Observations of discrete, global magnetospheric oscillations directly driven by solar wind density variations

L. Kepko and H. E. Spence
Center for Space Physics, Boston University, Boston, Massachusetts, USA

Received 9 September 2002; revised 29 January 2003; accepted 3 April 2003; published 26 June 2003.

[1] In this paper we present six events in which both the time series and the spectral content of solar wind number density fluctuations and magnetospheric magnetic field observations were highly correlated for intervals ranging from a few to twelve hours. The fluctuations were periodic and occurred at discrete frequencies which often matched the f = 1.3, 1.9, 2.6, and 3.4 mHz oscillations that have been attributed to global magnetospheric MHD cavity and/or waveguide modes. We also observed significant power in the sub-mHz region, with frequencies as low as f = 0.1 mHz. We show that these fluctuations were first observed in the solar wind, far upstream from the Earth, and argue that the convected density perturbations slowly alter the size of the magnetospheric cavity leading to the appearance of multiple, discrete magnetospheric oscillations. We argue that for these events the discrete frequencies were an inherent property of the solar wind and were not related to a possible cavity or waveguide mode of the magnetosphere. We then show that the density fluctuations, when converted into length scales, organize into scale sizes of L = 23, 30, 45, and 80–100 R_E. Finally, we speculate on a possible solar source for the periodic solar wind structures. *INDEX TERMS:* 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; 2752 Magnetospheric Physics: MHD waves and instabilities; 2740 Magnetospheric Physics: Magnetospheric configuration and dynamics; 2772 Magnetospheric Physics: Plasma waves and instabilities; *KEYWORDS:* ULF pulsations, solar wind density structures, global oscillations

Citation: Kepko, L., and H. E. Spence, Observations of discrete, global magnetospheric oscillations directly driven by solar wind density variations, *J. Geophys. Res.*, *108*(A6), 1257, doi:10.1029/2002JA009676, 2003.

1. Introduction

[2] Magnetospheric ULF pulsations can arise from a variety of sources, and these pulsations are often observed to occur at discrete frequencies over extended intervals of time. The frequencies of these pulsations are typically defined by internal magnetospheric properties, such as field line lengths, magnetic field profiles, and mass density distributions. The free energy needed to stimulate such pulsations can arise from local reconfiguration of magnetic stresses [e.g., *Nishida*, 1979; *Yumoto et al.*, 1989], wave-particle interactions [e.g., *Cornwall*, 1965; *Kennel and Petschek*, 1966], or a host of other sources which are internal to the magnetosphere (see reviews by *Takahashi* [1998] and *Yumoto* [1986] for additional examples). In addition, the solar wind can often provide a source of broadband energy which can then couple to discrete magnetospheric oscillations. For example, the generation of Kelvin-Helmholtz waves on the magnetopause, stimulated by the solar wind/magnetosphere interaction, can lead to a continuous distribution of field line resonances (FLR) in the Pc 4–5 band (45–600 s) [e.g., *Singer et al.*, 1977; *Anderson et al.*, 1990; *Nosé et al.*, 1995]. A second type of global oscillation is postulated to arise from the rapid increase in dynamic pressure associated with interplanetary shocks, which could supply the compressional energy required to stimulate global magnetospheric cavity mode oscillations. Although the cavity mode has been studied extensively through theory [e.g., *Kivelson et al.*, 1984; *Kivelson and Southwood*, 1986] and numerical simulation [*Allan et al.*, 1986; *Lee and Lysak*, 1989], observations of cavity mode signatures are rare [*Goldstein et al.*, 1999].

[3] It is also known that the position of the magnetopause responds directly to changes in the solar wind dynamic pressure. This interaction can lead to internal magnetic perturbations as the magnetospheric field increases or decreases as needed to balance the changing solar wind dynamic pressure [e.g., *Cahill and Winckler*, 1992; *Matsuoka et al.*, 1995]. However, there are few published reports of oscillatory magnetospheric perturbations that could be attributed directly to oscillatory changes in the solar wind dynamic pressure. A nice example of such driving was presented by *Sarafopoulos* [1995], who correlated dynamic pressure variations in the solar wind observed by ISEE-3 with magnetospheric lobe variations detected by IMP-8. In a separate study, *Korotova and Sibeck* [1995] argued that periodic Pi 3 perturbations observed on the ground and in the ionosphere were driven by bow shock generated pressure changes in the magnetosheath. *Lessard et al.* [1999] presented indirect evidence that field line resonances observed on the ground and in space following

0148-0227/03/2002JA009676$09.00

the onset of geomagnetic activity were externally driven, although they did not have solar wind data to confirm the hypothesis.

[4] Solar wind data from upstream solar wind monitors (such as the Wind spacecraft) during the ISTP era has allowed researchers to more directly examine the role that solar wind perturbations might provide in the direct driving of ULF pulsations. Recently, *Kepko et al.* [2002] and *Stephenson and Walker* [2002] independently correlated discrete solar wind number density oscillations with magnetospheric oscillations, at frequencies $f < 3$ mHz. Interestingly, the frequencies reported by *Kepko et al.* [2002] and *Stephenson and Walker* [2002] were close to the $f = 1.3$, 1.9, 2.6, and 3.4 mHz oscillations that have been observed in ground magnetometer [*Samson et al.*, 1992a; *Ziesolleck and McDiarmid*, 1994; *Francia and Villante*, 1997], HF radar [*Ruohoniemi et al.*, 1991; *Samson et al.*, 1991; *Walker et al.*, 1992; *Fenrich et al.*, 1995] and satellite measurements for the last decade. That these low-frequency oscillations occurred at repeatable, discrete frequencies and had been detected globally led *Harrold and Samson* [1992] and *Samson et al.* [1992b] to develop a magnetospheric cavity mode/waveguide model. (For the remainder of this paper we will adopt the nomenclature used by *Ziesolleck and McDiarmid* [1995] and refer to the $f = 1.3$, 1.9, 2.6, and 3.4 mHz oscillations as the cavity mode model of *Samson et al.* [1992b], or CMS, frequencies.). In these models the frequencies of the pulsations are determined by properties internal to the magnetosphere, such as the global Alfvén wave speed profile and the size of the magnetospheric cavity.

[5] While the cavity mode and waveguide models can successfully explain observations of magnetospheric oscillations with $f > \sim 1$ mHz, limits on the size of the magnetospheric waveguide preclude this as a reasonable explanation for oscillations with $f < 1$ mHz. Global magnetospheric oscillations with frequencies below 1 mHz are not uncommon and have been observed in both ground and radar measurements [*Herron*, 1967; *Rinnert*, 1996; *Huang et al.*, 2001] and in the magnetosphere [*Nikutowski et al.*, 1996; *Chen and Kivelson*, 1991; *Lessard et al.*, 1999]. Since global magnetospheric oscillations with $f < 1$ mHz are not likely associated with cavity or waveguide modes, simultaneous observations of sub-mHz oscillations and the CMS frequencies would call into question the nature of the CMS frequencies as manifestations of a cavity or waveguide mode. The events presented by *Kepko et al.* [2002] showed significant power at the CMS frequencies as well as power near 0.5 mHz. These same frequencies were observed in the solar wind far upstream of the Earth. These observations led *Kepko et al.* [2002] to conclude that the solar wind was a direct source for discrete magnetospheric oscillations; i.e., the magnetosphere was a passive oscillator, driven by external, periodic forcing. *Stephenson and Walker* [2002], using radar data, also argued that the solar wind was the source for the discrete frequencies they observed.

[6] In this paper we extend the work of *Kepko et al.* [2002] and present additional observations of ULF pulsations with $f < 2.5$ mHz observed far upstream by the Wind satellite concurrent (after ballistic propagation) with dayside geosynchronous observations of the same pulsations. In some events we also examine data from the Polar spacecraft at high-latitude and ground magnetic field measurements. Both the time series and spectral content of the solar wind and magnetospheric measurements show high correlation over a time interval of several hours up to half of a day. We suggest that the magnetosphere is directly driven by solar wind dynamic pressure variations, which we assert are an inherent feature of the solar wind. In this work we do not address the occurrence frequency of such solar wind oscillations. The discreteness of the pulsations arise because variations in the number density of the solar wind recur at regular intervals and is not due to any property internal to the magnetosphere. We also comment on the stability of the observed frequencies from one event to another. We show that while the frequencies may shift significantly from event to event, the spectral peaks are well organized after converting to solar wind speed dependent length scales. Normalizing to the mean measured solar wind velocity organizes the observations into narrow bins of scale sizes $L = 23$, 30, 45, and 80–100 R_E. Finally, we review observations of compressional waves in solar plumes and suggest a possible mechanism linking solar *p*-mode oscillations to the observed periodic solar wind density structures.

2. Events

[7] The solar wind data from all events presented in this paper are from instruments on board the Wind spacecraft. Solar wind plasma data are from the Solar Wind Experiment (SWE) [*Ogilvie et al.*, 1995], and are at 96-s resolution. Magnetic field data are from the Magnetic Field Investigation (MFI) [*Lepping et al.*, 1995] and were sampled every 60 s. For all events we also show geosynchronous magnetic field data from the GOES-8 spacecraft [*Singer et al.*, 1996] at 60-s resolution. GOES-8 was located on the dayside hemisphere for all the events presented here and crossed local noon near 1700 UT. The events were selected through visual identification, which was based on a high-correlation between Wind N fluctuations and GOES-8 B_z magnetic field perturbations. This selection criterion likely biased the selection towards large-amplitude and/or long-duration events. A more systematic, statistical study is underway.

2.1. 15 June 1999

[8] Twelve hours of solar wind data collected from instruments on board the Wind spacecraft, which was located at (205, −21, −7) R_E in GSM coordinates, are shown in Figure 1. A small shock was observed just after 1200 UT, as indicated by increases in $|v_x|$ and $|B|$. Note that variations in dynamic pressure were driven mainly by variations in the number density. This is shown in Figure 2 where we have plotted the observed dynamic pressure (ρv^2), the dynamic pressure with an average velocity $\left(\rho\bar{v}^2\right)$, and the dynamic pressure with an average number density ($\bar{\rho} v^2$). The plot clearly shows that it is the variation in number density that is principally responsible for variations in the dynamic pressure. This feature is common to all six events we will present.

[9] In the hours following the shock, waves with two distinct frequencies were present in the number density and dynamic pressure. The first is an ∼90 min wave, with peaks at 1215, 1345, 1515, 1700, and 1830 UT. The intensity of

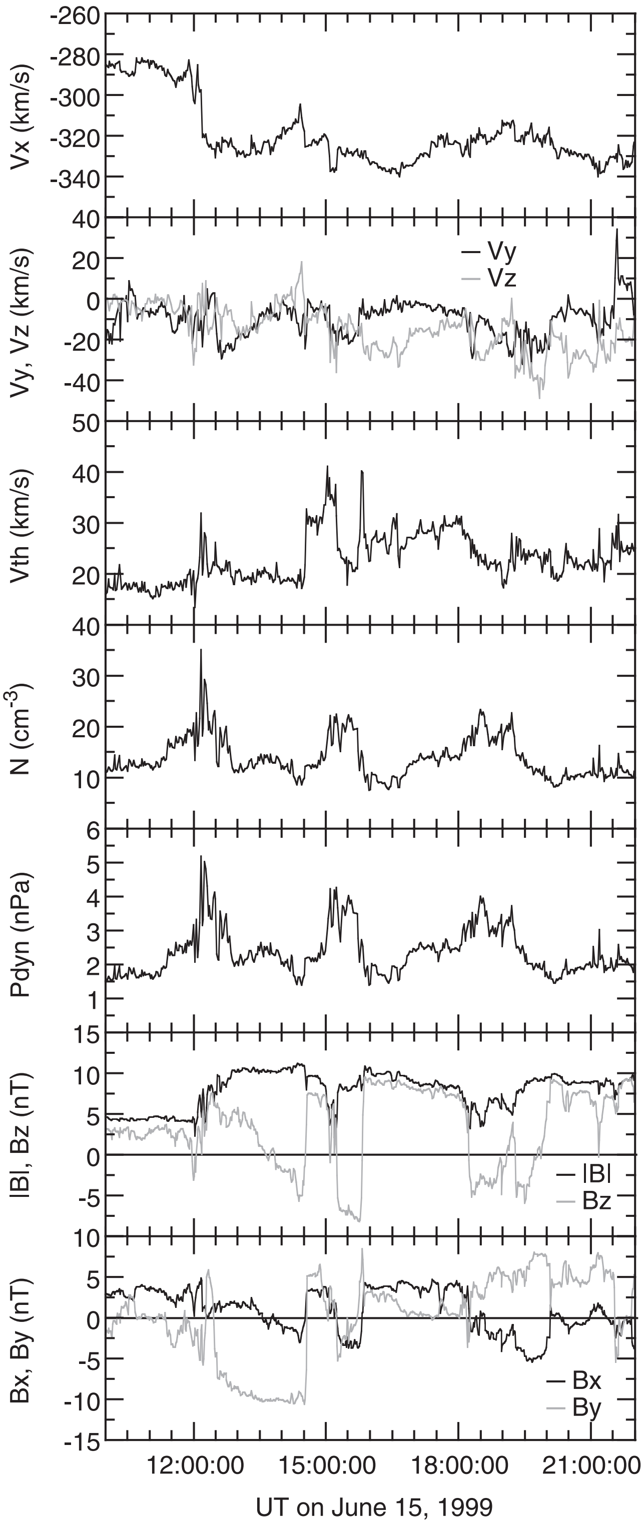

Figure 1. Solar wind data from the Wind spacecraft for 15 June 1999. Wind was located at (205, −21, −7) R_E in GSM coordinates.

the peaks is modulated at half that frequency so that the peaks 1215, 1515, and 1830 UT are larger, giving the appearance of a 3 hour period (T) oscillation. The times of these largest peaks correspond to large diamagnetic decreases in the magnetic field strength. The individual

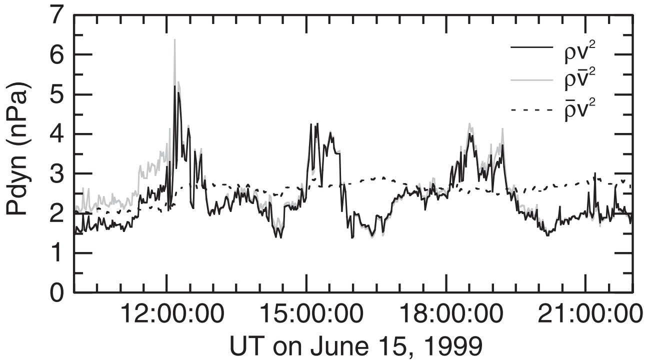

Figure 2. The observed dynamic pressure (ρv^2), the dynamic pressure with an average velocity $\left(\rho\bar{v}^2\right)$, and the dynamic pressure with an average number density $\left(\bar{\rho}v^2\right)$ for the 15 June 1999 event.

components of the interplanetary magnetic field do not exhibit the same periodicity. A second, higher-frequency wave, with $T \sim 10-15$ min, is also observed, most clearly between 1300 and 1400 UT.

[10] The GSM z (vertical) component of the magnetic field from the geosynchronous GOES-8 satellite and the ballistically time-shifted solar wind dynamic pressure from WIND

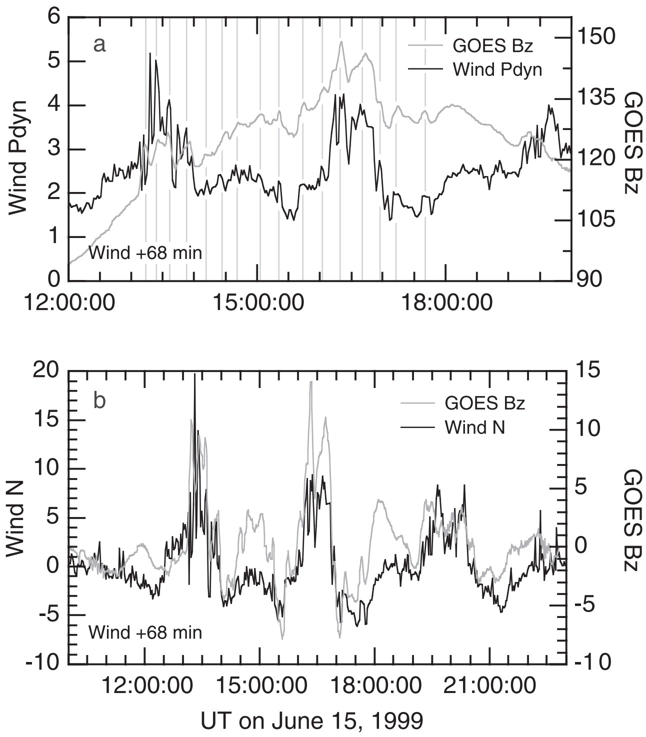

Figure 3. (a) Comparison of the solar wind dynamic pressure, ρv^2, measured by Wind (black) and the B_z component of the magnetic field measured by GOES-8 (grey). The Wind data have been time-shifted by +68 min to account for propagation to the magnetosphere. Vertical lines mark times when local peaks in the solar wind number density match magnetic perturbations at GOES-8. (b) The solar wind number density (black) and GOES-8 B_z component of the magnetic field with the background variations removed by running averages.

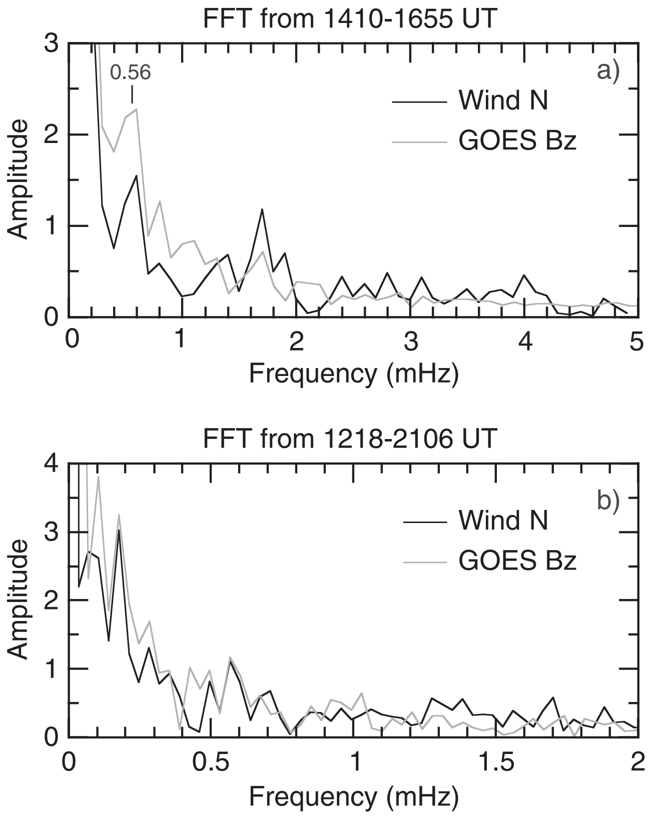

Figure 4. Fourier transforms of the solar wind number density and of the B_z component of the magnetic field from GOES-8 for 15 June 1999. In both plots the Wind transform was performed over a window −68 min from those listed. (a) Spectral estimates for the period 1410–1655 UT, showing a strong peak at f = 0.56 (T = 30 min), with an additional peak near f = 1.7 mHz. (b) A longer period Fourier transform over the interval 1218–2106 UT which shows spectral peaks at f = 0.1 and 0.2 mHz (T = 3 hours and 90 min). The f = 0.56 mHz peak is also evident.

are shown in Figure 3a. The time-shift determined from ballistic propagation is 66 min, which agrees well with the shift determined by visual inspection (68 min). GOES-8 was moving through the dayside magnetosphere and passed local noon near 1630 UT. Both the long- and short-period oscillations observed in the solar wind were also observed in the magnetic field measured by GOES-8. The ~10–15 min oscillations have been marked with vertical lines and appear highly periodic. Plots of the data with the background variations removed by 60-point (Wind) and 70-point (GOES-8) running averages are shown in Figure 3b. The high correlation between solar wind number density oscillations and magnetospheric magnetic field oscillations is clearly evident.

[11] Fourier transforms of the solar wind and magnetospheric data from the period 1410–1655 UT, with Wind offset −68 min from this window, confirms that the pulsations had a discrete peak near f = 0.56 mHz, or T = 30 min (Figure 4a). The Fourier transform of the Wind data also exhibits a peak near f = 1.7 mHz (T = 10 min), but this peak is not strongly present at GOES. A second set of Fourier transforms over the longer interval 1218–2106 UT (wind offset by −68 min from that window) show peaks near f = 0.1 and 0.2 mHz ($T \sim$ 3 hours and $T \sim$ 90 min, respectively), in addition to the f = 0.56 peak (Figure 4b). The spectral analysis confirms that the solar wind number density variations were highly periodic and that the geosynchronous magnetic field oscillated at these same discrete frequencies.

2.2. 4 February 1997

[12] This event is very similar to the previous example in that discrete, long-period oscillations in the solar wind

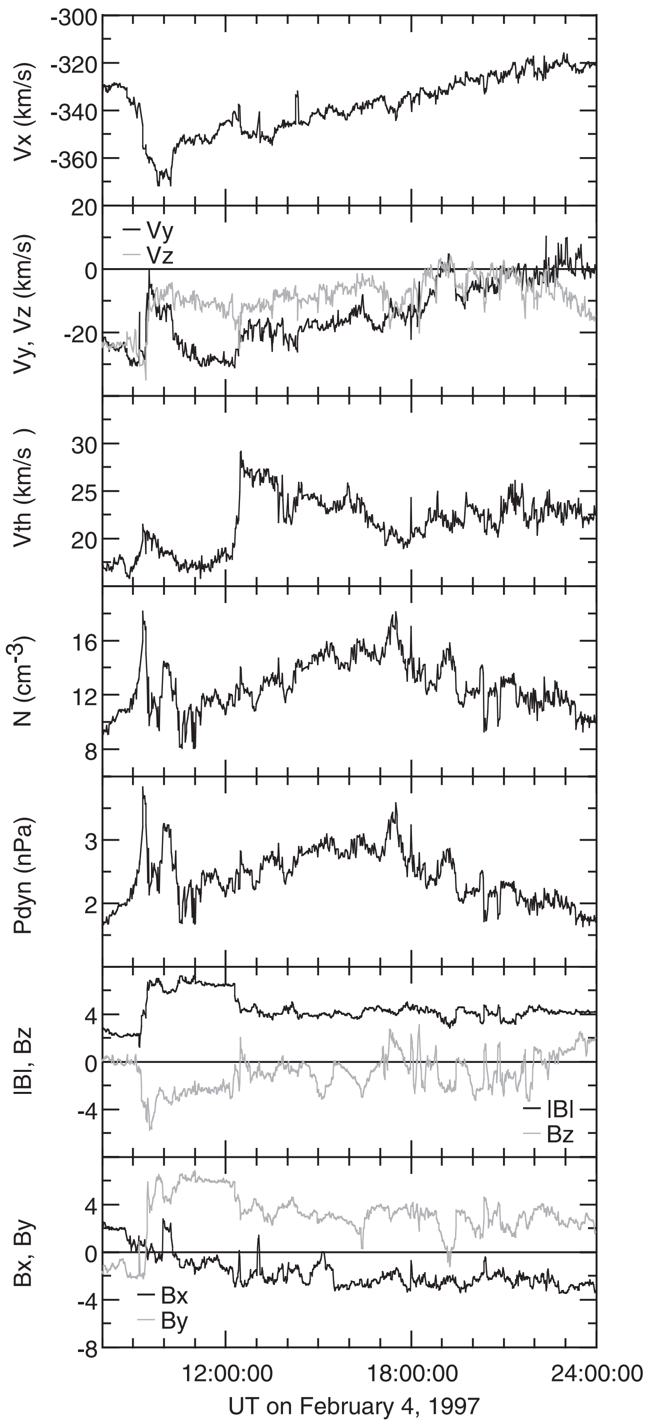

Figure 5. Solar wind data for the 4 February 1997 event. Wind was located at (190, −1, −18) R_E in GSM coordinates.

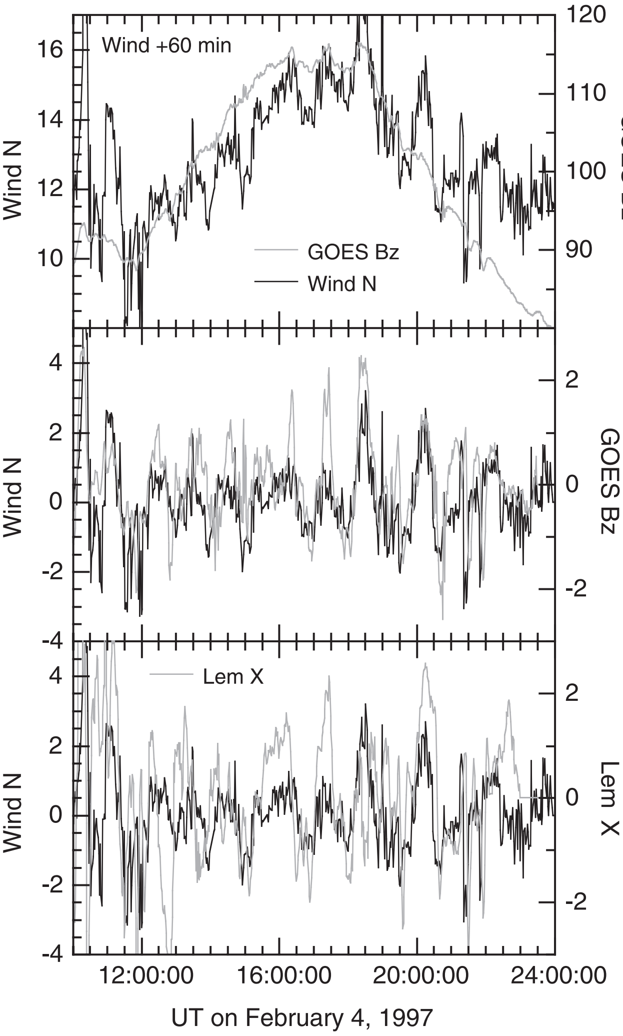

Figure 6. (a) The B_z component of the magnetic field measured by the GOES-8 geosynchronous spacecraft (grey) and the solar wind number density measured by Wind (black), time-shifted by +60 min, for 4 February 1997. (b) Same as Figure 6a, with the background trends removed. (c) Detrended solar wind number density measured by Wind (black) and the X component of the magnetic field measured by the ground station Learmonth (grey), also with the background trend removed.

number density are observed for several hours following a moderate shock. The solar wind data measured by Wind, located at (190, −1, −18) R_E in GSM coordinates, are shown in Figure 5. The shock was observed near 0930 UT, as indicated by increases in $|v_x|$, $|B|$, and the proton thermal velocity, v_{th}. A large density enhancement slightly preceded the arrival of the shock. A sharp decrease in $|B|$ concurrent with an increase in v_{th} occurred just after 1200 UT; this discontinuity did not appear in any of the other plasma parameters. For ∼10 hours following the shock, long-period oscillations with $T \sim 70$ min were observed in the number density and dynamic pressure. As in the previous event, variations in the solar wind dynamic pressure were driven mainly by variations in the number density.

[13] The GSM B_z component of the magnetic field from the GOES-8 geosynchronous spacecraft along with the number density measured by Wind are shown in Figure 6a. The Wind data have been time shifted by +60 min. Ballistic propagation yields a Δt = 57 min, which again agrees well with the visually determined time shift. The long-term sinusoidal trend observed by GOES is the diurnal variation. Small-amplitude, long-period oscillations ride this trend. We applied a running average on both traces to remove the trend (Figure 6b) to show the waves in more detail. The long-period ULF waves observed by GOES-8 were highly correlated with the time-shifted solar wind number density variations. A high correlation coefficient (R = 0.63) is calculated over the interval 1100–2130 UT. Magnetic field data from the Learmonth (Lem) magnetometer station (λ_{cgm} = −34.15°, Φ_{cgm} = 185.02°), also with the background variation removed by subtraction of running averages, are shown in Figure 6c. The magnetic local time (MLT) of Lem is $MLT = UT - 16.4$. During the interval plotted in Figure 6, Lem was rotating from the nightside through the dawn flank. There is a high correlation between the solar wind number density variations and magnetic perturbations measured by Lem (R = 0.55).

[14] The Polar spacecraft was located at high latitude during this interval and passed through the polar cap from dusk to dawn (Figure 7). The magnetic field lines at the positions of Polar were open and mapped to the distant magnetotail. The X component of the magnetic field data measured by Polar are shown in Figure 8. A 40-point running average has been subtracted to remove the large background trends. We also plot the detrended solar wind number density, time-shifted by +1 hour. The small (1–3 nT in an ∼110 nT field) perturbations measured by Polar track the solar wind density variations.

[15] Fourier transforms of the solar wind number density, GOES-8 B_z, and Learmonth X magnetic field component during the period 1230–2230 UT (Wind −1 hour from that window) are shown in Figure 9a. The spectral estimates have been averaged over 5 points. Three broad peaks are observed near f = 0.25, 0.7 and 1.3 mHz (T = 70, 25, and 13 min). A Fourier transform of the Polar magnetic field X component data over the interval 1200–1900 UT is shown

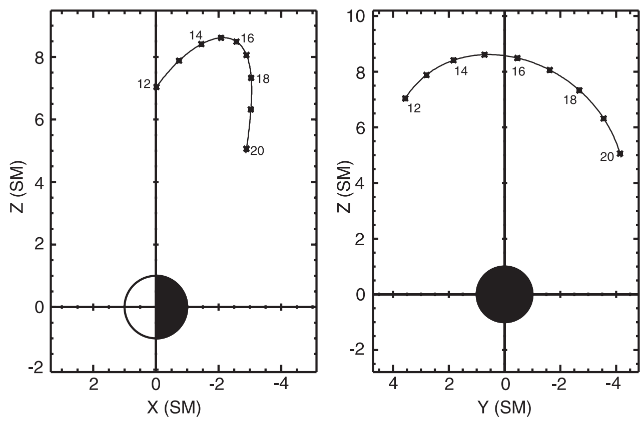

Figure 7. Orbit of the Polar spacecraft from 1200–2000 UT on 4 February 1997 projected onto the X-Z and Y-Z SM planes.

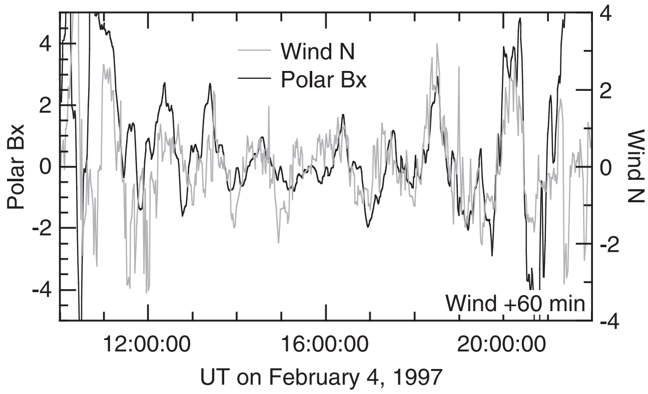

Figure 8. The GSM *X* component of the magnetic field measured by Polar on 4 February 1997 (black) and the solar wind number density measured by Wind, time-shifted by +1 hour (grey). Running averages has been subtracted for both traces.

in Figure 9b. In addition we show Fourier transforms of the solar wind number density from 1100–1900 UT and from 1130–2130 UT. All plots have been smoothed with a 3-point running average. Common spectral peaks are observed near f = 0.25 and 0.7 mHz, with two smaller peaks near f = 1.2 and 1.7 mHz.

2.3. 29 November 1996

[16] Solar wind number density measurements from the Wind spacecraft, located upstream at (55, 1, 3) R_E in GSM coordinates, are shown in Figure 10a. The data have been time-shifted by +14 min to account for propagation to the Earth. Plotted in Figure 10b are the *Z* component measurements of the magnetic field measured by the GOES-8 geosynchronous spacecraft. During the interval plotted in Figure 10b, GOES-8 moved from dawn flank to the dusk flank and passed local noon near 1700 UT. The Wind and GOES-8 data with the background trends removed by

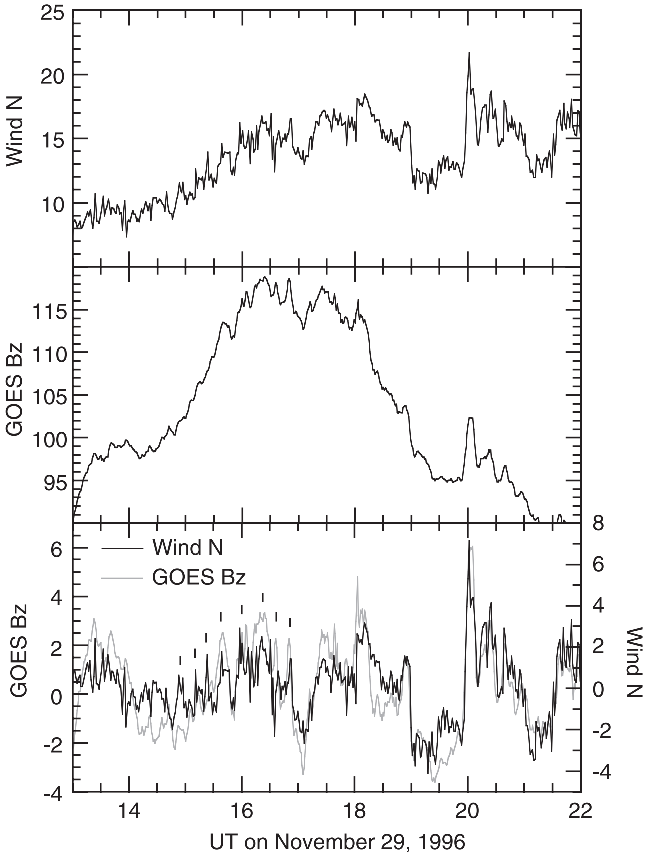

Figure 10. (a) Solar wind number density measured by the Wind spacecraft for the 29 November 1996 event. The data have been time-shifted by +14 min. (b) B_z component of the magnetic field measured by GOES-8. (c) Detrended Wind *N* and GOES B_z. Vertical ticks between 1400 and 1700 UT mark times when increases in *N* match perturbations in B_z.

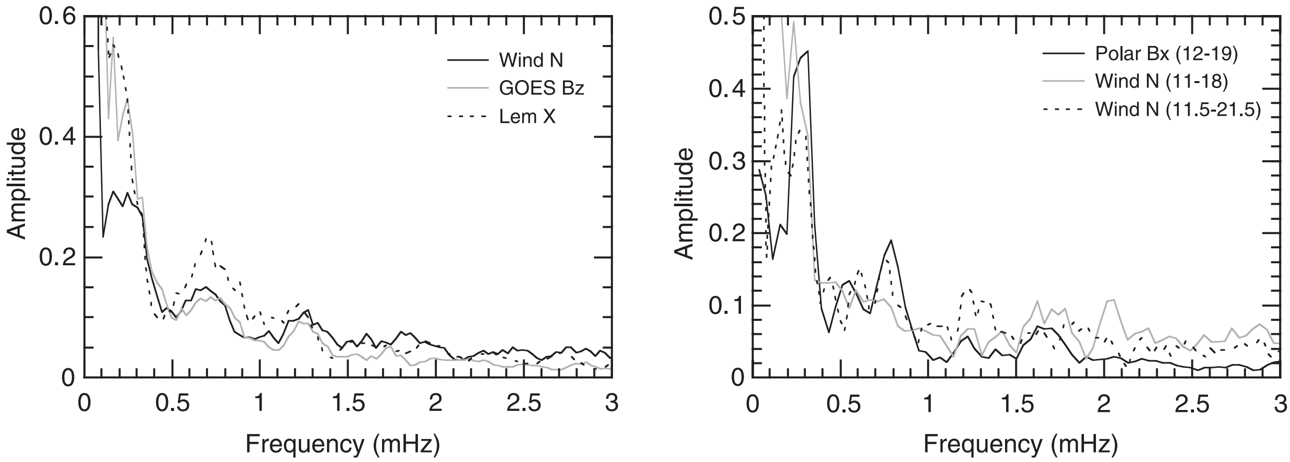

Figure 9. (a) Fourier transforms of the Wind number density (black), GOES B_z (grey), and Lem *X* (dashed) over the time interval 1230–2230 UT (Wind −1 hour from that window) on 4 February 1997. The spectral estimates were averaged over 5 points. (b) Fourier transforms of the detrended *X* component of the magnetic field measured by the Polar spacecraft (black) and of the number density measured by Wind (grey) over the interval 1200–1900 UT (Wind −1 hour from that interval). Also plotted for comparison is the Wind *N* transform over the interval shown in Figure 9a. In all cases the spectral estimates were averaged over 3 points.

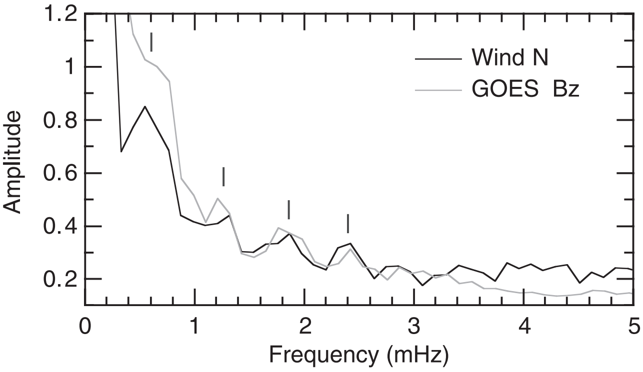

Figure 11. Fourier transforms of Wind N (black) and GOES-8 B_z (grey) over the interval 1460–1710 UT (GOES +14 min from that interval) on 29 November 1996.

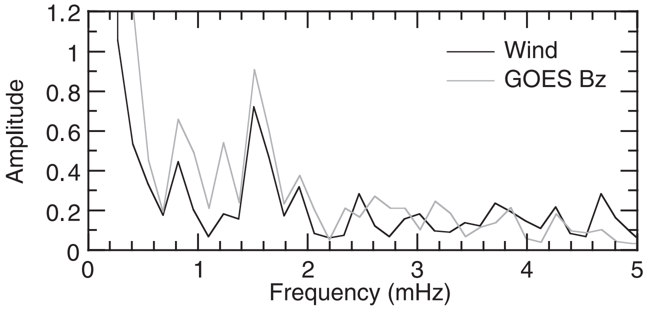

Figure 13. Fourier transforms of the Wind N (black) and GOES-8 B_z over the interval 1570–1770 UT (GOES-8 +19 min from that interval) on 21 September 1997.

subtraction of running averages are shown in Figure 10c. There is excellent agreement between solar wind number density fluctuations and magnetospheric magnetic field perturbations (the correlation coefficient R = 0.73 over the interval 1400–1700 UT; R = 0.74 over the interval 1400–2200 UT). The interval between 1500 and 1700 UT was characterized by highly periodic fluctuations with a period of 15 min (marked with vertical dashes in Figure 10c). Note also that a density discontinuity was observed by Wind just prior to 2000 UT, followed by successively damped perturbations. Very similar oscillations were observed by GOES-8. These observations of a progressively damped sinusoidal oscillation mimic the type of perturbation expected from a cavity oscillation stimulated by an initial broadband energy source. In this case, however, the perturbations are clearly directly driven by solar wind number density variations.

[17] Fourier transforms over the interval 1460–1710 UT (GOES +14 min from that interval) are shown in Figure 11. The spectral estimates have been averaged over 3 points. Significant common spectral peaks are observed at f = 0.6, 1.3, 1.9, and 2.4 mHz in both the GOES and Wind spectra.

2.4. Other Events

[18] Solar wind number density measurements from Wind (located at (83, 4, 0) R_E in GSM coordinates) and magnetic field B_z measurements from GOES-8 from 21 September 1997 are shown in Figure 12. The Wind data have been time-shifted by +19 min. Periodic variations in the number density were observed during the entire 4-hour interval, and these variations were associated with magnetic perturbations at GOES-8. During the period 1600–1800 UT the fluctuations observed at both spacecraft were highly periodic, with a period $T \sim 10$ min. Unaveraged Fourier transforms of both data sets over the interval 1570–1770 UT (GOES-8 +19 min from that window) are shown in Figure 13. The spectra are quite similar for $f < 2$ mHz, with a large peak near f = 1.5 mHz and a secondary peak near f = 0.8 mHz.

[19] On 3 August 1998 the Wind spacecraft was located near (92, 1, 3) R_E in GSM coordinates. The number density measurements showed long-period oscillatory perturbations during an 8-hour interval (Figure 14a). The B_z component of

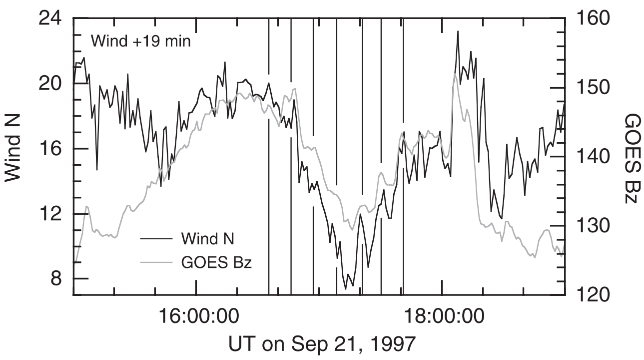

Figure 12. Solar wind number density from the Wind spacecraft (black) and GOES-8 B_z (grey) from 21 September 1997. Vertical lines denote times where local peaks in number density match magnetic field perturbations at GOES-8.

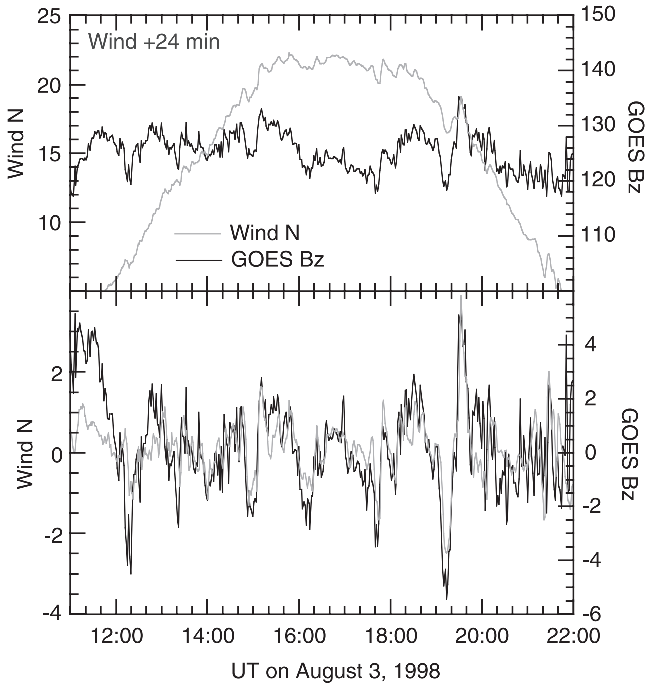

Figure 14. (a) Solar wind number density N measured by the Wind spacecraft (black) and GOES-8 B_z measurements (grey) from 3 August 1998. (b) The same as in Figure 14a, with the background variations removed by subtracting running averages. In both Figures 14a and 14b the Wind data have been time-shifted by +24 min.

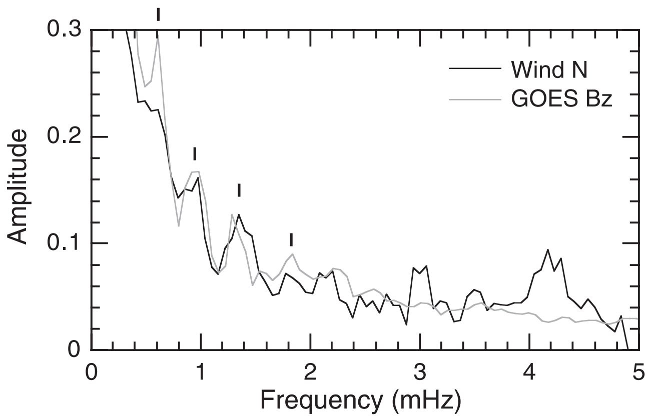

Figure 15. Fourier transforms of the solar wind number density (black) and GOES-8 B_z (grey) over the interval 1360–1810 UT (GOES-8 +24 min from that window) on 3 August 1998. The spectra were averaged over a 3-point window.

the magnetic field measured by GOES-8 showed similar perturbations. In Figure 14b we have plotted solar wind N and GOES-8 B_z data with the background trends removed by subtraction of running averages. The solar wind data have been time-shifted by +24 min. The perturbations observed by GOES-8 were well correlated with solar wind number density perturbations. Fourier transforms of both data sets show similar spectral characteristics at $f < 2$ mHz (Figure 15). In particular, common peaks near $f = 0.6$, 1.0, 1.3, and 1.8 mHz were observed.

[20] In the sixth and final event Wind was located in the far upstream solar wind at (226, 18, 10) R_E in GSM coordinates. In Figure 16 we show the solar number density measured by Wind and the B_z component of the magnetic field measured by GOES-8. The wind data have been time-shifted by +70 min. A series of four oscillations with a period of $T \sim 2$ hours ($f = 0.2$ mHz) were observed to begin just prior to 1600 UT. Similar oscillations were observed in the magnetic field by the GOES-8 geosynchronous spacecraft. Removing the background trend reveals more clearly the direct link between solar wind number density oscillations and the geomagnetic response (Figure 16b).

3. Discussion and Conclusions

[21] We presented six events in which the both the time series and spectral content of solar wind density and dynamic pressure variations were highly correlated with dayside geosynchronous magnetic field measurements. For the 4 February 1997 event the pulsations were also observed on the ground and at high latitude by the Polar spacecraft. The duration of high-correlation of the discrete oscillations ranged from ~2 hours (29 November 1996) to ~12 hours (4 February 1997). In several cases power was observed at frequencies that matched the CMS frequencies, which are often attributed to global magnetospheric cavity or waveguide modes. We found additional spectral peaks at lower frequencies, near $f = 0.1$, 0.2, and 0.6 mHz.

[22] As reviewed in the introduction, observations of global magnetospheric oscillations with power at repeatable, discrete frequencies led to the development of first the cavity mode model and then later the waveguide model, which allowed for lower frequencies. These models can easily account for the global occurrence as well as the discrete nature of such oscillations. However, constraints on the two properties that determine the lowest theoretical frequency, the size of the magnetospheric cavity and the internal wave speed, place the lower limit of a global magnetospheric oscillation at ~1 mHz. Discrete oscillations at frequencies <1 mHz therefore cannot be driven by waveguide modes. For the majority of our events we observed significant wave power at frequencies <1 mHz, often concurrent with the higher CMS frequencies. The simultaneous observations in the solar wind and magnetosphere of CMS frequencies and sub-mHz oscillations, while not necessarily precluding the existence of magnetospheric waveguide oscillations in general, does suggest a common mechanism for our events that most probably does not involve either a cavity or waveguide mode, or at the very least, minimizes the importance of these modes.

[23] The Polar observations of the 4 February 1997 event provide additional insight into the global magnetospheric response to periodic pressure variations. The Polar spacecraft was located in the polar cap on open field lines during the event. Comparison of the spectral content of the Polar magnetic field and the solar wind number density shows good agreement for $f < 2$ mHz, and common peaks were observed at $f = 0.2$, 1.3, and 1.7 mHz (Figure 9). Since the Polar spacecraft was connected to open field lines these oscillations could not be a result of waveguide oscillations internal to the magnetosphere. A similar situation was observed by *Lessard et al.* [1999] with ground magnetometer data.

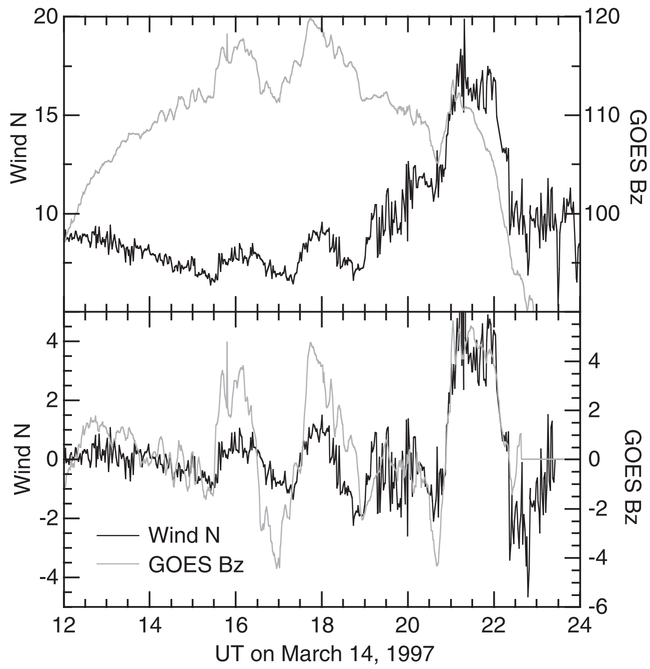

Figure 16. (a) Wind solar wind number density measurements (black) and magnetic field B_z component data from GOES-8 (grey) on 14 March 1997. (b) Same as Figure 16a, with the background variations removed by subtraction of running averages.

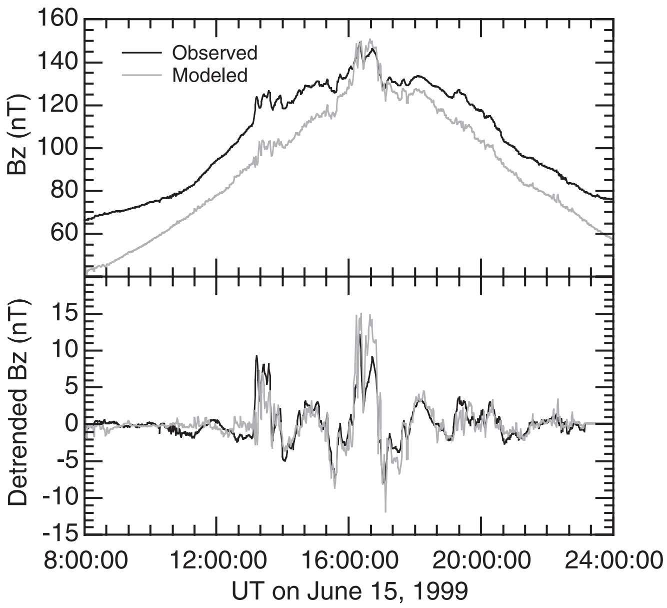

Figure 17. Observed (black) and *Tsyganenko and Stern* [1996] modeled (grey) magnetic field data from GOES-8 for the (a) 15 June 1999 and (b) 4 February 1997 events.

[24] In a previous paper [*Kepko et al.*, 2002] we presented two events with characteristics similar to the events analyzed in this paper. On the basis of those observations we suggested a direct mechanism for coupling the solar wind density variations with magnetospheric oscillations, which we reiterate here. We argue that the periods of the observed density variations ($T > 5$ min, $f < 2.5$ mhz) are longer than the Alfvénic travel time through the dayside magnetosphere, and therefore the interaction can be treated as quasi-static. The periodic solar wind dynamic pressure oscillations slowly alter the size of the magnetospheric cavity, causing the magnetospheric field to increase or decrease as needed to balance the dynamic pressure. If the external forcing is periodic and at discrete frequencies, then this process leads to global magnetospheric oscillations which are also discrete. In support of this contention we calculate here for two of the long-duration events the magnetospheric field from the *Tsyganenko and Stern* [1996] magnetospheric field model using the observed solar wind dynamic pressure as input. The results for the 15 June 1999 and 4 February 1997 events are shown in Figures 17a and 17b, respectively. We show also the data with the long-term trends removed by subtraction of running averages. Although the model field underestimates the observed magnetic field by $\sim$10 nT in both cases, the perturbations are strikingly similar. These results confirm that the observed global magnetospheric oscillations with $f < \sim 2-3$ mHz can be explained by a quasi-static forced breathing of the magnetosphere.

[25] Previous research has shown that the higher frequencies of the CMS set often exhibit characteristics of field-line resonances (FLR) [*Ruohoniemi et al.*, 1991; *Fenrich et al.*, 1995; *Samson et al.*, 1996]. Clearly, a quasi-static forced breathing in and of itself would not produce the phase reversals or localized amplitude maxima expected from FLRs [*Chen and Hasegawa*, 1974; *Southwood*, 1974]. One would naturally expect the compressional perturbations driven by external periodic forcing to couple to local toroidal mode Alfvén waves where the driving frequency matches the local toroidal mode resonant frequency [e.g., *Lee and Lysak*, 1991].

[26] One outstanding unknown in the field of global magnetospheric ULF pulsations is the reflectivity, or Q value, of the magnetospheric boundaries. It is important to note that Q is a function of frequency and that the following discussion is only applicable to the frequency range of pulsations observed in this paper (i.e., $f < 2-3$ mHz). We also distinguish between Q of the dayside magnetopause and internal turning point, which control the compressional oscillations, and the Q of the ionospheric endpoints which affects the resultant FLR. For high Q (high reflectivity), one would expect the internal magnetospheric oscillations to continue once the external driver has stopped, until the point when the compressional energy is completely fed into local FLR. For the cases presented here we find no evidence of continued compressional magnetospheric oscillations once the solar wind driver has stopped or changed the driving frequency. The data from the 29 November 1996 event in particular indicate that the magnetosphere is a heavily damped system for these frequencies. Highly periodic oscillations were observed both in the solar wind and dayside magnetosphere starting near 1500 UT and continued for $\sim$2 hours. Near 1700 UT the solar wind perturbations abruptly changed, and the magnetosphere responded immediately. Once the external driver stopped, the compressional oscillations in the magnetosphere stopped as well. Similarly, the oscillations following the 2000 UT shock abruptly stopped at 2100 UT. The oscillations of the 15 June 1999 event during the interval 1700–1900 UT exhibit similar characteristics (Figure 3). The Wind dynamic pressure measurements exhibit periodic fluctuations until just before 1800 UT, after which the fluctuations disappear for $\sim$1 hour. The B_z measurements from GOES-8 track the Wind dynamic pressure fluctuations very closely. Once the solar wind driver stopped oscillating at 1745 UT, the

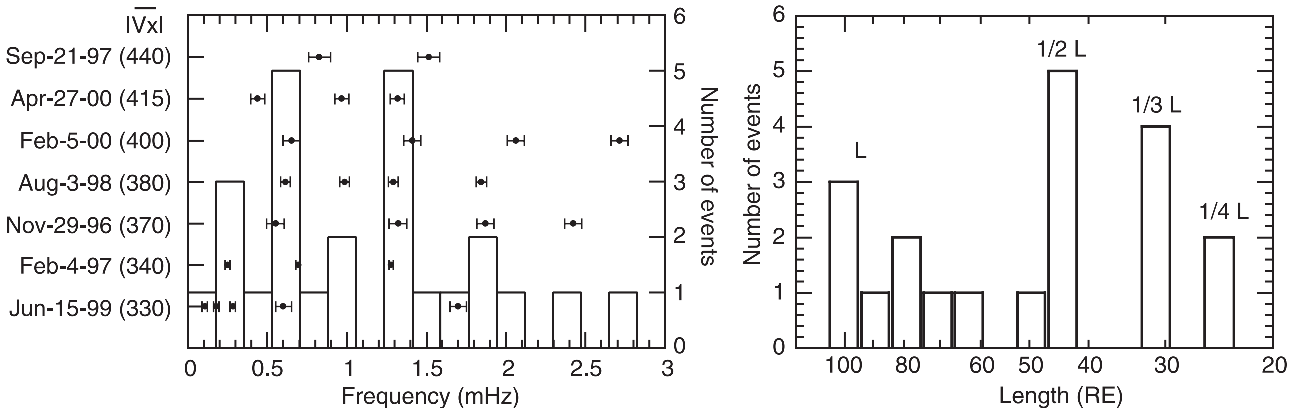

Figure 18. (a) Plot showing the frequencies observed for each event presented in this paper and those from *Kepko et al.* [2002]. Points represent the frequencies of local maxima, while error bars are 1/2 the frequency resolution of the Fourier transforms ($\pm\Delta f/2$). The dates are organized by increasing $\overline{|v_x|}$ observed in the solar wind during the event. We also plot a histogram of the observed frequencies, with a bin size of $\Delta f = 0.18$ mHz. (b) Scale sizes of the observed solar wind density structures calculated using $L = \overline{|v_x|}/f$, where f are the frequencies plotted in Figure 18a.

compressional component of the magnetospheric field at GOES-8 no longer showed oscillations. On the basis of these observations we conclude that the dayside magnetospheric boundaries appear to be highly damping (low Q) for radial compressional waves for frequencies $f < 2$–3 mHz. We note that theoretical work by *Mann et al.* [1999] concluded that the dayside magnetopause is a very poor reflector of MHD wave energy, which is in agreement with our observations. We emphasize that the preceding discussion is relevant only to the dayside compressional standing waves.

[27] An interesting result of the spectral analysis is that the spectral content of the solar wind number density variations and of the GOES geosynchronous magnetic field measurements are highly correlated below ~2.5–3 mHz (see especially Figures 11 and 15). At higher frequencies, however, the spectral content differs significantly. The most likely possibility for this difference is that the solar wind density structures at high frequencies ($f > 3$ mHz) are not coherent from the time when they are first observed by WIND to when they impact the magnetosphere. Note that the scale size of a 3 mHz perturbation in the solar wind is ~15 R_E, which is similar to the scale size of the dayside magnetosphere. Without widely spaced, multipoint solar wind measurements it is difficult to assess this possibility. Second, we note that the size of solar wind perturbations with frequencies >3 mHz are small compared with the scale size of the dayside magnetosphere, and our assumption about a quasi-static interaction are invalid. The response in the dayside magnetosphere to such a perturbation is likely to involve a summation of different wave modes launched as the perturbation impacts the dayside magnetopause. Whether this would alter the spectral content is not immediately clear. We also note that most theoretical studies examining global modes typically treat the magnetospheric compressional waves as standing waves, which is not applicable to the situation we are examining. Global MHD simulations of such interactions would be highly beneficial.

[28] Although the CMS frequencies are often described as occurring precisely at $f = 1.3$, 1.9, 2.6, and 3.4 mHz, there is evidence that the spectral peaks move around slightly in the frequency domain. *Ziesolleck and McDiarmid* [1995] examined the stability of the CMS frequencies using Canopus magnetometer data, and concluded that the CMS frequencies did not constitute a distinct set of multiple, discrete frequencies. *Francia and Villante* [1997] examined spectra from the low-latitude L'Aquilla (L = 1.6) ground station and found spectral peaks near the CMS frequencies. Examination of their spectra (see their Figure 1a) suggests that the oscillations occur over bandwidths of $\Delta f \approx 0.2$ mHz such that $f = 1.2$–1.4, 1.8–2.0, 2.4–2.6, and 3.2–3.4 mHz.

[29] We have plotted in Figure 18a the frequencies observed for each of the events presented in this paper. We also include the two events from *Kepko et al.* [2002]. Points represent the frequencies at which local maxima in the spectral power were observed. Error bars are 1/2 the frequency resolution of the individual Fourier transforms, given by $\Delta f_{fft} = 1/W$, where W is the window length over which the Fourier transform was performed. For the majority of events power was spread to more than one frequency estimate, and this therefore underestimates the spectral widths of the observed oscillations. For example, examination of the Fourier transforms from the 4 February 1997 event indicate the spectral widths are $\Delta f_{obs} \sim 0.3$ mHz, while the inherent spectral uncertainty due to the window size is $\Delta f_{fft} = 0.027$ mHz. Even when one takes into account the 5-point spectral averaging, it is clear that the oscillations on that day occurred over a bandwidth of a few tenths of mHz. We additionally plot in Figure 18a a histogram of the observed frequencies.

[30] Figure 18a shows a spread in the observed frequencies for each of the events, consistent with the proposal that the frequencies observed varied slightly from day to day. However, there are two frequency bandwidths, $f = 0.5$–0.7 mHz and $f = 1.25$–1.45 mHz, in which power was detected for a majority of events. This is most apparent in the histogram. Interestingly, the series of points between $f =$ 1.5 and 2.1 mHz show a correlation with increasing $\overline{|v_x|}$, where $\overline{|v_x|}$ is the average solar wind velocity for each event, as do the two points at $f = 2.4$ and $f = 2.7$ mHz. We calculated

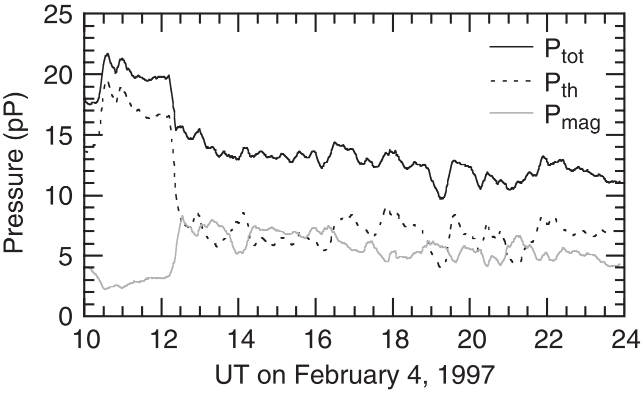

Figure 19. The thermal (dotted), magnetic (grey), and total (black) pressures for the 4 February 1997 event.

the scale size of the solar wind density perturbations, $L = \overline{|v_x|}/f_{obs}$, and plotted the results as a histogram in Figure 18b. The points at $f > 1.5$ mHz now align into narrow bands centered near $L = 23\ R_E$ and $L = 30\ R_E$. A third band appears near $L = 45\ R_E$ (corresponding to the $f \approx 1.3$ mHz band), while a broader fourth band encompasses points between 80 and 100 R_E. With the exception of the points with scale sizes of $L > 100\ R_E$ (which translate into $f < 0.5$ mHz), the majority of points in Figure 18b fall within four narrow bands of scale sizes L = 23, 30, 45 and 80–100 R_E. As indicated on the graph, we note that 45, 30, and 22.5 are the first (1/2 L), second (1/3 L) and third (1/4 L) harmonics of 90 (L).

[31] At first glance this result suggests that the periodic solar wind density variations do not occur at discrete frequencies; rather, they occur at discrete scale sizes. If this result is correct then we find it difficult to explain how the solar wind under such varied conditions could consistently form structures of the same scale size. However, if the density structures are all formed with the same initial velocity, v_0, then accelerated at a later time to their observed velocity, the scale sizes can be converted into initial frequencies, f_0, such that $f_0 = v_0/L$. Naturally, this scenario requires that the density structures form near the solar surface and become frozen-in to the flow before they are substantially accelerated to nominal solar wind speeds.

[32] Although we have identified the solar wind as a source of discrete magnetospheric pulsations, the exact mechanism generating the discrete frequencies (or scale sizes) remains unknown. One intriguing possibility is that the frequencies are related to solar oscillations. Several recent studies have reported observations of spectral peaks in the interplanetary magnetic field and particle data measured by the Ulysses spacecraft which were very close to the frequencies of solar *g*- and *p*-mode oscillations [*Thomson et al.*, 1995, 2001, 2002]. Theoretical solar *g*-mode oscillations are $<\sim 100\ \mu$Hz while the power of observed solar *p*-mode oscillations peaks in the range 1–5 mHz [*Libbrecht et al.*, 1990; *Elsworth et al.*, 1994]. While the overlap of our observed frequencies with the solar *p*-mode band could be coincidental, we outline here a hypothetical picture of how the compressional waves of solar *p*-modes might couple to solar wind density structures.

[33] The density variations studied in this paper can be classified generally as pressure balance structures (PBSs) [*McComas et al.*, 1996], in which variations in the thermal pressure are matched by opposite variations in the magnetic pressure, keeping the total pressure roughly constant. This is shown in Figure 19 where we have plotted the thermal, magnetic, and total pressures for the 4 February 1997 event. The thermal pressure was calculated assuming a mass density of protons. At the leading edge of the structure (near 1000 UT), the total pressure increased sharply, but during the interval 1200–2400 UT over which the density oscillations were observed (see Figure 5), the total pressure remained relatively constant.

[34] *Reisenfeld et al.* [1999] studied He abundances in PBSs and concluded that they were of solar origin and strongly suggested they most likely formed from polar plumes. A similar conclusion was reached by *Yamauchi and Suess* [2002] on the basis of Ulysses magnetometer observations. Polar plumes are high-density regions that are believed to originate at the boundaries of the chromospheric network and are likely associated with magnetic reconnection [*Walker et al.*, 1993; *Berger and Title*, 1996; *DeForest et al.*, 1997; *Del Zanna et al.*, 1997]. Using measurements from the SOHO Extreme Ultraviolet Imaging Telescope (EIT), *DeForest and Gurman* [1998] presented observations of outward propagating quasi-periodic sound waves in solar plumes that had a period of T = 10–15 min (f = 1.1–1.7 mHz), which is near one of the CMS frequencies. Using the white light channel (WLC) of the Ultraviolet Coronograph Spectrometer (UVCS), *Ofman et al.* [1997, 2000] showed periodic variations in the polarized brightness (a measure of the electron density) of coronal hole plumes at a solar distance of 1.9 $R_\odot$. An example of these periodic brightness variations is shown in Figure 20. This figure is adapted from *Ofman et al.* [2000] and shows the average of nine consecutive ~1 hour Fourier transforms of the polarized brightness. Clear peaks are present at f = 0.7, 1.3, and 2.4 mHz. We point out that the plume observations of *Deforest and Gurman* [1998] and *Ofman et al.* [1997, 2000] are in the polar regions of the Sun, not near the equator, where the solar wind observed by the Wind spacecraft likely originated. However, we can think of no reason why the physics of plumes would be different in the two regions. In addition, the speed of the solar wind at 1.9 $R_\odot$ is ~150 km/s so that if the structures are convected

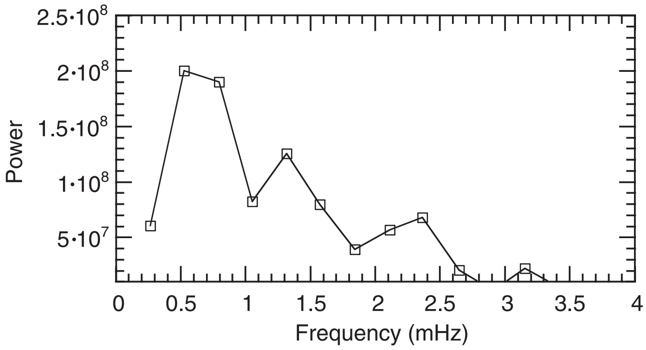

Figure 20. Average power spectrum of six consecutive ~1-hour Fourier transforms of the polarized brightness observed with the UVCS WLC in the south polar coronal hole at 1.9 $R_\odot$ on 28 February 1999. Adapted from *Ofman et al.* [2000].

with the solar wind, then the frequencies observed in the plumes would be somewhat lower than, but still of the same order as, those observed at 1 AU.

[35] A possible mechanism for the generation of the periodic solar wind density variations is interchange reconnection, which reconnects open flux tubes with closed flux tubes, leading to an influx of new plasma [*Fisk*, 1996; *Fisk and Schwadron*, 2001; *Wang*, 1998; *Crooker et al.*, 2002]. This could potentially lead to a solar wind that is structured with plasma of differing density. The compressional waves of the solar *p*-modes, which have frequencies in the mHz range, could conceivably regulate this reconnection. *Ofman et al.* [2000] suggested that it was possible that the periodic density fluctuations they observed at 1.9 $R_\odot$ could be associated with magnetic reconnection at the base of the solar corona. Though circumstantial, the evidence linking periodic pressure waves at the base of the corona, solar plumes and PBSs is intriguing enough to speculate that solar *p*-mode oscillations are the ultimate source for the periodicities observed in the solar wind number density and for the CMS frequency and lower oscillations observed in the magnetosphere. Clearly, though, more work is required before a definitive conclusion can be reached.

[36] **Acknowledgments.** We thank K. W. Ogilvie, A. J. Lazarus, and J. C. Kasper for providing the WIND SWE data and R. Lepping for providing the WIND magnetic field data. We are indebted to H. Singer for the GOES-8 magnetometer data. Data from the 210MM ground station Learmonth were provided by K. Yumoto. Polar magnetic field data are courtesy of C. T. Russell. We thank L. Ofman for providing valuable references. We also thank N. Crooker and H. Petschek for helpful discussions. Work at Boston University was supported by NASA grant NAG5-11751.

[37] Lou-Chuang Lee thanks the two reviewers for their assistance in evaluating this paper.

References

Allan, W., S. P. White, and E. M. Poulter, Impulse-excited hydromagnetic cavity and field-line resonances in the magnetosphere, *Planet. Space Sci.*, *34*, 371–385, 1986.

Anderson, B. J., M. J. Engebretson, S. P. Rounds, L. J. Zanetti, and T. A. Potemra, A statistical study of Pc 3–5 pulsations observed by the AMPTE/CCE magnetic fields experiment: 1. Occurrence distributions, *J. Geophys. Res.*, *95*, 10,495–10,523, 1990.

Berger, T. E., and A. M. Title, On the dynamics of small-scale solar wind magnetic elements, *Astrophys. J.*, *463*, 365, 1996.

Cahill, L. J., and J. R. Winckler, Periodic magnetopause oscillations observed with the GOES satellites on March 24, 1991, *J. Geophys. Res.*, *97*, 8239–8243, 1992.

Chen, L., and A. Hasegawa, A theory of long-period magnetic pulsations: 1. Steady state excitation of field line resonances, *J. Geophys. Res.*, *79*, 1024, 1974.

Chen, S., and M. G. Kivelson, On ultralow frequency waves in the lobes of the Earth's magnetotail, *J. Geophys. Res.*, *96*, 15,711, 1991.

Cornwall, J. M., Cyclotron instabilities and electromagnetic emission in the ultra low frequency and very low frequency ranges, *J. Geophys. Res.*, *70*, 61–69, 1965.

Crooker, N. U., J. T. Gosling, and S. W. Kahler, Reducing heliospheric magnetic flux from CMEs without disconnection, *J. Geophys. Res.*, *107*(A2), 1028, doi:10.1029/2001JA000236, 2002.

DeForest, C. E., and J. B. Gurman, Observation of quasi-periodic compressive waves in solar polar plumes, *Astrophys. J.*, *501*, 217–220, 1998.

DeForest, C. E., J. T. Hoeksema, J. B. Gurman, B. J. Thompson, S. P. Plunkett, R. Howard, R. C. Harrison, and D. M. Hasslerz, Polar plume anatomy: Results of a coordinated observation, *Solar Phys.*, *175*, 393–410, 1997.

Del Zanna, L., A. W. Hood, and A. W. Longbottom, An MHD model for solar coronal plumes, *Astron. Astrophys.*, *381*(3), 963–969, 1997.

Elsworth, Y., R. Howe, G. R. Isaak, C. P. McLeod, B. A. Miller, R. New, C. C. Speake, and S. J. Wheeler, Solar *p*-mode frequencies and their dependence on solar activity: Recent results from the BISON network, *Astrophys. J.*, *434*, 801–806, 1994.

Fenrich, F. R., J. C. Samson, G. Sofko, and R. A. Greenwald, ULF high- and low-m field line resonances observed with the Super Dual Auroral Radar Network, *J. Geophys. Res.*, *100*, 21,535, 1995.

Fisk, L. A., Motion of the footpoints of heliospheric magnetic field lines at the Sun: Implications for recurrent energetic particle events at high heliographic latitudes, *J. Geophys. Res.*, *101*, 15,547–15,553, 1996.

Fisk, L. A., and N. A. Schwadron, The behavior of the open magnetic field of the Sun, *Astrophys. J.*, *560*, 425–438, 2001.

Francia, P., and U. Villante, Some evidence of ground power enhancements at frequencies of global magnetospheric modes at low-latitudes, *Ann. Geophys.*, *15*, 12, 1997.

Goldstein, J., M. K. Hudson, and W. Lotko, Possible evidence of damped cavity mode oscillations stimulated by the January 1997 magnetic cloud event, *Geophys. Res. Lett.*, *26*, 3589, 1999.

Harrold, B. G., and J. C. Samson, Standing ULF modes of the magnetosphere: A theory, *Geophys. Res. Lett.*, *19*, 1811, 1992.

Herron, T. J., An average geomagnetic power spectrum for the period range 4.5 to 12,900 seconds, *J. Geophys. Res.*, *72*, 759, 1967.

Huang, C.-S., G. J. Sofko, A. V. Kustov, J. W. MacDougall, D. A. Andre, W. J. Hughes, and V. O. Papitashvili, Quasi-periodic ionospheric disturbances with a 40-min period during prolonged northward interplanetary magnetic field, *Geophys. Res. Lett.*, *27*, 1795, 2001.

Kennel, C. F., and H. E. Petschek, Limit on stably trapped particle fluxes, *J. Geophys. Res.*, *71*, 1–27, 1966.

Kepko, L., H. E. Spence, and H. J. Singer, ULF waves in the solar wind as direct drivers of magnetospheric pulsations, *Geophys. Res. Lett.*, *29*(8), 1197, doi:10.1029/2001GL014405, 2002.

Kivelson, M. G., and D. J. Southwood, Coupling of global magnetospheric MHD eigenmodes to field line resonances, *J. Geophys. Res.*, *91*, 4345–4351, 1986.

Kivelson, M. G., J. Etcheto, and J. G. Trotignon, Global compressional oscillations of the terrestrial magnetosphere: The evidence and a model, *J. Geophys. Res.*, *89*, 9851–9856, 1984.

Korotova, G. I., and D. G. Sibeck, A case study of transient event motion in the magnetosphere and in the ionosphere, *J. Geophys. Res.*, *100*, 35, 1995.

Lee, D.-H., and R. L. Lysak, Magnetospheric ULF wave coupling in the dipole field: The impulsive excitation, *J. Geophys. Res.*, *94*, 17,097–17,103, 1989.

Lee, D.-H., and R. L. Lysak, Monochromatic ULF wave excitation in the dipole magnetosphere, *J. Geophys. Res.*, *96*, 5811–5817, 1991.

Lepping, R. P., et al., The WIND magnetic field investigation, *Space Sci. Rev.*, *71*, 207, 1995.

Lessard, M. R., M. K. Hudson, B. J. Anderson, R. L. Arnoldy, H. Lühr, G. D. Reeves, N. Sato, and A. T. Weatherwax, Evidence for a global disturbance with monochromatic pulsations and energetic electron bunching, *J. Geophys. Res.*, *104*, 7011, 1999.

Libbrecht, K. G., M. F. Woodard, and J. M. Kaufman, Frequencies of solar oscillations, *Astrophys. J. Suppl.*, *74*, 1129–1149, 1990.

Mann, I. R., A. N. Wright, K. J. Mills, and V. M. Nakariakov, Excitation of magnetospheric waveguide modes by magnetosheath flows, *J. Geophys. Res.*, *104*, 333–354, 1999.

Matsuoka, H., K. Takahashi, K. Yumoto, B. J. Anderson, and D. G. Sibeck, Observation and modeling of compressional Pi 3 magnetic pulsations, *J. Geophys. Res.*, *100*, 12,103–12,115, 1995.

McComas, D. J., G. W. Hoogeveen, J. T. Gosling, J. L. Phillips, M. Neugebauer, A. Balogh, and R. Forsyth, Ulysses observations of pressure-balance structures in the polar solar wind, *Astron. Astrophys.*, *316*, 368–373, 1996.

Nikutowski, B., J. Büechner, S. Klimov, S. Romanov, A. Petrukovich, and S. Savin, Long periods of the ULF wave activity in the Earth's magnetotail lobes, *Adv. Space Res.*, *18*, 55–58, 1996.

Nishida, A., Possible origin of transient dusk-to-dawn electric field in the nightside magnetosphere, *J. Geophys. Res.*, *84*, 3409–3412, 1979.

Nosé, M., T. Iyemori, M. Suguira, and J. A. Slavin, A strong dawn/dusk asymmetry in Pc5 pulsation occurrence observed by the DE-1 satellite, *Geophys. Res. Lett.*, *22*(15), 2053–2056, 1995.

Ofman, L., M. Romoli, G. Poletto, G. Noci, and J. L. Kohl, Ultraviolet Coronograph Spectrometer observations of density fluctuations in the solar wind, *Ap. J. Lett.*, *491*, 111, 1997.

Ofman, L., M. Romoli, G. Poletto, G. Noci, and J. L. Kohl, UVCS WLC observations of compressional waves in the south polar coronal hole, *Ap. J.*, *529*, 592–598, 2000.

Ogilvie, K. W., et al., SWE, a comprehensive plasma instrument for the Wind spacecraft, *Space Sci. Rev.*, *71*, 55, 1995.

Reisenfeld, D. B., D. J. McComas, and J. T. Steinberg, Evidence of a solar origin for pressure balance structures in the high-latitude solar wind, *Geophys. Res. Lett.*, *26*, 1805–1808, 1999.

Rinnert, K., Quasi-periodic precipitation with periods between 40 and 60 minutes, *Ann. Geophys.*, *14*, 707, 1996.

Ruohoniemi, J. M., R. A. Greenwald, K. B. Baker, and J. C. Samson, HF radar observations of Pc 5 field line resonances in the midnight early morning MLT sector, *J. Geophys. Res.*, *96*, 15,697, 1991.

Samson, J. C., R. A. Greenwald, J. M. Ruohoniemi, T. J. Hughes, and D. D. Wallis, Magnetometer and radar observations of magnetospheric cavity modes in the Earth's magnetosphere, *Can. J. Phys.*, *69*, 929, 1991.

Samson, J. C., D. D. Wallis, T. J. Hughes, F. Creutzberg, J. M. Ruohoniemi, and R. A. Greenwald, Substorm intensifications and field line resonances in the nightside magnetosphere, *J. Geophys. Res.*, *97*, 8495, 1992a.

Samson, J. C., B. G. Harrold, J. M. Ruohoniemi, R. A. Greenwald, and A. D. M. Walker, Field line resonances associated with MHD waveguides in the magnetosphere, *Geophys. Res. Lett.*, *19*, 441, 1992b.

Samson, J. C., L. L. Cogger, and Q. Pao, Observations of field line resonances, auroral arcs, and auroral vortex structure, *J. Geophys. Res.*, *101*, 17,373, 1996.

Sarafopoulos, D. V., Long duration Pc 5 compressional pulsations inside the Earth's magnetotail lobes, *Ann. Geopys.*, *13*, 926–937, 1995.

Singer, H. J., C. T. Russell, M. G. Kivelson, E. W. Greenstadt, and J. V. Olson, Evidence for the control of Pc 3, 4 magnetic pulsations by the solar wind velocity, *Geophys. Res. Lett.*, *4*, 377–379, 1977.

Singer, H. J., L. Matheson, R. Grubb, A. Newman, and S. D. Bouwer, Monitoring space weather with GOES Magnetometers, *SPIE Proc*, *2812*, 1996.

Southwood, D. J., Some features of field line resonances in the magnetosphere, *Planet Space Sci.*, *22*, 483, 1974.

Stephenson, J. A. E., and A. D. M. Walker, HF radar observations of Pc5 ULF pulsations driven by the solar wind, *Geophys. Res. Lett.*, *29*(9), 1297, doi:10.1029/2001GL014291, 2002.

Takahashi, K., ULF waves: 1997 IAGA division 3 reporter review, *Ann. Geophys.*, *16*, 787–803, 1998.

Thomson, D. J., C. G. Maclennan, and L. J. Lanzerotti, Propagation of solar oscillations through the interplanetary medium, *Nature*, *376*, 139, 1995.

Thomson, D. J., L. J. Lanzerotti, and C. G. Maclennan, Interplanetary magnetic field: Statistical properties and discrete modes, *J. Geophys. Res.*, *106*, 15,941–15,963, 2001.

Thomson, D. J., L. J. Lanzerotti, and C. G. Maclennan, Studies of some statistics of the interplanetary magnetic field and implications for discrete modes, *Adv. Space Res.*, *29*, 1911–1916, 2002.

Tsyganenko, N. A., and D. P. Stern, Modeling the global magnetic field of the large-scale birkeland current systems, *J. Geophys. Res.*, *101*, 27,187–27,198, 1996.

Walker, A. D. M., J. M. Ruohoniemi, K. B. Baker, R. A. Greenwald, and J. C. Samson, Spatial and temporal behavior of ULF pulsations observed by the Goose Bay HF radar, *J. Geophys. Res.*, *97*, 12,187, 1992.

Walker, A. B. C., Jr., C. E. DeForest, R. B. Hoover, and T. W. Barbee Jr., Thermal and density structure of solar plumes, *Solar Phys.*, *148*, 239, 1993.

Wang, Y.-M., Network activity and the evaporative formation of polar plumes, *Astrophys. J.*, *501*, L145–L150, 1998.

Yamauchi, Y., and S. T. Suess, Relation between pressure balance structures and polar plumes from Ulysses high-latitude observations, *Geophys. Res. Lett.*, *29*(10), 1383, doi:10.1029/2001GL013820, 2002.

Yumoto, K., Generation and propagation mechanisms of low-latitude magnetic pulsations—A review, *J. Geophys. Res.*, *60*, 79–105, 1986.

Yumoto, K., K. Takahashi, T. Saito, F. W. Menk, B. J. Fraser, T. A. Potemra, and L. J. Zanetti, Some aspects of the relation between Pi 1–2 magnetic pulsations observed at L = 1.3–2.1 on the ground and substorm-associated magnetic field variations in the near-Earth magnetotail observed by AMPTE CCE, *J. Geophys. Res.*, *94*, 3611–3618, 1989.

Ziesolleck, C. W. S., and D. R. McDiarmid, Auroral latitude Pc 5 field line resonances: Quantized frequencies, spatial characteristics, and diurnal variations, *J. Geophys. Res.*, *99*, 5817, 1994.

Ziesolleck, C. W. S., and D. R. McDiarmid, Statistical survey of auroral latitude Pc 5 spectral and polarization characteristics, *J. Geophys. Res.*, *100*, 19,299–19,312, 1995.

L. Kepko and H. E. Spence, Center for Space Physics, Boston University, 725 Commonwealth Ave., Boston, MA 02215, USA. (lkepko@bu.edu; spence@bu.edu)