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Magnetospheric responses to sudden and quasiperiodic solar wind variations

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[1] On April 13 (day 103), 2001, 0700–1400 UT, the Polar satellite experienced different plasma regimes (i.e., magnetosphere, magnetosheath, and solar wind) because of the solar wind dynamic pressure variations and its high orbital inclination near the subsolar magnetopause meridian. When Polar was in the magnetosheath, quasiperiodic spacecraft potential (SP) variations, corresponding to density variations, with a recurrence time of ~3–10 min were observed. Using simultaneous solar wind observations, it was confirmed that the magnetosheath SP variations were inherent in the solar wind. We observed an almost one-to-one correspondence between the SP variations and the geomagnetic field perturbations at lower latitudes (L = 1.1–2.8) on the nightside. At higher latitudes (L = 2.9–6.1) on the dayside, however, the field perturbations are more complicated than the magnetosheath SP variations. This suggests that if the magnetospheric perturbations produced by the external source (solar wind/magnetosheath pressure variations) deeply penetrate into the magnetosphere, the lower-latitude data on the nightside are important to monitor the external source variations. In addition, we observed the radial electric field oscillations excited nearly simultaneously with the magnetic field enhancement, associated with a sudden increase in the solar wind dynamic pressure, when Polar was in the magnetosphere. These oscillations may be considered as transient standing Alfvén waves excited by externally applied pressure changes as reported by previous studies. *INDEX TERMS:* 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; 2752 Magnetospheric Physics: MHD waves and instabilities; 2728 Magnetospheric Physics: Magnetosheath; 2724 Magnetospheric Physics: Magnetopause, cusp, and boundary layers; *KEYWORDS:* magnetosphere, solar wind, spacecraft potential, magnetosheath, magnetospheric response

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1. Introduction

[2] Identification of the source mechanisms is one of the critical topics in studies of magnetospheric pulsations. It has been generally accepted that solar wind or magnetosheath pressure (i.e., external pressure) variations are an obvious candidate for the origin of geomagnetic pulsations [e.g., *Korotova and Sibeck*, 1994, 1995; *Matsuoka et al.*, 1995]. The external pressure variations have been divided into two types: sudden and quasiperiodic changes. If sudden and/or step-like increases in the solar wind dynamic pressure hit the magnetopause, the magnetosphere is compressed and broadband fast mode waves may be launched because of the impulsive nature of the source. Observations suggest that such fast mode waves couple to local standing Alfvén waves [*Kaufmann and Walker*, 1974; *Baumjohann et al.*, 1984; *Laakso and Schmidt*, 1989], which are characterized by an azimuthal magnetic field oscillation and a radial electric field oscillation, through the field line resonance process. The theoretical description of the coupling process is well established for a monochromatic source [*Chen and Hasegawa*, 1974; *Southwood*, 1974] and for an impulsive (i.e., broadband) source [*Hasegawa et al.*, 1983; *Kivelson and Southwood*, 1985]. If the standing Alfvén waves excited by broadband source are detected at radially separated points in the magnetosphere, different frequencies will be observed at different locations because the frequencies of the standing Alfvén waves depend on magnetic field

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Table 1. List of SAMNET Ground Magnetometer Stations

		Geographic		Geomagnetic		
Station	Code	Latitude, deg	Longitude, deg	Latitude, deg	Longitude, deg	L
Kilpisjarvi	KIL	69.0	20.8	65.8	104.6	6.1
Faroes	FAR	62.1	353.0	60.8	78.1	4.3
Hankasalmi	HAN	62.3	26.7	58.6	105.2	3.8
Borok	BOR	58.0	38.3	53.9	113.7	2.9

strength, plasma mass density, and the length of the field line at the observing point. Step-like changes in the solar wind dynamic pressure result in bipolar magnetic field variations at high latitude and simple step function increases at low latitude in the horizontal (H) component, called sudden commencements (sc) if a geomagnetic storm follows and sudden impulse (si) events otherwise [e.g., *Wilson and Sugiura*, 1961]. The propagation properties and field variations of sc and si have been extensively investigated by several authors [*Araki*, 1994; *Petrinec et al.*, 1996; *Lee and Hudson*, 2001; *Chi et al.*, 2001].

[3] When the external pressure changes periodically in a sinusoidal manner, the magnetopause is driven at the same period and the magnetospheric field will be perturbed by the magnetopause motions. Quasiperiodic external pressure variations on time scales of several minutes have been reported by *Sibeck et al.* [1989], *Sibeck* [1994], and *Fairfield et al.* [1990]. Such time scales are in the Pc5 (period = ~150–600 s) range. Previous studies using data on the ground and in space showed that solar wind dynamic pressure variations directly drive Pc5-band pulsations [*Korotova and Sibeck*, 1994, 1995; *Matsuoka et al.*, 1995]. However, it should be noted that quasiperiodic external pressure variations are not always intrinsic solar wind phenomena. *Fairfield et al.* [1990] reported that, even in the absence of solar wind dynamic pressure variations, magnetopause motions can be produced by upstream pressure variations associated with the bow shock. Quasiperiodic magnetopause motions can also be associated with the Kelvin-Helmholtz (K-H) instability on the magnetopause, and the instability has been considered as the source of Pc5 pulsations [e.g., *Ohtani et al.*, 1999].

[4] A number of recent papers have reported high-latitude ground-based observations of discrete frequencies (1.3, 1.9, 2.6, 3.4 and 4.2 mHz) in the Pc5 range [e.g., *Samson et al.*, 1991, 1992a, 1992b; *Ruohoniemi et al.*, 1991; *Mathie et al.*, 1999; *Mathie and Mann*, 2000]. Such low-frequency pulsations have been reported even at a low-latitude (L = 1.6) station [*Francia and Villante*, 1997]. The discrete-Pc5 pulsations have been interpreted by field line resonances, driven by a magnetospheric waveguide formed between the flankside magnetopause and internal turning points within the magnetosphere [e.g., *Harrold and Samson*, 1992; *Samson et al.*, 1992b]. However, some ground pulsations in the frequency band of ~1–5 mHz may be directly related to intrinsic solar wind structure rather than to the waveguide mode because solar wind pressure fluctuations directly drive magnetospheric pulsations. Therefore, it is important to examine the solar wind conditions at times when the magnetic pulsations are observed on the ground.

[5] In this paper we mainly focus on the magnetospheric responses to the spacecraft potential variations in the magnetosheath observed by Polar. Although it is well known that the spacecraft potential can be used as a good indicator of the ambient plasma density and the spacecraft potential have been used to identify plasma regimes near the magnetosphere [e.g., *Pedersen*, 1995], there are no observations of the magnetospheric responses to the magnetosheath spacecraft potential variations to the authors' knowledge. On the orbit selected for study quasiperiodic spacecraft potential variations were observed in the magnetosheath. We show an almost one-to-one correspondence between the spacecraft potential variations and geomagnetic field perturbations at low latitudes. This is consistent with a previous study [*Russell et al.*, 1992] that suggested ground field variations at low latitudes are dominated by magnetopause motions corresponding to solar wind dynamic pressure changes.

[6] The organization of this paper is as follows. Section 2 briefly describes the data sets used in this study. Section 3 presents observations and describes data analysis. In section 4 we briefly discuss the magnetospheric response to quasiperiodic external pressure variations. Section 5 gives the conclusions.

2. Data Sets

[7] The Polar data examined in this study consist of the spin averaged (~6 s) electric field [*Harvey et al.*, 1995] and magnetic field [*Russell et al.*, 1995] data. Polar is in a highly elliptical orbit, with an apogee of ~9 R_E, initially over the north pole. Since its launch in 1996, the orbit has precessed towards the equator by about 75 degrees (15 degrees per year). In April 2001, the apogee was nearly on the subsolar geomagnetic meridian plane.

[8] We compare the Polar data with the magnetic field data from the GOES satellites and ground stations. The geostationary GOES 8 and 10 satellites are located at geographic longitudes of ~76°W and ~135°W, respectively. The original high time resolution (0.512 s) magnetic field data were averaged down to the same resolution (5 s) as the ground station data. We used data from eight ground stations: four from the U.K. Subauroral Magnetometer Network (SAMNET) [*Yeoman et al.*, 1990] and four from the network of stations located near the 210° magnetic meridian (210MM) [*Yumoto et al.*, 1996]. The locations of the SAMNET and 210MM ground stations are listed in Tables 1 and 2, respectively. Data from all ground stations were resampled at 5-s intervals after averaging the original 1 second data.

[9] The solar wind and interplanetary magnetic field (IMF) data were measured by the Wind, ACE, and Cluster satellites. The key parameter Wind (~94 s for the solar wind experiment and ~46 s for magnetic field) and ACE (~64 s

Table 2. List of 210MM Ground Magnetometer Stations

		Geographic		Geomagnetic		
Station	Code	Latitude, deg	Longitude, deg	Latitude, deg	Longitude, deg	L
Tixie	TIX	71.6	128.8	65.7	196.9	5.9
Magadan	MGD	60.0	150.9	53.6	218.7	2.8
Moshiri	MSR	44.4	142.3	37.6	213.2	1.6
Biak	BIK	−1.1	136.1	−12.2	207.3	1.1

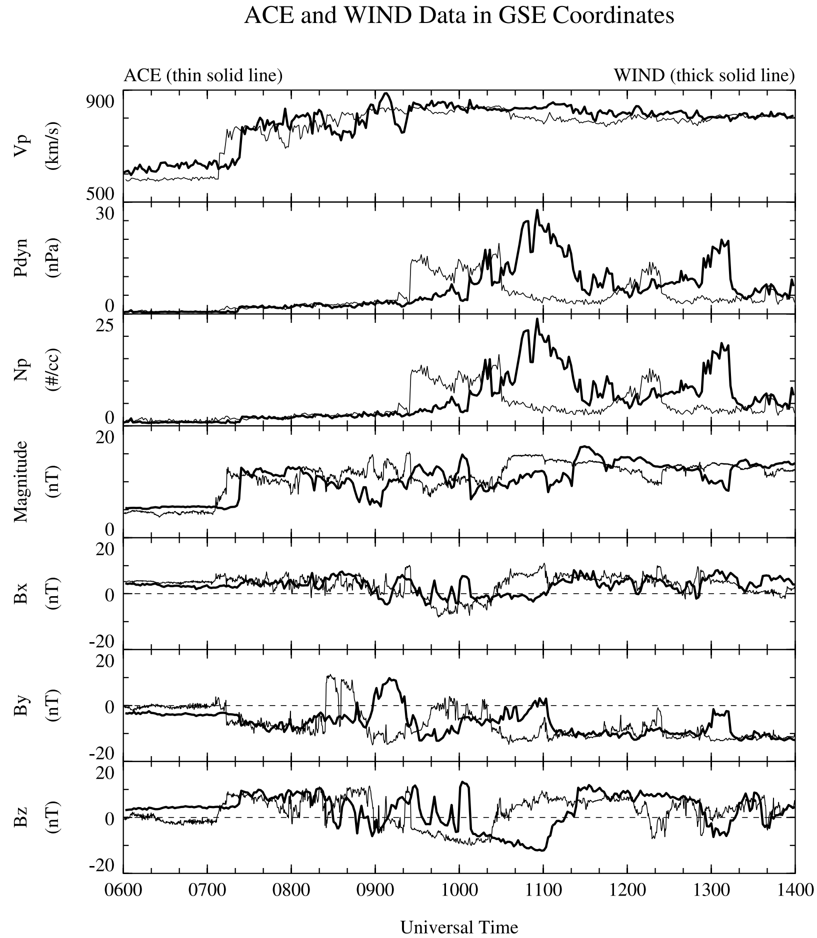

Figure 1. Wind and ACE solar wind observations in GSE coordinates.

for solar wind experiment and ~16 s for magnetic field) data were obtained from the CDAWeb data service (http://rumba.gsfc.nasa.gov/cdaweb/). During the time interval studied, the magnetic field data from Cluster had large data gaps. We only use the spin averaged (~4 s) spacecraft potential data [*Gustafsson et al.*, 1997] from Cluster to compare with the Polar observations.

3. Observations

3.1. Solar Wind Observations

[10] Figure 1 shows the upstream solar wind conditions observed by ACE and Wind from 0600 to 1400 UT. The seven panels illustrate the solar wind velocity, dynamic pressure (nMV^2), density, and the IMF in GSE (geocentric solar ecliptic) coordinates. During the time interval Wind moved from GSE (x, y, z) ~ (4.2, −263.4, −1.1) to (4.3, −263.6, −1.2) R_E, while ACE was located near GSE (x, y, z) ~ (221.5, −6.5, −20.3) R_E. ACE and Wind detected the passage of an interplanetary discontinuity (i.e., sudden increases in the solar wind speed, density, and the IMF strength) near 0706 and 0722 UT, respectively. The propagation time of the solar wind discontinuity from ACE to Wind is ~10 min which suggests that the discontinuity front was tilted from the Sun-Earth axis by ~60°. We note that the steep field variation near 0712 UT at ACE was used to determine the discontinuity arrival time.

[11] Wind observed large increases in the solar wind dynamic pressure during the intervals, 0940–1115 UT and 1250–1315 UT, mainly due to density variations. During both intervals the IMF strength decreased. That is, the large-scale density and field fluctuations in the solar wind are anti-correlated with each other. These signatures indicate a balance between the thermal and magnetic pressures in the solar wind [*Burlaga and Ogilvie*, 1970; *Vellante and Lazarus*, 1987; *Roberts et al.*, 1987]. At ACE the large-scale anti-correlation between the density and field were also observed for the enhanced dynamic pressure intervals. However, IMF and plasma data observed at ACE are different from those observed at Wind. This may be due to the Wind location, 263 R_E transverse to the Sun-Earth line.

[12] During the period from 0600 to 1400 UT, the four Cluster satellites were just upstream of the bow shock and moved from GSE (x, y, z) ~ (14.9, −11.9, 3.6) to (13.8, −13.4, −0.7) R_E. The four satellites observed nearly identical variations in spacecraft potential (hereafter referred to as SP), corresponding to density variations [*Pedersen*, 1995]. A comparison of the SP variations in the solar wind and in the magnetosheath will be shown in next section.

3.2. Polar Observations

[13] Figure 2 illustrates the Polar, GOES 8, and GOES 10 orbits in SM (solar magnetic) coordinates for 0700–1400

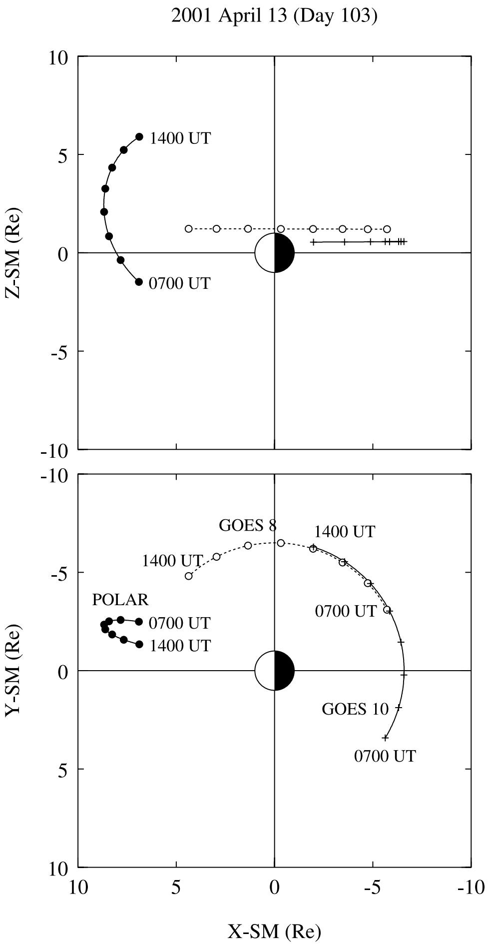

Figure 2. The trajectories of Polar (solid circles), GOES 8 (open circles), and GOES 10 (crosses) for the time interval from 0700 to 1400 UT, April 13, 2001. The orbits are projected onto the solar magnetic (upper panel) *x-z* and (lower panel) *x-y* plane.

UT on April 13 (day 103), 2001. During this 7-hour interval, Polar crossed L shells between ~8 and ~16 near the subsolar magnetic meridian (magnetic local time (MLT) = ~10.7–11.3), moving from $-11°$ to $40°$ magnetic latitude and from 7.5 to 9.2 R_E geocentric distance. The small local time variation for this time interval indicates that the Polar orbital plane is nearly parallel to a magnetic meridian plane.

[14] Figure 3 shows the magnetic field, SP, and electric field data observed by Polar for the time interval of Figure 2 (vector quantities are in GSE coordinates.). The SP is a balance between the photoelectron current from the spacecraft and the incoming thermal electron current from the plasma in the region where both currents are dominant current sources. The SP is inversely proportional to $\ln(nT^{1/2})$, where n is the plasma density and T is the electron temperature, and can be used as a good indicator of the ambient plasma density [e.g., *Pedersen*, 1995]. Note that SP is plotted positive downward. This is similar to a logarithmic plot of the plasma density, i.e., larger (smaller) values indicate lower (higher) densities. Polar was initially in the magnetosphere as indicated by the strongly northward magnetic field and moved into the magnetosheath after the magnetopause crossing near 0938 UT (marked by the vertical dashed line), identified by the southward rotation of the magnetic field. While approaching the magnetopause from the magnetosphere, Polar observed transient SP enhancements, in some cases up to ~10 V. These transient increases in SP may be interpreted as a brief satellite entry into the inner low-latitude boundary layer (LLBL) [*Kim et al.*, 2001b]. During the interval of 0938–1400 UT, Polar was in the magnetosheath and entered the solar wind (marked by the horizontal bars in the total magnetic field panel) several times after crossing the bow shock. The solar wind region is clearly distinguishable from the magnetosheath region by inspection of the magnetic field, which has a smaller magnitude and is less variable.

[15] In the magnetosphere Polar observed a sudden increase in the magnetic field intensity at ~0733 UT (indicated by the vertical dotted line), which is caused by the inward motion of the magnetopause as a result of an increase in the solar wind dynamic pressure observed at ACE near 0706 UT and at Wind near 0722 UT, respectively (see Figure 1). The sudden field enhancement was accompanied by a sudden decrease in SP, corresponding to density increase. The in-phase field and density changes would be explained in terms of a fast-mode nature of this event. The magnetic field strength remained enhanced until the satellite crossed the magnetopause, indicating that Polar was in the compressed magnetosphere. In the E_x component an ~8-min oscillation started just after the magnetic field enhancement and disappeared as the satellite approached the magnetopause. There are two large spikes near 0840 UT in the E_x component when the SP suddenly increased. They may be due to the transient satellite entry into the boundary layer. The ~8-min oscillation is also seen in the E_y component, but with a smaller amplitude than that in E_x. In the B_y component, there is an oscillation starting after the magnetospheric compression, but its period was much higher than the E_x oscillation. Similar fluctuations can barely be seen in the B_x and B_z components.

[16] To separate the field perturbations into the transverse and compressional components, the Polar field data have been rotated into mean-field-aligned coordinates in which $\hat{e}_z$ is along the averaged magnetic field defined by taking the 5-min boxcar running averages of the ~6-s data, the azimuthal direction $\hat{e}_y$ is parallel to $\hat{e}_z \times \mathbf{r}$, where $\mathbf{r}$ is the spacecraft position vector with respect to the center of the Earth, and the radially outward component is given by $\hat{e}_x = \hat{e}_y \times \hat{e}_z$. Figure 4 shows the field perturbations in the magnetosphere and the power spectra for the interval from 0730 to 0820 UT. The periodic oscillations are clear in the azimuthal (B_{yMFA}) magnetic field and radial (E_{xMFA}) electric field components. The B_{yMFA} and E_{xMFA} oscillations produce dominant spectral bands at ~6.5–7.5 mHz and ~1.3–2.8 mHz, respectively. Standing Alfvén waves are characterized by field perturbations in the azimuthal magnetic field and radial electric field [*Cahill et al.*, 1986]. Previous studies have reported the excitation of the standing Alfvén waves just after the magnetospheric compression [e.g., *Baumjohann et al.*, 1984; *Laakso and Schmidt*, 1989]. Therefore, we consider the dominant spectral bands in the radial electric field component and the azimuthal magnetic field component as the fundamental and second mode standing Alfvén waves, respectively, in terms of the polarization of

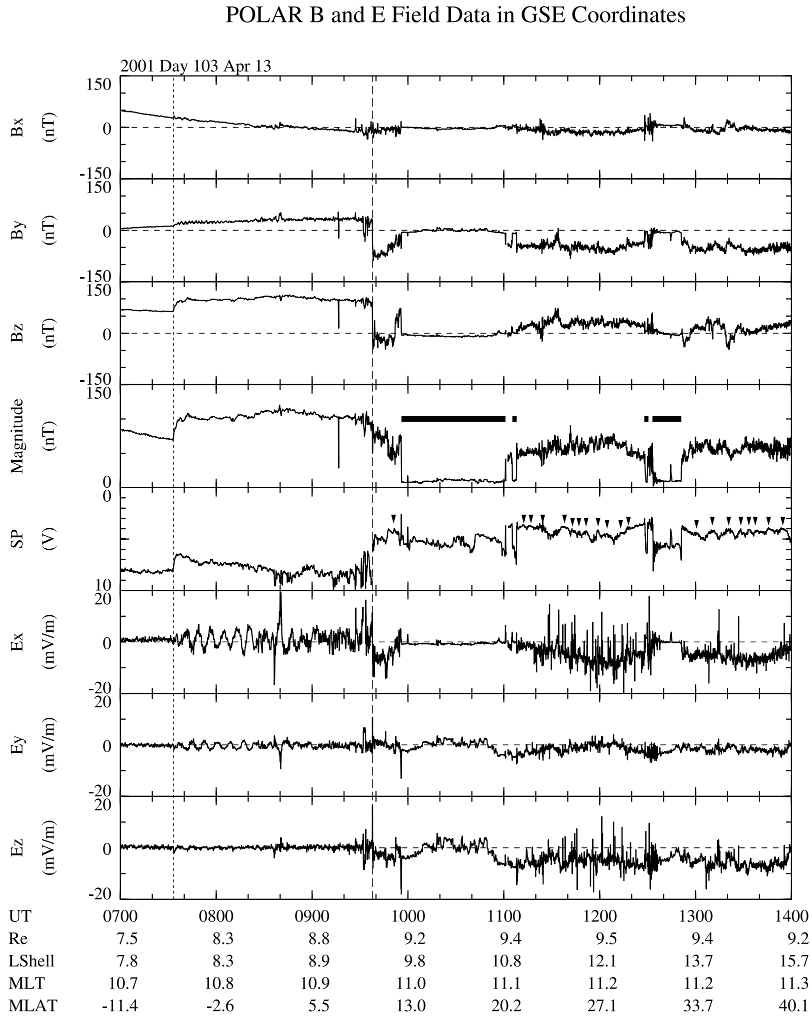

Figure 3. Polar magnetic field, spacecraft potential (SP), and electric field. Components are plotted in GSE coordinates. Satellite position is indicated at the bottom. SP is plotted positive downward. The vertical dotted and dashed lines indicate the onset time of the magnetic field enhancement and the magnetopause crossing, respectively. The solid bars indicate the time intervals of the solar wind entries. The arrow heads in the SP panel indicate the smallest value of SP.

the pulsations. Since the fundamental (second) mode has a magnetic field node (antinode) and an electric field antinode (node) at the magnetic equator, Polar near the magnetic equator may be missed the fundamental mode in the magnetic field data and the second mode in the electric field data.

[17] Figure 3 also shows that Polar observed quasiperiodic SP perturbations in the magnetosheath. The smallest value of SP perturbations are marked by the arrowheads in the SP panel. Some of the SP perturbations showed in-phase oscillations with the magnetosheath magnetic field strength as plotted in Figure 5, indicating the field strength oscillated out of phase with the plasma density. The density fluctuations in the magnetosheath have been reported previously and interpreted in terms of standing slow-mode waves near the magnetopause [*Song et al.*, 1990, 1992] or convected slow-mode waves generated at the bow shock [*Seon et al.*, 1999]. Another possible source of the magnetosheath density fluctuations is transmission of fluctuations in the solar wind through the bow shock.

[18] In order to compare the observations in the solar and in the magnetosheath, the density from ACE, SP from Cluster satellite 3, and SP from Polar are plotted in Figure 6. The ACE data have been lagged by a constant time delay by 28 min. We can confirm that the SP variations observed by Polar in the magnetosheath (marked by the horizontal bars) are very consistent with those in the solar wind observed by Cluster. These observations provide that the SP variations (i.e., density variations) in the magnetosheath originate in the solar wind. The key parameter density data ($\sim$64 s) from ACE also showed variations roughly similar to the SP variations in the magnetosheath for the intervals, $\sim$0940–0955 UT and $\sim$1250–1400 UT.

[19] Returning to Figure 3, the averaged magnetosheath field strength increased gradually until around 1209 UT after the inbound (from the solar wind to the magnetosheath) bow shock crossing at $\sim$1108 UT and then the field strength decreased until near the outbound (from the magnetosheath to the solar wind) bow shock crossing at $\sim$1228 UT. After

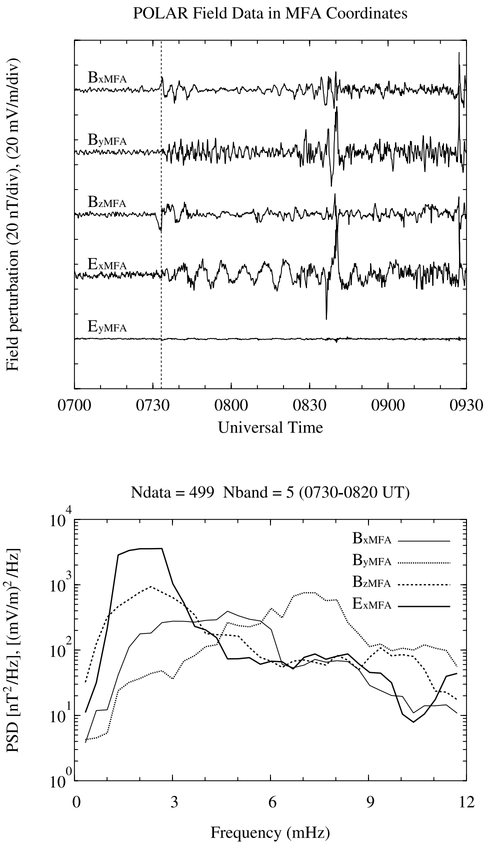

Figure 4. Polar magnetic and electric field perturbations in MFA coordinates (upper panel). Power spectra of Polar magnetic and electric field components for the time interval of 0730–0820 UT (lower panel).

the inbound bow shock crossing at ~1251 UT, the sheath field strength increased again until around 1306 UT. These large-scale field fluctuations in the magnetosheath also showed in-phase variations with SP.

3.3. Geosynchronous Magnetic Field Observations

[20] Figure 7 exhibits 5-s averaged magnetic field data from GOES 8 and GOES 10 for the 7-hour interval studied in this paper. The magnetic fields are presented in dipole VDH coordinates, where V is perpendicular to the magnetic dipole axis and is radially outward, D is magnetically eastward, and H is antiparallel to the dipole (northward). During this time interval, GOES 8 (MLT = UT − 5.0 hours) moved from 0200 to 0900 MLT and located near ~10.5° magnetic latitude, and GOES 10 (MLT = UT − 9.0 hours) moved from 2200 to 0500 MLT and near ~4.8° magnetic latitude, as shown in Figure 2. Unlike the Polar observation near the subsolar magnetospheric region, the magnetic field strength (BT) observed at the GOES satellites on the nightside decreased slightly after the magnetospheric compression at 0733 UT (marked by the vertical dotted line). This may be due to a tail current variation, caused by the change of the solar wind dynamic pressure [e.g., *Rufenach et al.*, 1992; *Matsuoka et al.*, 1995].

[21] For the time interval from 0733 to 0956 UT, GOES 8, which moved from ~2.5 to ~5.0 MLT, observed four wave packets starting at ~0734, ~0827, ~0905, and ~0930 UT in the transverse (azimuthal) BD component, whereas the BD perturbations for four wave packet intervals at GOES 10, located near midnight, were not as clear as at GOES 8. The wave packets at GOES 8 have spectral peaks near ~6 mHz (data not shown). As GOES 10 moved toward dawn, quasiperiodic oscillations were observed in BD, but their periods were much longer than those of the four wave packets at GOES 8.

[22] Figure 8 shows a comparison of the radial electric field perturbations at Polar and the azimuthal magnetic field perturbations at GOES 8 and 10 in mean-field-aligned coordinates with the solar wind dynamic pressure variations observed by the Wind satellite. The Wind data have been lagged by a constant time delay of 12 min. The first and second wave packets at GOES 8 are associated with the solar wind dynamic pressure increases. These suggest that the source of the azimuthal oscillations at GOES 8 is on the

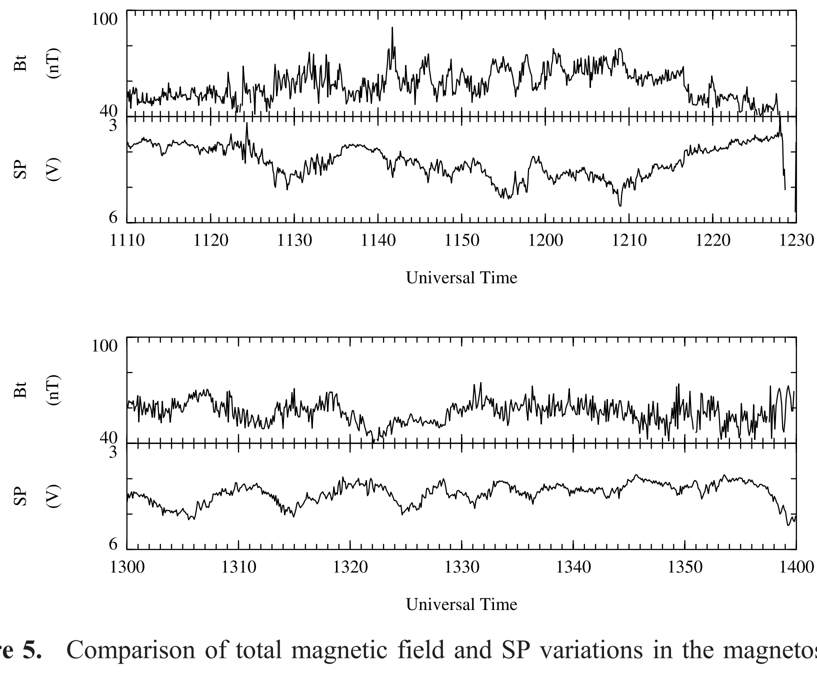

Figure 5. Comparison of total magnetic field and SP variations in the magnetosheath.

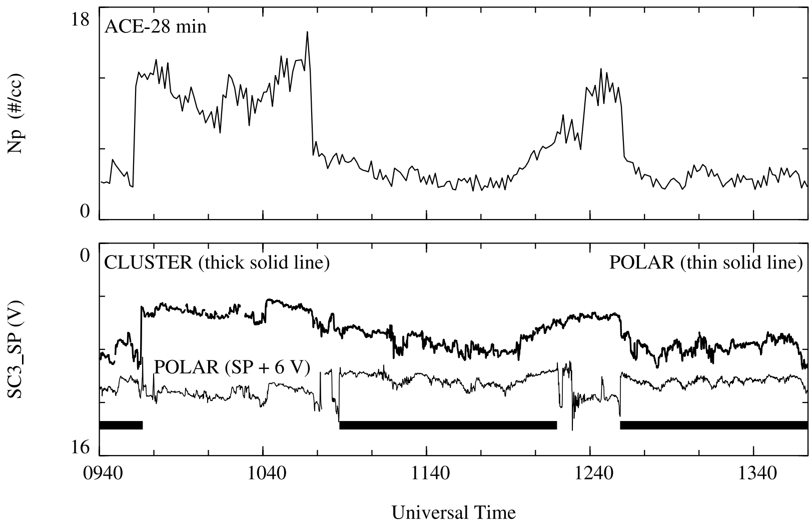

Figure 6. (top) Solar wind density observed at ACE. The AEC data were lagged 28 min. (bottom) Cluster (thick line) and Polar (thin line) spacecraft potential data. The horizontal bars indicate the time intervals when Polar was in the magnetosheath.

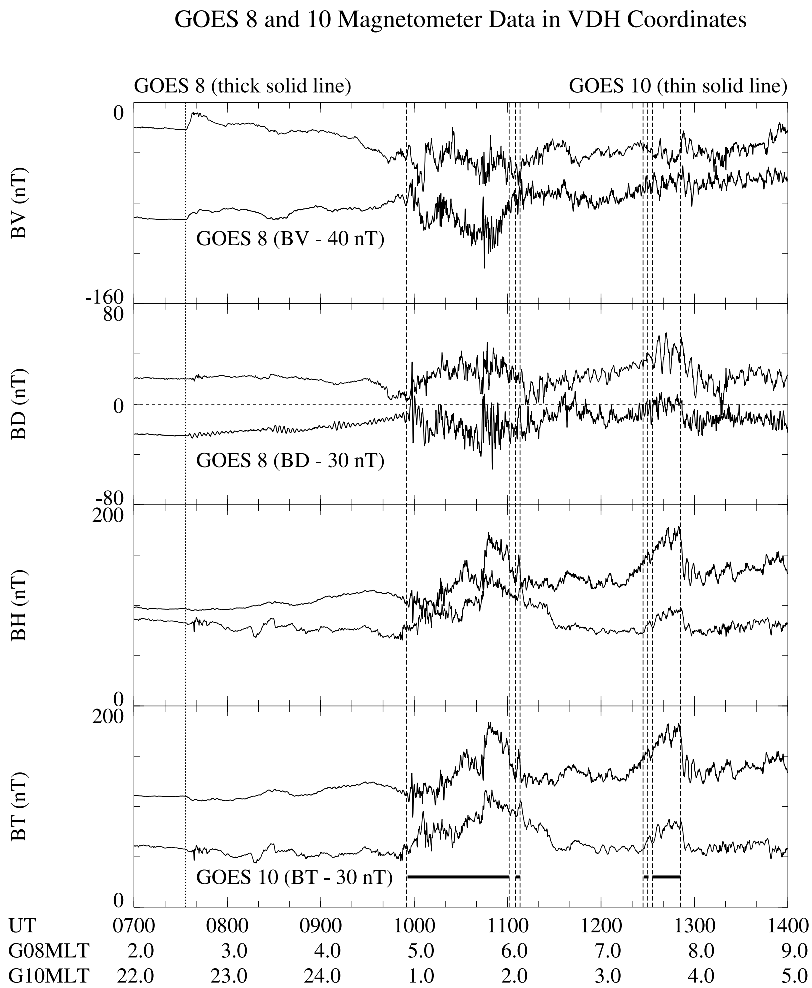

Figure 7. Magnetic field data measured on GOES 8 and 10 during the interval 0700–1400 UT in VDH coordinates. The vertical dotted and dashed lines indicate the time of the magnetic field enhancement and the bow shock crossings by Polar. The horizontal bars in the bottom panel indicate the time intervals of the solar wind entries of Polar.

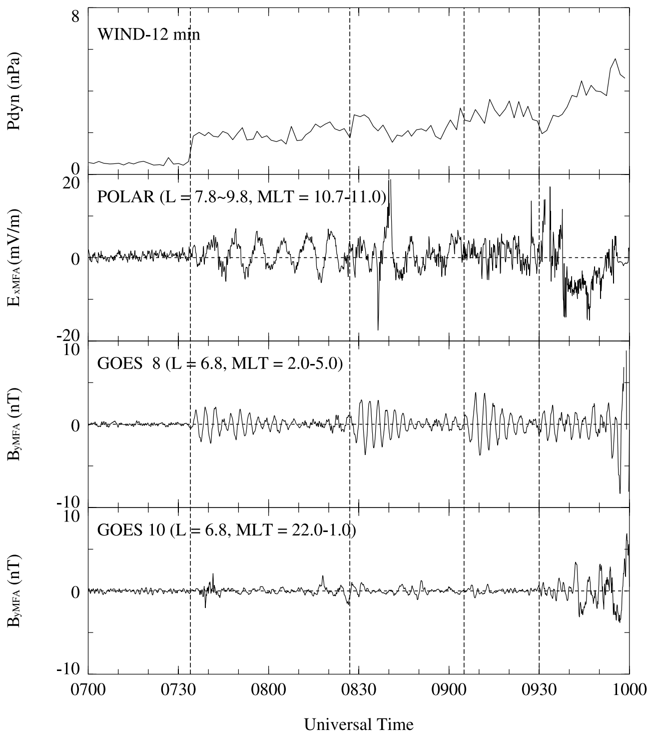

Figure 8. (top to bottom) Solar wind dynamic pressure observed at Wind. Polar electric field perturbation in the radial component. GOES 8 magnetic field perturbation in the azimuthal component. GOES 10 magnetic field perturbation in the azimuthal component. The vertical dashed lines indicate the onset times of the azimuthal oscillations at GOES 8.

dayside. We suggest, therefore, that the generation mechanism of the transverse oscillations at GOES 8 is the same as that of the radial electric oscillations at Polar, that is, toroidal mode waves excited by the external pressure changes. Although there were no clear sudden changes in the solar wind dynamic pressure corresponding to the third and fourth wave packets, the radial electric field perturbations at Polar were changed at the time when the third and fourth wave packets started (i.e., sudden disappearance of quasiperiodic oscillations for the third and sudden large electric field enhancement for the forth). These signatures may be attributed to the satellite's entry into the boundary layer and magnetosheath, respectively, because of inward magnetopause motions. Thus, the third and fourth azimuthal oscillations at GOES 8 would be associated with the dayside source rather than the nightside source [*Takahashi et al.*, 1996; *Kim et al.*, 2001a].

[23] It should be noted that the field perturbations at Polar and GOES 8 were excited nearly simultaneously after the onset of the magnetospheric compression at 0733 UT although GOES 8 was located on the nightside. This can be interpreted in terms of a source location and fast-mode speed from source to each satellite. As mentioned above, the discontinuity front in the solar wind was tilted by ~60° to the Sun-Earth axis. This indicates that the discontinuity front first hits on the morningside magnetopause (LT = ~0800–1000). If we assume that the magnetopause on that region is located at 13 R_E from the earth, Polar and GOES 8 were ~6.6 and ~15.4 R_E, respectively, away from the source region. If fast-mode wave propagates radially from the source region, the average fast-mode speed from source to GOES 8 is larger than that from source to Polar by a factor of ~2.3. These average propagation speeds are not far from the empirical model of fast-mode wave speed [*Moore et al.*, 1987]. However, we note that the above argument should not be taken too literally because the fast mode speed varies greatly in the magnetosphere.

[24] Returning to Figure 7, the magnetic fields at both GOES satellites were strongly disturbed for the interval from ~1000 to 1400 UT, and their strengths increased for the intervals of the Polar entries into the solar wind (marked by the horizontal bars). Some of the field perturbations may correspond to the magnetopause motions associated with the external pressure variations. We will compare them with the SP data at Polar and ground magnetic field data below.

3.4. Ground Observations

[25] Figure 9 shows 5-s averaged samples of the *H* (northward) component of the magnetic field observed at the SAMNET and 210MM stations. At the time of the magnetospheric compression, ~0733 UT, the SAMNET stations were on the morningside, while the 210MM stations were around afternoon. At the low-latitude (MSR and BIK), mid-latitude (BOR and MGD), and high-latitude (KIL, TIX, FAR, and HAN) stations, there is a change in the *H*-component of the magnetic field at the onset of the magnetospheric compression. Three wave packets, starting at ~0734, ~0826, and ~0907 UT, are seen in the *H* component at FAR. These could be interpreted as a field line resonance at FAR because the oscillations are only enhanced at FAR and their periods are different from the periods of the magnetic field oscillations at other SAMNET stations. The onset times of the oscillations are very close to those of the transverse oscillations at GOES 8.

[26] When the bow shock crossings were observed by Polar (marked by the horizontal bars in the upper panel of Figure 9), the magnetic fields at the SAMNET and 210MM stations were strongly disturbed. The amplitude and shape of the field variations at the SAMNET stations during the interval from ~0955 to ~1101 UT are different from those at the 210MM stations. That is, the SAMNET stations show periodic pulsations and latitude dependence of the pulsations period, but the 210MM stations show more irregular perturbations than at the SAMNET. Such complicated and global ground magnetic field signatures caused by sudden changes in the solar wind dynamic pressure have been studied in detail by several authors [e.g., *Araki*, 1994; *Petrinec et al.*, 1996; *Chi et al.*, 2001; *Lee and Hudson*, 2001]. In this study we focus only on the relation between the quasiperiodic SP variations in the magnetosheath and their corresponding features on the ground. We note that some parts of the geomagnetic field perturbations at 210MM on the nightside could be associated with substorms, but the Pi2 pulsations which are normally found at substorm onsets could not be identified.

[27] In order to compare the SP variations in the magnetosheath and the magnetic field variations at geosynchronous orbit and on ground, we have plotted in Figure 10 the *H*-components for SAMNET and 210MM stations, the magnetic field strengths at GOES 8 and 10. The magneto-

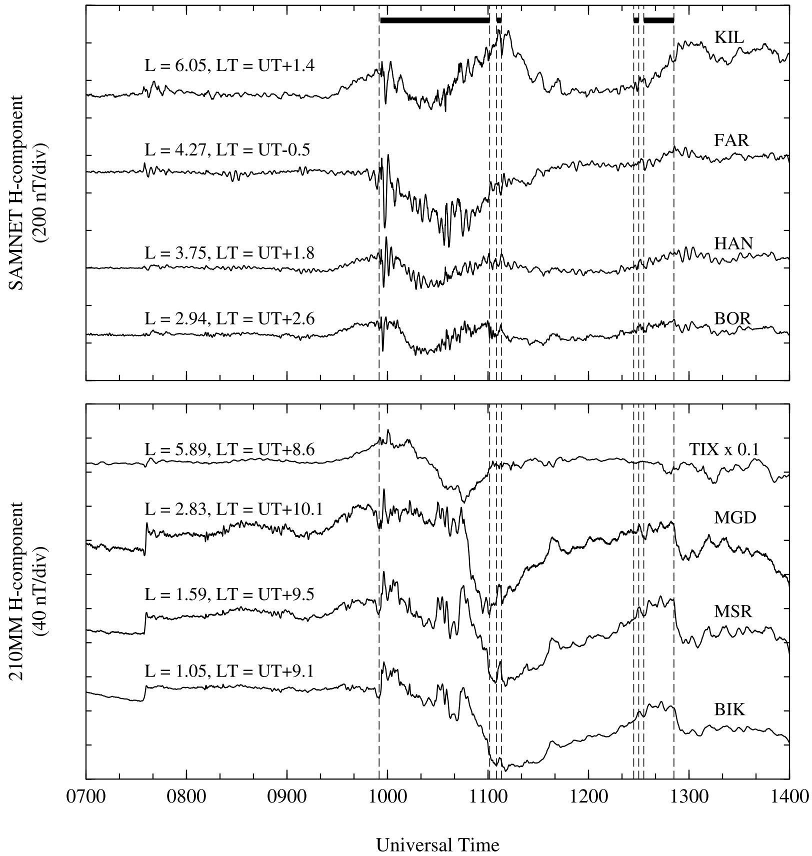

Figure 9. The *H* component of the magnetic field at selected SAMNET (top) and 210MM (bottom) stations. The horizontal bars in the top panel indicate the time intervals of the solar wind entries of Polar.

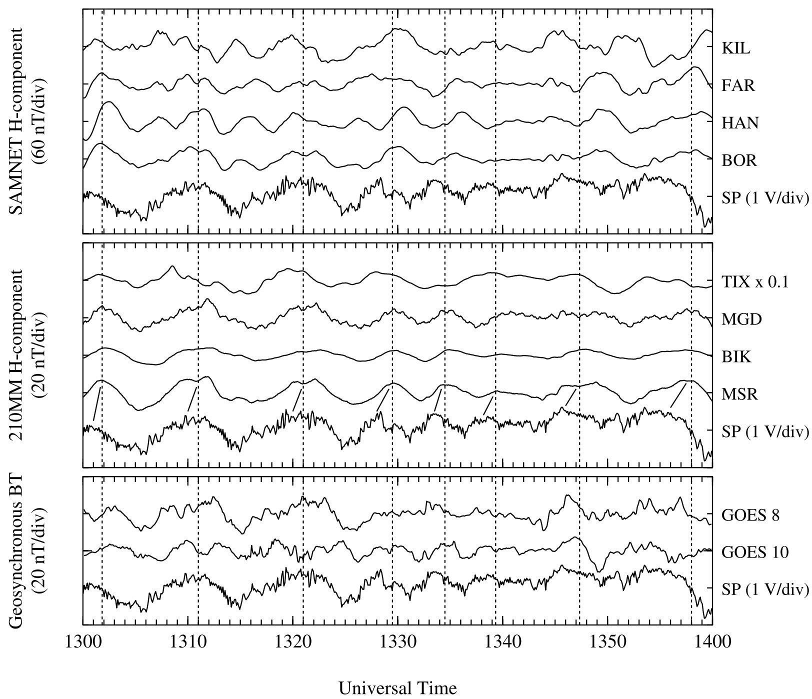

Figure 10. (top to bottom) The *H* component of the selected SAMNET and 210MM magnetometers, and magnetic field strengths at GOES 8 and GOES 10. The spacecraft potential (SP) in the magnetosheath are plotted at the bottom of each panel. The vertical dashed lines in each panel indicate the positive peaks of the oscillations at MSR.

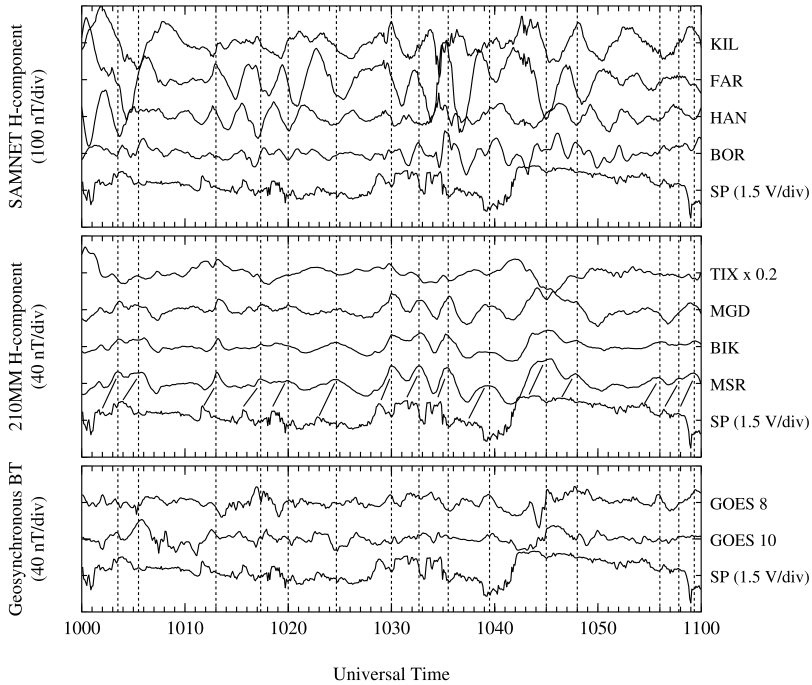

Figure 11. Same as Figure 10, but for the interval from 1000 to 1100 UT when Polar was in the solar wind.

sheath SP variations observed by Polar were plotted at the bottom of each panel. The magnetic field data on the ground and in space have been filtered by removing 300-s running averages. The most prominent feature in Figure 10 is an almost perfect one-to-one correspondence between the SP variations in the magnetosheath, which were inherent in the solar wind (see Figure 6), and the geomagnetic field perturbations at 210MM stations on the nightside. These observations indicate that the density fluctuations in the solar wind and magnetosheath can be a direct cause of the ground magnetic field perturbations on the nightside. Some of the magnetic field fluctuations at SAMNET stations on the dayside and at geosynchronous orbit correspond to the SP variations, but their signatures were more complicated than those at 210MM stations.Figure 11 shows a comparison of the SP variations in the solar wind observed by Polar and magnetic field fluctuations on the ground and in space on the same format as Figure 10. We also found that the ground magnetic field fluctuations at lower latitudes (MGS, MSR, and BIK) on the nightside have high correlation with the SP variations in the solar wind. The SAMNET data in Figure 11 show latitude dependence of the pulsation period. The period is longest at KIL (L = 6.1) and shortest at BOR (L = 2.9). This may be interpreted by standing Alfvén waves on individual field lines.

4. Discussion

[28] We have presented the magnetospheric response to two types of external pressure variations: sudden and quasiperiodic changes. Our observations are consistent with previous studies, i.e., sudden changes in the solar wind dynamic pressure excite standing Alfvén waves in the magnetosphere and the solar wind dynamic pressure variations directly drive the magnetospheric oscillations. However, there are very few observations to compare the magnetosheath pressure variations and low-latitude geomagnetic perturbations on the nightside. In this section, we discuss only the magnetospheric response to the quasiperiodic magnetosheath SP variations.

[29] We observed that the SP variations in the magnetosheath originate in the solar wind and they are correlated with the magnetosheath field strength (i.e., anti-correlation between density and field strength variations). The density and field variations in our study are opposite to the upstream pressure variations associated with the bow shock, that is, the correlated density and magnetic field strength fluctuations [e.g., *Fairfield et al.*, 1990].

[30] Since density changes cause dynamic pressure variations ($\delta P = (\delta n)MV^2$), quasiperiodic density enhancements in the magnetosheath, which is of solar wind origin, propagating tailward will perturb the magnetopause. When the solar wind speed is high, such magnetopause motions are easily observed by a satellite near the magnetopause. Therefore, it should be carefully examined whether quasiperiodic magnetopause motions are caused by the K-H instability or external density variations because the level of both mechanisms depends on solar wind velocity. We note that the solar wind speed was $\sim$800 km/s for the interval of quasiperiodic SP variations. In considering the excitation of the magnetopause motions by external driving source, it is not always necessary to invoke the fast-mode signature (i.e., in-phase density and magnetic field strength variations) in the magnetosheath when the solar wind speed is high.

[31] As mentioned in the introduction, discrete frequencies (1.3, 1.9, 2.6, 3.4, and 4.2 mHz) in the Pc5 band have been frequently observed at high-latitude ground stations and attributed to discrete field line resonances driven by the waveguide mode in the local midnight and predawn sector

[e.g., *Ruohoniemi et al.*, 1991; *Samson et al.*, 1991, 1992a, 1992b]. Such discrete Pc5 frequency bands have been observed even at a low-latitude station (L = 1.6) [*Francia and Villante*, 1997]. We showed the one-to-one correspondence between the SP variations in the magnetosheath and the geomagnetic field perturbations at lower-latitude ground stations on the nightside. Such fluctuations have a recurrence time of ~3–10 min, which is comparable to the repetition time scale (~5–10 min) of the solar wind pressure pulses reported by *Sibeck et al.* [1989] and *Sibeck* [1994]. The recurrence time scale corresponds to the Pc5 frequency range. Therefore, we suggest that some geomagnetic pulsations in the Pc5 frequency band at local times away from noon are directly related to intrinsic solar wind structure rather than to the waveguide mode.

[32] We observed that the geomagnetic field perturbations at lower latitudes (L = 1.1–2.8) on the nightside are nearly identical to the SP variations in the magnetosheath. The dayside ground data at higher latitudes (L = 2.9–6.1) were less coherent with the magnetosheath SP variations. These signatures may be interpreted by a previous study by *Russell et al.* [1992]. The authors reported that the best correlation between ground level changes and the change in the solar wind dynamic pressure occurs at geomagnetic latitudes from 15° to 30°. All of the dayside ground stations in our study are located at magnetic latitudes higher than the best correlation geomagnetic latitudes (see Table 1). If sc/si model [*Araki*, 1994] is applied to the quasiperiodic solar wind dynamic pressure variations, geomagnetic field variations at higher latitudes are more complicated than those at lower latitudes because of ionospheric current effect generated by Alfvén wave propagating on high-latitude geomagnetic field lines. The ground data on the dayside are more easily perturbed by the current than on the nightside. This argument would explain why the BOR data showed more complicated signatures than the perturbations at MGD, which were nearly identical to the magnetosheath SP variations, although they are located at nearly same latitude. Another interpretation of less coherent dayside data with solar wind and magnetosheath density fluctuations is the interference between incoming and reflected perturbations. When the magnetosphere is continuously perturbed by monochromatic fluctuations at the magnetopause, the incoming source waves driven at the magnetopause may be masked by the oscillations reflected at the inner boundary, perhaps the plasmapause and/or ionosphere [*Lee and Lysak*, 1991]. Therefore, more complicated perturbations will be observed on the dayside magnetosphere. This effect may increase near the meridian plane of the source region if the perturbations propagate from the dayside to the nightside. In order to examine whether the interference effect is important at dayside low-latitude region, we need to compare simultaneous observations at low latitudes on the dayside and nightside. Unfortunately, the dayside low-latitude (from 15° to 30°) ground data were not available for the interval in this study. In the near future, we will present a numerical and observational study, how different locations (i.e., dayside and nightside) in the magnetosphere would respond to low-frequency (Pc5-band) driving source.

[33] The perturbations observed at low latitudes may be associated with fast mode waves propagating tailward [*Matsuoka et al*, 1995], launched at the driven magnetopause. The time delay between the magnetosheath SP variations and MSR H-component perturbations for the interval in Figure 10 was in ~60–70 s. Recently, the propagation time delay of MHD waves (i.e, fast mode, Alfvén mode, and the sum of the two) from a point source at L = 10 at the equator to radially separated ground points was calculated by *Chi et al.* [2001]. The estimated time delay is ~60 s from the source point to the Earth surface. If we consider a time delay of ~10 s between 1200 and 2400 MLT on the ground for the waves launched from 10 RE at noon [*Francis et al.*, 1959], our observations (~60–70 s) are consistent with the model predictions.

5. Conclusion

[34] We showed that the geomagnetic field perturbations at lower-latitude (L = 1.1–2.8) ground stations on the nightside are nearly identical to the SP variations in the magnetosheath, which were inherent in the solar wind. The higher-latitude (L = 2.9–6.1) dayside responses to the SP variations were more complex. These observations suggest that the solar wind variations can be a direct source of geomagnetic field per-turbations at a region away from the subsolar point and that the lower-latitude data on the nightside are important to monitor the external pressure variations. Therefore, geomagnetic field signatures observed at the dawn/duskside and/or nightside should be carefully examined whether they are attributed to a magnetospheric waveguide or they are directly related to intrinsic solar wind structure. We do emphasize the importance of combined ground and solar wind observations to determine the source mechanism of low- frequency (Pc5-band) perturbations in the magnetosphere.

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