these available observations and the interpretations made, it can be concluded that the current
2.2. Solar Wind Conditions

The Geotail and IMP8 spacecraft were located in the upstream solar wind at \( r_{\text{GSM}} = (6, -26, 5) R_E \) and \( r_{\text{GSM}} = (18, -33, 15) R_E \), respectively. Both spacecraft observed steady solar wind conditions during the event starting at 0125 UT after a reduction of the \( B_y \) component of the interplanetary magnetic field from \(-2.8 \) to zero.

2.3. Locations of the Polar and GOES 8 Spacecraft

Figure 5 shows the locations of the Polar and GOES 8 spacecraft in the noon-midnight meridian (Figure 5a) and the magnetic field line locations of these spacecraft and selected ground stations in the equatorial current sheet (Figure 5b). A superposition of the International Geomagnetic Reference Field (IGRF) and the magnetic field model of Tsyganenko (-89) (T89) was used to determine the location of the field lines in the equatorial current sheet. In addition to the dipole tilt angle, the T89 model requires the \( K_{p} \) index as input. It was determined by comparing the actual Polar magnetic field measurements obtained by the Magnetic Field Experiment (MFE) (Burruss et al., 1995) with the T89 model predictions. The best fit to the data was achieved by using \( K_{p} = 2 \). At 0145 UT, the Polar and GOES 8 spacecraft were located in the premidnight sector at \( r_{\text{GSM}} = (-6.6, 1.0, 0.7) R_E \) and \( r_{\text{GSM}} = (-4.4, 4.6, -0.3) R_E \), respectively. Since the dipole tilt angle during this event was approximately \(-17^\circ\), these spacecraft were not located as close to the magnetic equator as their \( Z_{\text{GSM}} \) coordinates may indicate. According to Figure 5a, it is apparent that the spacecraft separation of \(-1.9 R_E \) in \( Z_{\text{GSM}} \) leads to a considerable separation in the equatorial current sheet. At 0145 UT, the magnetic field lines of Polar and GOES 8 mapped to \( r_{\text{GSM}} = (-15.1, 2.5, -2.4) R_E \) and \( r_{\text{GSM}} = (-4.4, 5.2, -1.0) R_E \) (Figure 5b). The locations of the field lines of NAO, HLL, and FAR at 0145 UT are also shown.

In addition to the magnetic field mapping, direct information of the Polar location in the tail can be obtained from actual Polar measurements. Figure 6 shows an over-
Figure 4. Midlatitude magnetic field X and Y component in Ottawa (OTT) and St. John's (STJ). view of selected Polar measurements during the event (outward pass from the outer electron radiation belt to the tail lobe). Figure 6a shows high-energy electron fluxes as measured by the Imaging Electron Sensor of Comprehensi- sive Energetic Particle and Pitch Angle Distribution Experi- mental [Blake et al., 1995] (CEPPADS) mission. The outer electron belt can be associated with the high fluxes before ~0130 UT (the enhanced fluxes after ~0145 UT are related to the substorms activity). The plasma sheet electron population was observed by the HYDRA instrument [Scudder et al., 1995] (Figure 6b). The sharp decrease of the electron fluxes at ~0235 UT indicates the boundary between the plasma sheet and the northern tail lobe. Prior to the boundary crossing, the Polar spacecraft potential measured by the Electric Field Instrument [EFT] [Harvey et al., 1995] dropped suddenly in response to low electron fluxes in the vicinity of the plasma sheet boundary. Comparison of the electron fluxes and the spacecraft potential observed at ~0145 UT to those observed near the plasma sheet boundary at 0237 UT, suggests that Polar was located near the plasma sheet boundary at ~0145 UT.

[1] In the ionosphere, the foot point of Polar at 0145 UT was located ~15° south and ~10° west of NAQ and ~40° east of the foot point of GOES 8 (Figure 2). As the auroral electrojet enhancement initiated south of NAQ and near the Greenland west coast, the Polar foot point was favorably located with respect to the early changes in the electrojet.

2.4. Magnetic Field Observations at GOES 8

[2] Figures 7a–7c show magnetic field measurements in a magnetic field-aligned coordinate system at GOES 8. X is aligned with the ambient field (the observed field boxcar averaged with width of 35 min); Y is perpendicular to the plane defined by the X component and the ambient field, and Z is aligned with the spacecraft position (positive toward the west); and Z completes a right-handed triad. Figure 7d shows the eleva-

tion angle of the magnetic field at GOES 8. In order to best represent temporal variations of the magnetic field eleva-
tion angle, a linear trend has been subtracted from the elevation angle defined as 180° arctan(By/Bx)°, where By and Bx are the magnetic northward and radial components, respectively. Such a linear trend is introduced by the motion of GOES 8 toward the nighttime as deduced from the T90 recycle in the streamline analysis of one hour. From 0145 to 0155 UT, the magnetic field was fairly constant relative to the deflections observed after 0155 UT (the periodic fluctua-
tions during 0145–0153 UT are discussed in detail in sections 2.5 and 3). The negative (0155–0207 UT) and then positive (after 0207 UT) deflections can be interpreted as a passage of the upward field trend toward GOES 8. This is most probably related to the westward expansion of the current wedge observed at OTT.

2.5. Polar Observations

[1] Figure 8 shows observations of several instruments on board Polar in comparison with the observations of GOES 8 and NAQ summarized in Figures 5a, 8b, and 8c. The X component magnetic north (the magnetic field observations at NAQ indicates the earliest signature of the negative bay onset at ~0145 UT (Figure 8a). In order to study the pulsations superimposed on the developing electrojet, Figure 8b shows the X component at NAQ after detrending over 180 s. The detrending was carried out by boxcar-averaging the original signal with a width of 180 s and subtracting the average signal from the original signal. The amplitudes of the pulsations ~0.5 nT were considerable in comparison with the magnitude of the negative bay (~300 nT; Figure 8a). At GOES 8, magnetic pulsations with amplitudes of the order of 1 nT were observed in close temporal association with the ground pulsations (Figure 8c); the ambient field at GOES 8 shows in Figure 7a detrended over 180 s). The electron data from the CEPPADS and HYDRA instruments shown in Figures 6a and 6b are replotted in Figures 8d and 8e, respectively. Figures 8e, 8f, 8g, and 8h show magnetic field data obtained from the THEMIS and HYDRA instruments shown in Figures 6a and 6b. The THEMIS and HYDRA instruments shown in Figures 6a and 6b. The THEMIS and HYDRA instruments shown in Figures 6a and 6b. The THEMIS and HYDRA instruments shown in Figures 6a and 6b. The THEMIS and HYDRA instruments shown in Figures 6a and 6b. The THEMIS and HYDRA instruments shown in Figures 6a and 6b. The THEMIS and HYDRA instruments shown in Figures 6a and 6b.
auroras. Considering the time of the oscillations and the large Poynting flux toward the ionosphere, we define the substorm onset time to be the first enhancement in the magnetic ($\sim 1$ nT, Figure 8b) and electric fields ($\sim 10$ mV m$^{-1}$, Figure 8k) at 0144:23 UT. The magnetic field configuration started to become more dipolar $\sim 2$ min after the onset time as indicated by the elevation angle in Figure 8f.

Prior to the onset, there were weak dynamic signatures at Polar and GOES 8 at 0139:00 UT. On the ground, only a weak signature can be identified. Between 0139 and 0145 UT the decrease of the magnetic field X component both at Polar (Figure 8g) and at GOES 8 (Figure 7a), suggests that the signature was rather a causal precursor of the onset than a transient perturbation.

3. Spectral Analysis of the Observed Pulssations

Further analysis of the pulsations observed at Polar, GOES 8, and on the ground is based on the Fast Fourier Transformation (FFT). The time interval transformed into the frequency domain ranges over an integer number of cycles with a period of 180 s. The period of 180 s was estimated from the time series shown in Figures 8b, 8c, and
Figure 6. Overview of (a) high-energy electrons (17-200 keV), (b) plasma sheet electrons (0.1-20 keV), and (c) spacecraft potential as observed by CEMPII/MELS, HYIIRNA, and EFI, respectively. See color version of this figure at back of this issue.

(b) Such time intervals are used in order to reduce smearing of the frequency component of interest. Substantial smearing can be expected as only a small number of cycles with period of ~180 s are present in the time series, especially in \( \delta f \) at Polar.

(c) At Polar, the pulsations occurred mostly in the \( B_y \) component. This can be verified by the amplitude spectra of the signals of Figures 6a, 8a, and 8b (Figure 9). The spectrum of the \( B_y \) and \( B_z \) are relatively flat compared to the spectrum of the \( B_x \) component. Its spectrum shows two peaks, one centered around 6.5 mHz (maximum amplitude at 5.6 mHz) and the other around 18 mHz. As the \( B_x \) component is roughly aligned with \( Y_{\text{abs}} \), the pulsations can be considered as toroidal.

(d) At GOES 8, the compressional component \( (B_z) \) has an amplitude spectrum peaked at the same frequency range as the spectrum of the torsoidal pulsations at Polar (Figure 10). The frequencies higher than 0.005 mHz are mainly caused by the transverse components \( (B_y \) and \( B_x \). The amplitude of the compressional pulsations at GOES 8 is smaller by an order of magnitude than that observed at Polar.

In order to compare the spectra of the toroidal \( (B_x) \) pulsations at Polar and the compressional pulsations at GOES 8 to the spectrum of the pulsations at NAQ, Figure 11 shows the spectrum of the determined northward component at NAQ (dotted line). It is peaked in the same frequency range as \( B_x \) at Polar and \( B_y \) at GOES 8. In addition, the spectrum of the electric field \( E_y \) component at Polar is also shown with dash-drawn line. It has characteristics similar to those of the magnetic field \( B_y \) component at Polar. This justifies the filtering of the electric field signals in Figures 9 and 8.

Finally, we study the phase shifts between the signals of Figures 8a (NAQ, dotted line) and 8b (GOES 8) with the use of high-performance computing for detailed analysis. The phase shifts are determined using cross correlation techniques, which allow for the accurate measurement of time delays between signals.

Figure 7. (a) The ambient magnetic field \( X \) and the components \( Y \) and \( Z \) perpendicular to the ambient field at GOES 8 (see text for the definition of the coordinate system used). (b) Elevation angle of the magnetic field (see text for the definition). (c) The vertical axis indicates a dynamic signature at Polar prior to the onset (01:39 UT), followed by Figure 8e, the onset time defined from the Polar observations (01:44 UT, Figure 8f), and the beginning of a magnetic field variation perpendicular to the ambient field at GOES 8 (01:53 UT).
Figure 8. (a) The northward component at NAQ, (b) the 180-s delayed northward component at NAQ, (c) the 180-s delayed ambient field at GOES 8, (d) ULF/VLF electrons (17-200 keV), (e) H(1) electrons (0.1-20 keV), (f) measured magnetic field (dotted) deviation angle with respect to the elevation angle of the 199 model, (g) ambient magnetic field at Polar, (h) Y and (i) Z components of the perpendicular magnetic field at Polar, (j) XFLR and (k) ZECO components at Polar (the red curves show the low-pass filtered (7 mls) 180-s delayed signals), and (l) Parallel Polanyi flux (positive toward the ionosphere). The vertical lines indicate the onset time (01:14:23 UT) and the transient signature at 01:19:00 UT as determined from the ERI instrument (Figure 8a). See color version of this figure at back of this book.

8: Bx, By, Bz (Polar: Bx, Bz) and Bx (Polar: Bz) First, the signals were low-pass filtered based on the spectral analysis shown in Figure 1. Figure 12 shows cross-correlation as functions of lag time from the onset time. At Polar, By and Bx are uncorrelated with a phase shift of 35 s (lag time: 35 s), which can also be verified by computing the time series of Bx and By in Figures 8b and 8k. The correlation coefficients is 0.58. The ground response (detrended XFLR) is delayed by 171 s with respect to Bx at Polar (Figure 12; dotted line). In this case, the correlation coefficient is 0.63. The maximum correlation coefficient of Bx at Polar and Bx at GOES 8 is only 0.37 with time lag of 105 s (Figure 12; dotted line). Although the phase of these two signals are very similar to each other. With such a low correlation, the cross-correlation between detrended XFLR and Bx at GOES 8 is also shown in Figure 12 (dashed line). The maximum correlation coefficient of these two signals is 0.68 with time lag of 129 s. This implies that Bx at GOES 8 were delayed by 246 s from Bx at Polar. On the basis of these phase shifts, we conclude that the pulsations in the frequency range around 0.001 Hz at GOES 8 and on the ground at NAQ were delayed at least about 2 min from the pulsations observed at Polar.

4. Pulsations and Substorm Activity

[2] In order to interpret the presented observations, we seek answers to three questions: (1) how are the pulsations related to the auroral electron and substorm current wedge; (2) what is the spatial origin of the pulsations; and (3) what is the relation of the variations to the plasma sheet dynamics? [3] The activations at Polar occurred in very close proximity to the negative bay onset. Note that the use of ground magnetometers may introduce an uncertainty in the timing of the initial auroral brightening. A time lag between the magnetograms and the auroral break up can be introduced if the break up did not occur in the meridian of the magnetometer chain. As there were no global auroral images, this cannot be fully confirmed. On the basis of the midlatitude magnetometer data, the center of the upward FAC of the current wedge was located east of 101°W and west of 91°W, and the center of the current wedge was located west of 101°W during the early expansion phase. According to the observations of the SAMNET stations, the downward FAC of the current wedge was located west of 91°W at the SAMNET stations. These observations indicate that the current wedge was initiated around the meridian of the Greenland west coast stations.

[4] Furthermore, indirect evidence of Polar being magnetically conjugate with the auroral break up area can also be presented. As mentioned earlier, the large parallel Polanyi flux (positive toward the ionosphere) indicates strong auroral activity near the Polar atmosphere. For example, since large Polanyi fluxes on auroral field lines have been shown to be magnetically conjugate with bright auroral displays [Bytnerowicz et al., 2000], the magnetic conjugates (−25 nT) on the ground were a considerable fraction of the magnitude of the negative bay (−300 nT). The observations were closely related spatially to the auroral electrojet, which followed the poleward movement of the electrojet (Figure 3).

These considerations suggest that the pulsations were an integral part of the initiation of the substorm current wedge and the substorm onset.
We argue that the oscillations were initiated near the plasma sheet boundary rather than in the inner magnetosphere. According to the magnetic field model used (T99), the Polar field line mapped to $X_{\text{equ}} \approx -15.1 R_E$ during the substorm growth phase, the magnetic field configuration is more stretched than that of T99 (Pulkkinen et al., 1991), and mapping of the Polar field line even further in the tail might be expected. Such a mapping is supported by the HYDRA electron measurements, since, prior to the onset time, these measurements indicated that the plasma sheet was relatively thin at Polar, if compared to the extent of the plasma sheet after the substorm. The low electron flux observed by HYDRA indicate that Polar was located in the vicinity of the plasma sheet boundary. This conclusion is also consistent with the spacecraft potential measured by EPI. Toivanen et al. (2001b) noted a similar discrepancy in the location of the Polar field line in the midnight plasma sheet deduced from magnetic field mapping and from the particle measurements: according to the magnetic field mapping the Polar field line crossed the equatorial current sheet at $X_{\text{equ}} \approx -10 R_E$, whereas the particle measurements indicated that Polar was actually in the tail lobes. Furthermore, high-frequency electromagnetic oscillations and associated parallel Poynting fluxes similar to those in the event studied have typically been observed near or at the plasma sheet boundary during substorms (Kelling et al., 2000). These arguments suggest that the Polar field line mapped close to the distant X-line separating the tail lobes and plasma sheet.

The oscillations were not initiated in the inner magnetosphere. The amplitudes of the 6-mHz oscillations at Polar were larger by a factor of 10 than those observed at GOES 8. In principle, small amplitudes at GOES 8 could be explained if the node of the pulsations was located near GOES 8 at the magnetic equator. However, the exponential decay of the oscillations at Polar is more coherent than the waveform observed at GOES 8. Finally, the oscillations were first observed at Polar and only later at GOES 8. These arguments imply a radial propagation of these oscillations inward rather than outward. In addition, the elevation angle of the magnetic field at GOES 8 indicated that upward field-aligned current was located tailward of GOES 8. This indicates that the region of current disruption and the substorm current wedge were located outside the geosynchronous orbit.
5. Summary and Discussion

We presented observations from the Polar spacecraft of large-amplitude transverse electromagnetic 6-mHz oscillations in the high-altitude plasma sheet in association with a laminar substorm onset on 10 October 1999. In addition to the Polar observations, we used the Greenwood west coast magnetometer chain and the GOES 8 spacecraft. Polar was magnetically conjugate with the Greenland chain, and GOES 8 was located 2 hours west of the chain. The observational geometry is shown in Figure 5. The rich database allowed us to (1) study the spatial origin of the pulsations in the magnetotail, (2) determine the timing of the pulsations relative to negative bay onset and other substorm signatures, and (3) relate the pulsations to the plasma sheet dynamics. The key observations can be listed as the following:

[1] At 01:30:00 UT a dynamic signature was observed at Polar including weak variations of electric and magnetic field and associated Peary flux parallel to the ambient magnetic field. Also the high-energy electron fluxes increased slightly. Importantly, the ambient magnetic field started to decrease at Polar and GOES 8 and decreased continuously until the substorm onset, indicating that the signature was not transient.

[2] At 01:44:23 UT the first signatures of the wave activity were observed at Polar. Polar was located near the plasma sheet boundary, 6-mHz oscillations with peak amplitudes of 10 nT and 20 mV/m were identified. These oscillations were transverse and polarized as BB | Y (toroidal). Oscillations with frequencies of 18 mHz on higher were superimposed on the 6-mHz oscillations driving parallel Peary flux predominantly toward the ionosphere. On the ground, a negative bay with a magnitude of 300 nT was initiated at NOAQ. About 2 min later, 6-mHz oscillations with an amplitude of 50 nT was embedded in...
the developing auroral electroat. Also at GOES 8, the magnetic field showed oscillations primarily at frequencies of ~6 mHz (compositional) and 14 mHz (nonsinusoidal). The 6-mHz oscillations started about two minutes after the timing of the wave front at Pola. The SAMSNET stations west of Greenland at HIL and FAR showed a negative bay and bulk of Pi2 pulsations (~17 mHz) starting at about 01:46.30 UT. Together with the HIL and Faro, the STJ and STI, SAMSNET stations indicated that the center of the substorm current wedge was located near the Greenland west coast channel. This indicates the auroral activity at the Polar foot point. At GOES 8 or on the ground, no dynamic signature was identified.


Our interpretation of the key observations is in accordance with the predictions of the NENL model. According to this model, reconnection of the tail lobe magnetic fields opens fast earthward flows and the braking of the fast flows is the inner magnetosphere at the interface of the dipolar and tail-like magnetic fields drives field-aligned currents of the substorm current wedge. During the expansion phase the region of dipolar field configuration has been expected to expand tailward [e.g., Baker et al., 1996]. The timing of various signatures was consistent with the prediction of the NENL model. Most notably, the pulsations were first observed near the plasma sheet boundary and later on the ground and at the geostationary orbit. Moreover, the expansion of the region of enhanced electron flux past the Polar location (~3 min after the wave activity started at Polar indicates that the pulsations are generated in the near geomagnetic field line. The simultaneous observation of auroral proton emissions at STJ and the boundary and the outflow propagating boundary of the enhanced plasma sheet electron fluxes and peaks Poynting flux. The basis of these considerations on the spatial origin of the pulsations, we associated the pulsations with the magnetic reconnection, the subsequent Earthward flows, and braking of these flows.

[3] Here, we suggest that under some magnetospheric conditions, the braking of the earthward flow and the diversion of the cross-tail current from the braking region do not occur monoviscosely. In other words, the process of the flow braking is not current driven but may involve periodic fluctuations in the strength of the diverted current depending, for example, on the ionospheric conditions controlling the dissipation. Thus it can be consistent with the generation mechanism of the observed pulsations could be distinct from the generation mechanism of Pi2 pulsations. Note, for example, that the frequency of the Pi2s at FAR (17 mHz) were clearly higher than that of the Pi2 pulsations (6 mHz). The oscillations of the flow braking process may have then resulted in compressional waves that were then observed at GOES 8 with the same frequency. The frequency of the waves at GEOS 8 similar to the observation that at Polar can be attributed to the behavior of the compression and toroidal waves: the compressional waves such as Pi2s in the inner magnetosphere are known to exhibit a constant frequency over a wide L range, whereas the frequency of toroidal waves varies with L. [Yakushin et al., 1996].

[4] Long-period waves are often associated with propagated substorm onset mechanisms in the near-Earth region including those based, for example, on the ballooning instability [Oran et al., 1991]. Such association can, however, be biased, because the observations in the near-Earth tail are more frequently acquired near the equator than in the high-latitude plasma sheet. For example, according to statistical results of Sakaout and McPherson [1983], magnetic pulsations in the Pi2 frequency range at geostationary distances can be classified primarily by two types of pulsations: (1) a wave with a significant compressional component and (2) a pure transverse wave in the geomagnetic component. The oscillations studied here fall into the second category. Sakaout and McPherson [1983] concluded that the pure transverse waves are quite rare, while the compressional wave occurs during almost every substorm. In fact, in one of their example events, the toroidal pulsations occurred when the magnetic field was directed almost radially inward (elevation angle of 22°), which is a very tail-like field configuration at the geosynchronous orbit. Under such field conditions the field line of a geosynchronous spacecraft may map far beyond geostationary distance, in which the pulsation peaks. Thus it was the case with Polar during the event studied. The occurrence of the studied pulsations at geosynchronous spacecraft may roughly correspond to the occurrence of high-energy particle drops at such spacecraft.

[5] The results and suggestions presented in this paper are based on a single event. However, on the basis of lat-e Haider Kushner and Nakajima for their assistance in evaluating this paper.

References


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Figure 1. Deflections of the horizontal (a) north-south and (b) east-west, and (c) vertical magnetic field CGM components as functions of CGM latitude and time (CGM, Corrected Geomagnetic). The magnitudes were interpolated in the latitude range of the Greenland west coast stations. At 0144:23 (vertical line), Polar observed the first dynamical signatures (defined in Figure 8c) associated with the ground onset.
Figure 8. Overview of (a) high-energy electrons (17-200 keV), (b) plasma sheet electrons (0.1-20 keV), and (c) spacecraft potential as observed by CEPAP/VEES, HYDRA, and E/SS, respectively.
Figure 8. (a) The northward component at NAQ, (b) the 180-s detrended northward component at NAQ, (c) the 180-s detrended ant crossings at GOES 8, (d) CEPPAD electrons (17-200 keV), (e) HYDRA electron (0.1–20 keV), (f) measured magnetic field elevation angle with respect to the elevation angle of the T99 model, (g) ambient magnetic field at Polar, (h) Y and (i) Z components of the perpendicular magnetic field at Polar, (j) X_{Polar} and (k) Z_{Polar} components at Polar (the red curves show the low-pass filtered (<7 mHz) 180-s detrended signals), and (l) Parallel Bolding flux (positive toward the ionosphere). The vertical lines indicate the onset time (01:14:23 UT) and the transient signature at 01:30:00 UT as determined from the IMF environment (Figure 6).