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Relative occurrence rates and connection of discrete frequency oscillations in the solar wind density and dayside magnetosphere

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Recommended Citation

Viall, N. M., L. Kepko, and H. E. Spence (2009), Relative occurrence rates and connection of discrete frequency oscillations in the solar wind density and dayside magnetosphere, J. Geophys. Res.,114, A01201, doi:10.1029/2008JA013334.

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 114, A01201, doi:10.1029/2008JA013334, 2009

Relative occurrence rates and connection of discrete frequency oscillations in the solar wind density and dayside magnetosphere

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Received 17 April 2008; revised 3 October 2008; accepted 27 October 2008; published 3 January 2009.

[1] We present an analysis of the occurrence distributions of statistically significant apparent frequencies of periodic solar wind number density structures and dayside magnetospheric oscillations in the $f = 0.5-5.0$ mHz range. Using 11 years (1995–2005) of solar wind data, we identified all spectral peaks that passed both an amplitude test and a harmonic F test at the 95% confidence level in 6-hour data segments. We find that certain discrete frequencies, specifically $f = 0.7$, 1.4, 2.0, and 4.8 mHz, occur more often than do other frequencies over those 11 years. We repeat the analysis on discrete oscillations observed in 10 years (1996–2005) of dayside magnetospheric data. We find that certain frequencies, specifically $f = 1.0$, 1.5, 1.9, 2.8, 3.3, and 4.4 mHz, occur more often than do other frequencies over those 10 years. Many of the enhancements found in the magnetospheric occurrence distributions are similar to those found in the solar wind. Lastly, we counted the number of times the same discrete frequencies were identified as statistically significant using our two spectral tests on corresponding solar wind and magnetospheric 6-hour time series. We find that in 54% of the solar wind data segments in which we identified a spectral peak, at least one of the same discrete frequencies was statistically significant in the corresponding magnetospheric data segment. Our results argue for the existence of inherent apparent frequencies in the solar wind number density that directly drive global magnetospheric oscillations at the same discrete frequencies, although the magnetosphere also oscillates through other physical mechanisms.

Citation: Viall, N. M., L. Kepko, and H. E. Spence (2009), Relative occurrence rates and connection of discrete frequency oscillations in the solar wind density and dayside magnetosphere, *J. Geophys. Res.*, *114*, A01201, doi:10.1029/2008JA013334.

1. Introduction

[2] Sets of multiple, discrete, magnetospheric ULF oscillations have been observed in satellite [*Lyons et al.*, 2002], HF radar [*Ruohoniemi et al.*, 1991; *Samson et al.*, 1991; *Walker et al.*, 1992; *Fenrich et al.*, 1995] and ground magnetometer [*Samson et al.*, 1992a; *Ziesolleck and McDiarmid*, 1994, 1995; *Chisham and Orr*, 1997; *Villante et al.*, 2001] measurements for more than a decade. Because of the repeatability, global nature, and stability of the multiple discrete oscillations over several hours, the observations have been interpreted as manifestations of magnetospheric cavity and/or waveguide modes. In these models, the solar wind provides broadband energy that couples to the eigenmodes of the magnetospheric cavity. Therefore the observed discrete frequencies depend on internal properties of the magnetosphere, principally the radial Alfvén speed profile [e.g., *Harrold and Samson*, 1992; *Samson et al.*, 1992b].

[3] Among the sets of discrete frequencies observed is the most commonly cited set occurring near $f = 1.3$, 1.9, 2.6 and 3.4 mHz [*Samson et al.*, 1991; *Fenrich et al.*, 1995]. Since the initial work on these frequencies, other research groups have observed slightly different sets, both in event and statistical studies. We begin with a discussion of statistical analyses using the average spectral power observed in the magnetosphere. *Francia and Villante* [1997] analyzed the average spectra recorded at a low-latitude ground magnetic field data from 1985–1986 and 1989–1990 and identified spectral power enhancements near $f = 1.4$, 1.9, 2.5, 3.6, and 4.2 mHz, with a smaller enhancement near $f = 0.7$ mHz. They concluded that their results provided evidence in support of global cavity modes of the magnetosphere. *Villante et al.* [2001] studied the average dayside spectra of the magnetic field recorded at a low-latitude magnetometer for 1997–1998 and identified significant spectral enhancements near $f = 1.1$, 1.7, 2.3, 2.8, and 3.7 mHz. *Villante et al.* [2001] argued that while these observed spectral power enhancements varied slightly from the more commonly cited set, these also represented manifestations of global magnetospheric cavity mode oscillations. *Francia et al.* [2005] analyzed the average spectra of magnetic field recorded at an Antarctic magnetometer in 1996. They identified discrete power enhancements at $f = 1.8$, 2.5 and

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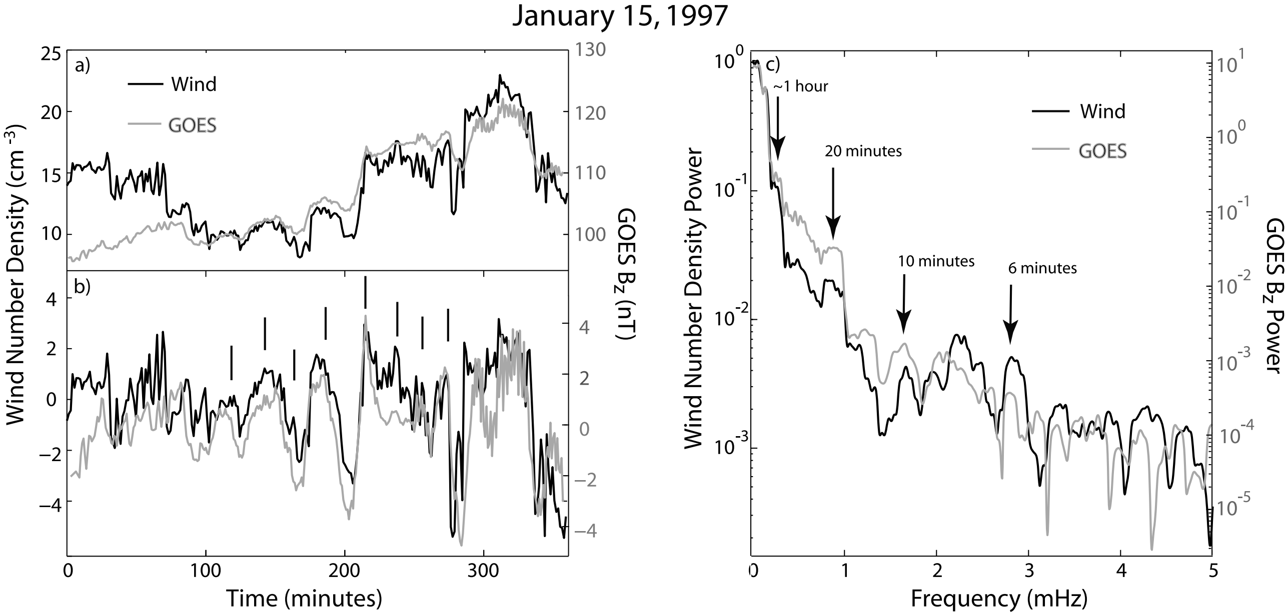

Figure 1. (a) Solar wind number density (black) with +40-minute time shift and GOES-8 magnetic field (Bz) (gray) data for 15 January 1997. (b) Same as Figure 1a but with the background trend removed. Tick marks indicate a common 20-minute periodicity. (c) Fourier amplitude spectra of both time series shown in Figure 1a. Arrows indicate common spectral enhancements that are observed near $f = 0.2$, 0.8, 1.7, and 2.8 mHz.

3.1 mHz, and concluded that the selective energization of those frequencies may have been the result of waveguide modes driven by flows in the magnetosheath. *Thomson et al.* [2007] identified not only discrete frequencies in the magnetosphere's magnetic field (observed with both ground and satellite magnetometers), but also identified the same discrete frequencies in the interplanetary magnetic field, and related them to solar oscillations.

[4] While the analyses mentioned above utilized average spectra, other research groups have instead analyzed occurrence distributions of discrete frequencies observed in shorter time intervals. Note that analyses using average spectra [e.g., *Villante et al.*, 2001; *Francia and Villante*, 1997] differ from those that calculate the occurrence rate of discrete frequencies. Although both techniques reveal information about the wave activity in the magnetosphere, the former technique reveals information regarding the overall distribution of spectral power, while the latter is regarding oscillation at particular, discrete frequencies. *Ziesolleck and McDiarmid* [1994] reported on event studies of Pc 5 ($f = 1.67 - 6.67$ mHz) magnetospheric oscillations in which various sets of multiple discrete frequencies were observed, although the frequency sets often differed from the set of *Samson et al.* [1991]. In a follow-up study, *Ziesolleck and McDiarmid* [1995] calculated the occurrence rate of discrete Pc 5 frequencies observed by auroral latitude magnetometers at all local times and found a broad distribution across their analyzed frequency range (1–5 mHz), with occurrence enhancements near $f = 2$ and 3 mHz, and a smaller occurrence enhancement near 4 mHz. *Chisham and Orr* [1997] calculated the occurrence rate of discrete Pc 5 frequencies observed by midlatitude magnetometers and found occurrence enhancements near $f = 2.1$, 3.1, 3.9 and possibly 4.9 mHz, largely in agreement with the observations of *Ziesolleck and McDiarmid* [1995]. *Baker et al.* [2003] conducted a 10-year study of magnetic oscillations observed in the CANOPUS magnetometer data. In contrast with the other statistical analyses demonstrating that particular frequencies occur more often than others in the magnetosphere, *Baker et al.* [2003] concluded that there were no enhancements in the occurrence distribution of discrete ground based pulsation frequencies in the Pc 5 frequency band that persisted across all 10 years.

[5] Recent event studies have revealed the existence of highly periodic number density (and dynamic pressure) variations upstream in the solar wind that were followed by magnetospheric oscillations [*Kepko et al.*, 2002; *Stephenson and Walker*, 2002; *Kepko and Spence*, 2003; *Villante et al.*, 2007]. These studies questioned the conclusion that observations of multiple, discrete, ULF oscillations are necessarily manifestations of magnetospheric cavity modes. Figure 1 is an event similar to those studied by *Kepko et al.* [2002] and *Kepko and Spence* [2003], in which periodic solar wind number density structures directly drove magnetospheric oscillations [from *Viall et al.*, 2008]. Here we show a 6-hour time series from 15 January 1997 of the solar wind number density (black), measured by the Wind SWE instrument, and the B_z (vertical) magnetic field component at geosynchronous orbit (gray), measured by the GOES-8 magnetometer. Wind was located at (121, 28, 9) R_E in GSE coordinates and GOES-8 was moving through the prenoon sector during the event. We applied a +40-minute time shift to the Wind data to account for propagation. Figure 1b shows the Wind number density and GOES magnetic field time series with the background trends removed. Tick marks identify clear 20-minute ($f = 0.8$ mHz) oscillations observed

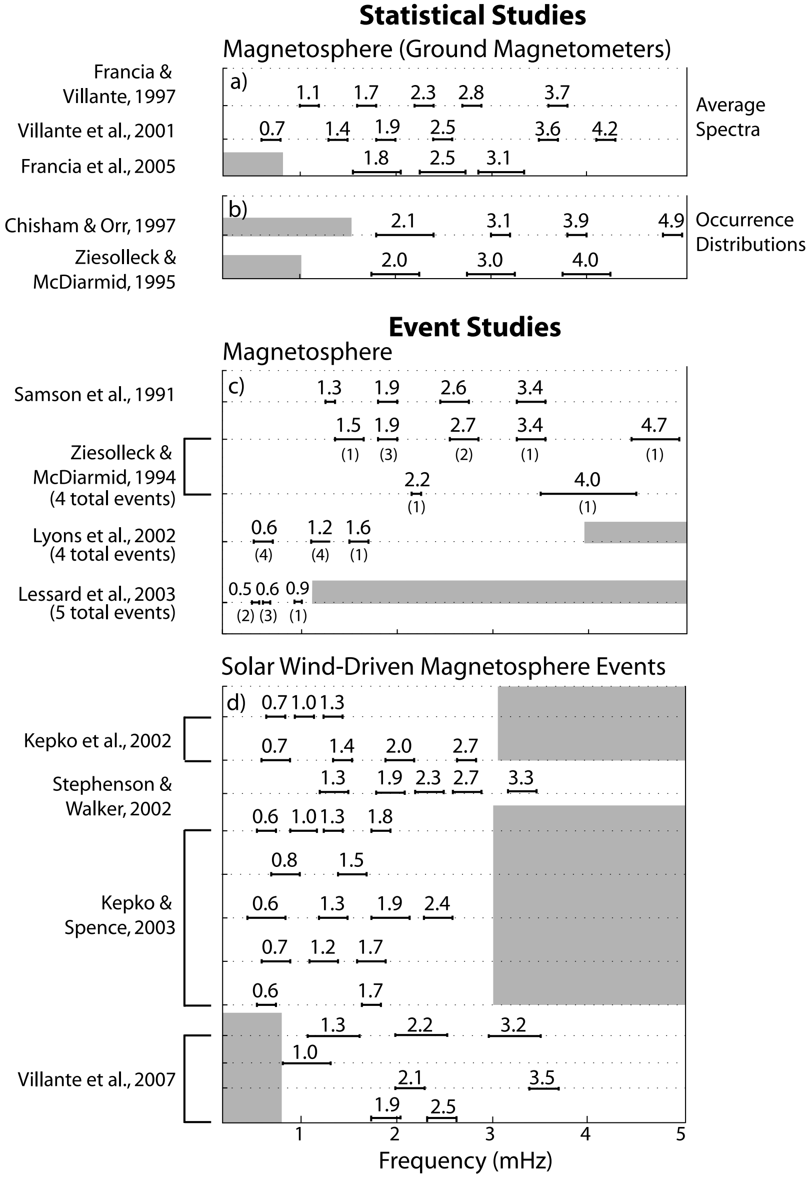

Figure 2. (a) List of enhancements in the average spectra of magnetospheric magnetic field. (b) List of enhancements in the occurrence distribution of magnetospheric frequencies. (c) Frequencies identified in four representative event studies of magnetospheric oscillations. The total number of events examined for each paper and the number of times each frequency was observed in each paper are indicated in parentheses. (d) Frequencies identified in event studies of magnetospheric oscillations that were directly driven by solar wind periodic density structures. Gray bars indicate frequency range not analyzed.

in both the solar wind and the magnetosphere. The spectral estimates (described in section 2) of both time series, calculated over the interval 11:42–17:42 UT (−40 minutes for the Wind data), show spectral enhancements near $f = 0.2$, 0.8, 1.7 and 2.8 mHz (Figure 1c). In this example, the common spectral peaks in the Wind and GOES spectral estimates correlate well at frequencies less than ~3 mHz but are poorly correlated above. This is likely due to a cutoff frequency in the magnetosphere, above which the solar wind cannot directly drive globally coherent oscillations [*Kepko and Spence*, 2003].

[6] Events such as these led *Kepko et al.* [2002] to argue that the periodic number density variations, shown to be periodic dynamic pressure variations, directly drove discrete oscillations at the same periodicity in the magnetosphere. In their follow-up paper, *Kepko and Spence* [2003] used the observed dynamic pressure from two of their event studies to drive a magnetospheric magnetic field model, and demonstrated that the addition of periodic solar wind number density variations reproduced the observed magnetospheric oscillations in the magnetospheric model. Recently, *Motoba et al.* [2007] used a global MHD simulation to examine the global response of the magnetosphere-ionosphere system to a 10-minute solar wind density oscillation. They demonstrated that the global geomagnetic field oscillations had a

quasi-sinusoidal waveform at the same periodicity as the solar wind number density oscillations (10 minutes).

[7] Frequencies less than 1 mHz are lower than the frequencies reasonably allowed for in magnetospheric cavity mode models and the observation of discrete oscillations at frequencies below 1 mHz provides additional evidence in support of the idea of directly driven magnetospheric oscillations. *Lessard et al.* [2003] showed five examples of global magnetospheric oscillations at discrete frequencies below 1 mHz, and suggested that either solar wind oscillations were driving the magnetospheric oscillations or that the oscillations propagated sunward from the magnetotail. They pointed out that the latter idea seemed unlikely. In an event study, *Erikkson et al.* [2006] correlated Pc 5 pulsations observed in HF radar with upstream solar wind pressure oscillations and found particularly good correlation in the 0.8–1.2 mHz frequency band. We note that the example of directly driven magnetospheric oscillations shown in Figure 1 represents an instance when similar discrete frequencies were observed upstream in the solar wind and in the magnetosphere, with frequencies both above (f = 1.7 mHz) and well below (f = 0.2, 0.8 mHz) 1 mHz occurring simultaneously.

[8] Figure 2 summarizes the discrete spectral or occurrence enhancements identified in the magnetospheric statistical research as well as representative event studies of discrete frequency observations discussed in this introduction. The values and approximated bandwidths are as presented in the respective papers. The gray bars indicate the range of frequencies not examined. While there is variability in the statistical and event study results, overall there seems to be a pattern to the frequencies that different research groups have observed. For example, frequencies in bands near f = 0.7, 1.2–1.5 and 1.9–2.0 mHz are often observed in the event studies as well as the statistical results. These previous studies suggest that particular sets of discrete frequencies occur more often than others in the magnetosphere, but that the frequency bands are broad (perhaps a few tenths of mHz wide) and probably wander slightly.

[9] Intervals in which multiple discrete frequency oscillations are observed in the magnetosphere occur regularly. As Figure 2 illustrates, there is evidence that certain frequencies occur more often than others. Furthermore, *Kepko et al.* [2002] and *Kepko and Spence* [2003] demonstrated that, on occasion, solar wind number density variations occur at multiple, discrete frequencies and directly drive magnetospheric oscillations at the same discrete frequencies. However, these previous papers presented only a few event studies and did not determine if the discrete apparent frequencies in the solar wind were recurrent. Additionally, event studies cannot determine how often the periodic solar wind number density structures directly drive magnetospheric oscillations at the same discrete frequencies.

[10] *Kepko and Spence* [2003] argued that the observed solar wind number density oscillations were not propagating waves, but were periodic structures frozen in the solar wind on timescales at a minimum equivalent to the propagation time from the Wind spacecraft (L1) to the magnetosphere. They suggested that the length scales, rather than the frequencies of the periodic number density structures might be the appropriate parameter to examine. *Viall et al.* [2008] analyzed the radial length scales of periodic solar wind number density structures in 11 years of Wind data, and showed that periodic number density structures occurred at particular radial length scales more often than at others. As periodic density structures convect past the magnetosphere, they appear at apparent frequencies in Earth's reference frame, with frequencies dependent on the radial length scale of the structure and the solar wind velocity. The solar wind velocity occurrence distribution at 1 AU is bimodal during solar minimum, having a peak associated with both slow and fast wind, and is a continuum during solar maximum with a single peak in the velocity distribution [e.g., *Zurbuchen et al.*, 2002]. *Viall et al.* [2008] found that periodic radial length scales occurred in a majority of the solar wind data analyzed, suggesting that periodic length scales are a prevalent feature of ambient solar wind. Each radial length scale will appear in Earth's reference frame most often at the apparent frequency associated with the most probable solar wind velocity. Therefore the periodic solar wind number density structures may occur at particular apparent frequencies more often than at others.

[11] In this paper, we present an analysis of the relative occurrence rate of statistically significant spectral enhancements between f = 0.5 and 5.0 mHz identified in solar wind number density data and dayside GOES magnetometer data. We answer the question of whether the occurrence distributions of significant spectral peaks contain enhancements at particular frequencies. We first describe data preparation and analysis methodology, which utilizes the techniques of *Thomson* [1982] and *Mann and Lees* [1996]. We then determine the relative occurrence rate of statistically significant oscillations in 6-hour intervals of solar wind number density and GOES magnetometer data. The results from both data sets exhibit enhancements at particular frequencies in the occurrence distributions of significant spectral peaks. For both data sets, we observe the occurrence enhancements at similar frequencies consistently over the entire analyzed interval. The enhancements in the occurrence distribution of magnetospheric frequencies are similar to, but not exactly the same as, the enhancements in the solar wind occurrence distribution, implying that the magnetosphere is often directly driven, but also oscillates at frequencies in the f = 0.5–5.0 mHz range due to other physical processes. Finally, we count the number of times the same discrete frequencies were identified as statistically significant on corresponding solar wind and magnetospheric time series. This provides an estimate of how often solar wind number density structures directly drive the same discrete oscillations in the magnetosphere.

2. Methods

[12] We examined 11 years (1995–2005) of number density measurements from the Solar Wind Experiment (SWE) on the Wind spacecraft [*Ogilvie et al.*, 1995]. Following *Viall et al.* [2008], we interpolated the solar wind data to a common 100-second time step, and analyzed overlapping 6-hour data segments, with a 10-minute shift. We excluded from our analysis all segments that contained shocks, discontinuities, data jumps, data gaps, and data obtained inside the magnetosphere.

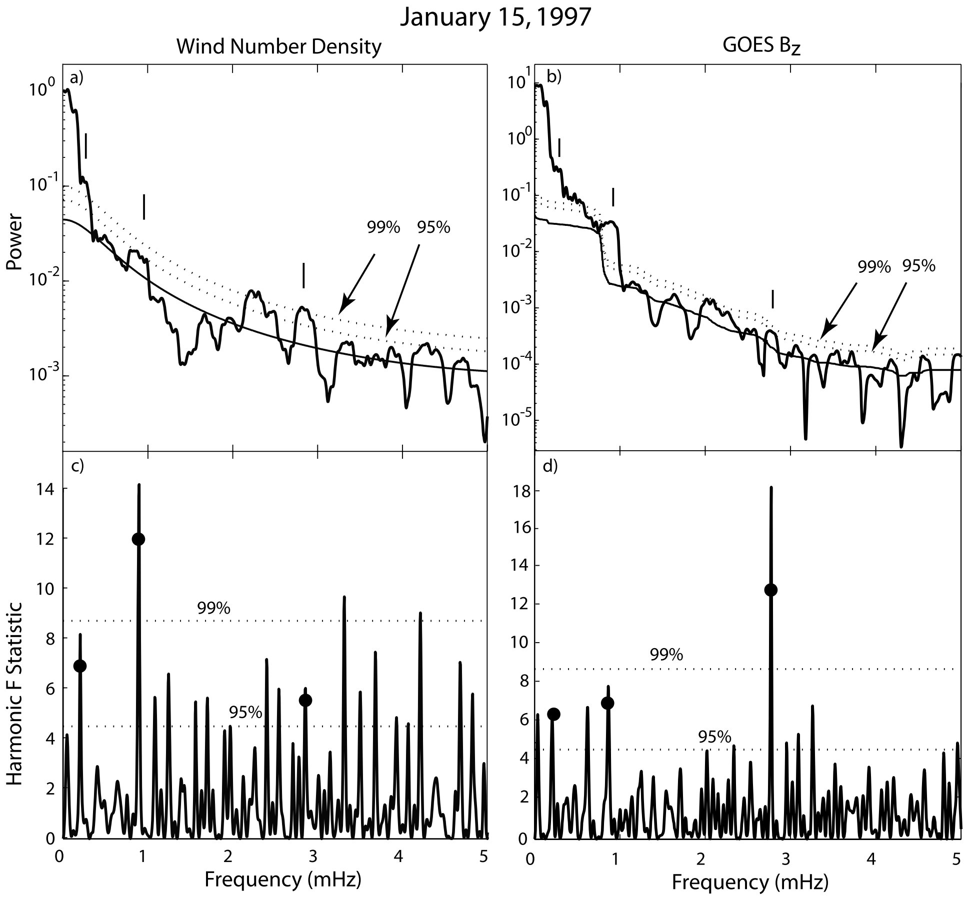

Figure 3. (a and b) Fourier spectral estimates: autoregressive background fit (solid line), and narrow band amplitude test at the 95% and 99% significance levels (dashed lines) of the corresponding solar wind and magnetospheric data, respectively, from the 15 January 1997 event shown in Figure 1. (c and d) A modified *F* test for phase coherent signals (harmonic *F* test), with dashed lined indicating the 95% and 99% significance levels. Three spectral peaks pass both tests simultaneously at the 95% level and are indicated with vertical ticks in Figures 3a and 3b and dots in Figures 3c and 3d.

[13] For the dayside magnetosphere analysis, we examined 10 years (1996–2005) of the vertical (z) component of the magnetic field data, taken with the GOES magnetometer [*Singer et al.*, 1996], which has a 60-second sampling rate. Because of failure of the transverse component of the GOES-7 magnetometer from May 1993 onwards, we were unable to obtain usable data for 1995 (H. Singer, private communication). We used data obtained with GOES 8 for 1996–1998, and data obtained with GOES 10 for 1999–2005. As with the solar wind data, we analyzed overlapping 6-hour segments, stepping by 10 minutes, but analyzed only segments that had a mean time within one hour of local noon. When the solar wind dynamic pressure oscillations directly drive magnetospheric oscillations, the magnetospheric response is most notable on the dayside regions. While the interaction is a global one, on the nightside and on the flanks the directly driven oscillations may occur in conjunction with other dynamics.

[14] We refer the reader to *Viall et al.* [2008] for a complete description of the spectral technique we employ, as well as our data preparation. The spectral analysis technique is based on multitaper windowing [*Thomson*, 1982], an autoregressive background fit, and a modified *F* test [*Mann and Lees*, 1996]. We require that a signal pass both the *F* test, which tests for phase coherent signals, and the narrow band test, which tests for significant power relative to the background spectral shape, at the 95% confidence levels. For the solar wind number density, we model the background using a first-order autoregressive (AR(1)) function, while for the magnetospheric field we use a median smoothed spectra. The solar wind is turbulent, resulting in a red noise spectrum that can be modeled using the spectra of the AR(1) process; the dayside magnetosphere is not well approximated by the AR(1) function because it is not fully turbulent.

[15] We perform spectral analysis on the solar wind and magnetospheric data segments using the criteria discussed above and by *Viall et al.* [2008]. Figure 3 shows the results of the spectral analysis technique applied to the Wind number density time series and the GOES magnetic field time series from the 15 January 1997 event presented in Figure 1. The spectral estimates of the solar wind number density and magnetospheric Bz calculated using the multitaper method are plotted in Figures 3a and 3b respectively,

Table 1. Statistics of the Analyzed Segments[a]

	SW Segments Analyzed		SW, ≥ 1 Significant Frequency		Magnetosphere Segments Analyzed		Magnetosphere, ≥ 1 Significant Frequency	
Year	*n*	%	*n*	%	*n*	%	*n*	%
1995	30,814	57	16,751	54	. . .	. . .	. . .	. . .
1996	27,188	51	14,852	55	4392	93	2362	54
1997	24,356	45	13,105	54	4277	90	2492	58
1998	21,205	39	13,576	64	4383	92	2542	58
1999	8969	17	5297	59	3589	76	1974	55
2000	11,789	22	7694	65	4710	99	2774	59
2001	6381	12	4176	65	4724	99	2730	58
2002	11,302	21	7192	64	4709	99	2707	57
2003	18,467	34	11,080	60	4739	99	2547	54
2004	21,228	39	12,805	60	4707	99	2662	57
2005	27,639	51	17,380	63	2479	52	1409	57

[a] The first (third) column shows the total number and percentage of all of the 6-hour intervals that were analyzed for each year in the solar wind (dayside magnetosphere). Those numbers indicate how many segments we removed using the criteria discussed in section 2. The second (fourth) column shows the total number and percentage of analyzed segments that contained at least one statistically significant frequency between $f = 0.5$ and 5.0 mHz in the solar wind (dayside magnetosphere).

along with the background spectra (solid line) and the narrow band test thresholds at both the 95% and 99% levels (dashed lines). At the 95% confidence level, $f = 0.2$, 0.8, 2.2, 2.8 and 4.2 mHz pass the narrow band (amplitude) test for the solar wind spectra. At the 95% confidence level, $f = 0.2$, 0.8, 2.1, 2.3, 2.8, 3.8 and 4.5 mHz pass the narrow band test for the magnetospheric spectra. Figures 3c and 3d show the results from the F test of both 6-hour time series. Seventeen frequencies pass the F test at the 95% confidence level (lower dashed line) for the solar wind data, and ten pass the F test for the magnetospheric data. Requiring that frequencies pass both tests simultaneously considerably reduces the number of peaks counted as compared to either test alone. Our requirement that frequencies pass both tests simultaneously at the 95% level yields $f = 0.2$, 0.8 and 2.8 mHz (indicated with vertical dashes in Figure 3a and dots in Figure 3c). The same three frequencies passed both tests simultaneously for the 6-hour magnetosphere data segment. The $f \sim 0.8$ mHz peak identified in this analysis is the $\sim$20 minute oscillation we identified visually in both of the time series presented in Figure 1.

[16] We applied this spectral technique to the Wind and GOES data sets, and calculated occurrence distributions of statistically significant frequencies. To improve counting statistics, we calculated occurrence distributions for 3-year intervals. The occurrence distributions were calculated by counting the number of times a frequency was found in a $6\Delta f$ wide band, shifting by $3\Delta f$ for each subsequent occurrence distribution point. $6\Delta f$ is the inherent bandwidth of the multitaper spectral estimate as we applied it here. We then applied the bootstrap method to determine which enhancements were statistically significant in the occurrence distributions. The bootstrap method and our implementation of it are discussed in more detail by *Viall et al.* [2008]. Briefly, for each 3-year interval we take randomly sampled sets of the statistically significant frequencies to produce 1000 (500) different occurrence distributions of frequencies found in the magnetosphere (solar wind). For each bootstrap sample, we calculated an occurrence distribution and background fit. Next, we subtracted the fit and calculated the residual for each bootstrap sample. We consider an occurrence enhancement statistically significant if the mean residual at that frequency is at least one standard deviation above zero, however we focus our analysis on enhancements that are two or more standard deviations above zero.

3. Results

3.1. Solar Wind Number Density

[17] We analyzed 11 years of solar wind number density data from Wind and recorded spectral peaks that passed both the narrow band test and a modified F test simultaneously at the 95% confidence level. The number of 6-hour segments analyzed and the number that contained at least one significant frequency between $f = 0.5$ and 5.0 mHz (the Nyquist frequency) are shown in Table 1. The low numbers for 1999–2002 are due to the Wind perigee passes, which we explicitly excluded from analysis. With these frequencies, we calculated the occurrence distributions of statistically significant frequencies between $f = 0.5$ and 5.0 mHz. While all frequencies in the analyzed frequency range were identified at least some of the time, some frequencies were observed much more often than others, resulting in enhancements in the occurrence distributions at particular frequencies. Using the same methods as described by *Viall et al.* [2008], we test for statistically significant enhancements in the occurrence distribution using the bootstrap method.

[18] Figure 4 shows the mean residuals calculated using the bootstrap occurrence distributions of frequencies identified in 3-year intervals, stepping by one year. Using 3-year occurrence distributions smoothes out year-to-year variations, improves counting statistics, and reveals underlying stability of the observed frequency sets. The uncertainty (±one sigma) of the residual value at each frequency is indicated with a vertical line and dots indicate statistically significant occurrence enhancements at the greater than one (light gray), two (dark gray) and three (black) standard deviation thresholds. The uncertainty is very small relative to the occurrence enhancement amplitudes. Figure 4 shows that, for a given occurrence distribution, some frequencies occur more often than others. Four bands centered near $f =$ 0.7, 1.4, 2.0, and 4.8 mHz are statistically significant at the three-sigma level for the majority of the nine

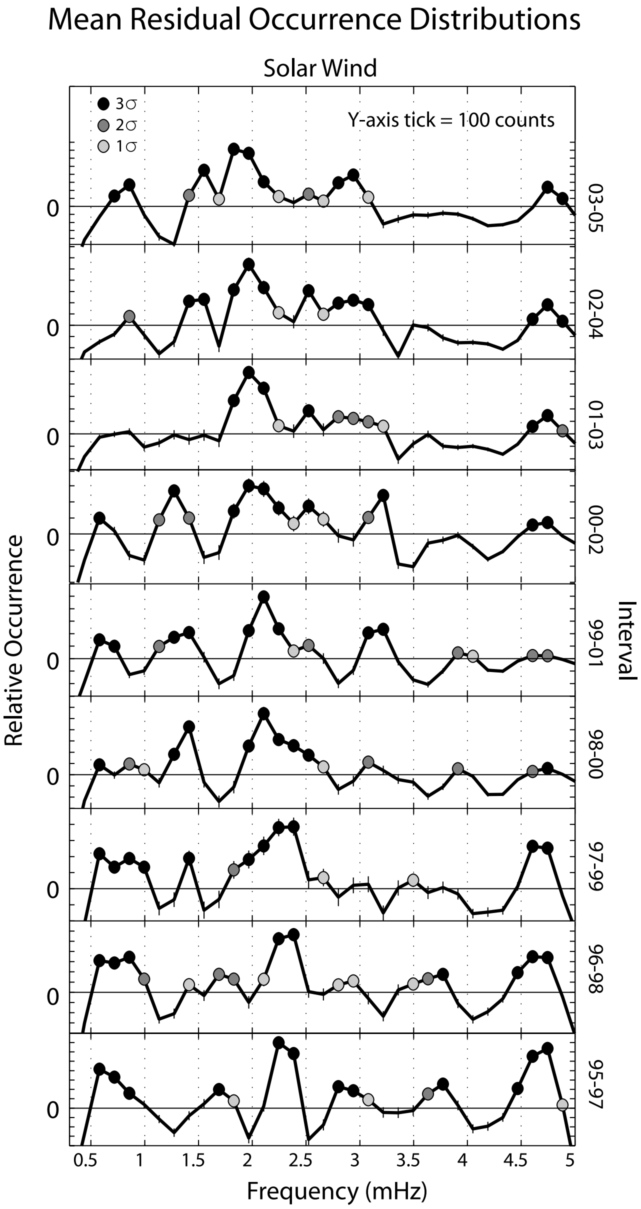

Figure 4. Mean residuals of 3-year occurrence distributions of all statistically significant frequencies for 1995–2005 found in the solar wind number density. Vertical lines at each frequency indicate ±1 standard deviation of the residual at that frequency, and dots indicate statistically significant occurrence enhancements at the 1 (light gray), 2 (dark gray), and 3 (black) standard deviation thresholds. y axis tick marks indicate 100 counts. The horizontal line indicates a mean residual value of zero.

intervals. These enhancements are broad, sometimes as wide as 0.5 mHz, and the center frequency shifts slightly from distribution to distribution. The frequency sets evolve gradually over the 11-year period as well. For example, the two peaks near $f = 1.8$ and 2.4 mHz in 1995–1997 appear to merge into a single peak near 2 mHz. Similarly, a peak near 2.8 mHz in 1995–1997 gradually disappears in subsequent years, and then reappears in 2001–2003.

3.2. Dayside Magnetospheric Oscillations

[19] We analyzed 10 years (1996–2005) of the B_Z component of the magnetic field in the dayside magnetospheric data, identifying discrete oscillations between $f = 0.5$ and 5.0 mHz. As with the solar wind, the number of 6-hour segments analyzed and the number that contained at least one significant frequency between $f = 0.5$ and 5.0 mHz are shown in Table 1. In general, the number of analyzed segments is lower for the magnetosphere than the solar wind, because we analyze only magnetospheric segments that have a mean time within an hour of local noon. The low number of analyzed segments during 2005 is due to a lack of GOES magnetometer data the last half of the year. For each segment, we kept all frequencies that passed both the narrow band test and the F test simultaneously at the 95% significance level. With these statistically significant frequencies, we calculate occurrence distributions for 3-year intervals from 1996–2005 and applied the bootstrap method to the occurrence distributions, as with the solar wind data. As with the solar wind results, all frequencies in the analyzed frequency range were identified at least some of the time, however some frequencies were observed much more often than others, resulting in enhancements in the occurrence distributions at particular frequencies.

[20] Figure 5 shows the mean residuals using the bootstrap samples of frequencies identified in the dayside magnetosphere for 3-year intervals, in the same format as Figure 4. Occurrence enhancements near $f = 1.0$, 1.5, 1.9, 2.8, 3.3, and 4.4 mHz are statistically significant in a majority of the occurrence distributions. While there is consistency across all 10 years, there is also gradual evolution of the frequency sets, as we found for the solar wind density results. For example, peaks near $f = 1.9$ and 2.9 mHz are present in the first two distributions (1996–1998 and 1997–1999), their center frequency shifts in the middle three distributions, and then returns in the 2001–2003 distribution persisting through the 2003–2005 distribution. A peak near 1.0 mHz changes width, encompassing initially up to $f \sim 1.3$ mHz in the 1996–1998 distribution, and down to $f \sim 0.8$ mHz in the 2003–2005 distribution; its center shifts slightly from $f \sim 1.1$, through $f \sim 1.0$ to $f \sim 0.9$, and it is absent in 1999–2001.

4. Summary and Discussion

[21] Figure 6 summarizes and tabulates the results for the solar wind (1) and dayside magnetosphere (2) studies, and the statistical results from other research groups using the occurrence distribution method (3) (as shown in Figure 2b). We list the statistically significant occurrence enhancements present at the three-sigma threshold for the solar wind, and those at the one-sigma threshold for the magnetosphere. Occurrence enhancements at the one-sigma level for the magnetospheric results persist throughout the eight distributions, and provide confidence that the results are significant. Values indicated in Figures 6a and 6b are the center of the band that we considered statistically significant, and the bars below represent the approximate bandwidth, determined by the statistically significant portion of the band. For Figure 6c, the values and approximated bandwidths are as presented in the respective papers. The gray bars indicate the range of frequencies not examined.

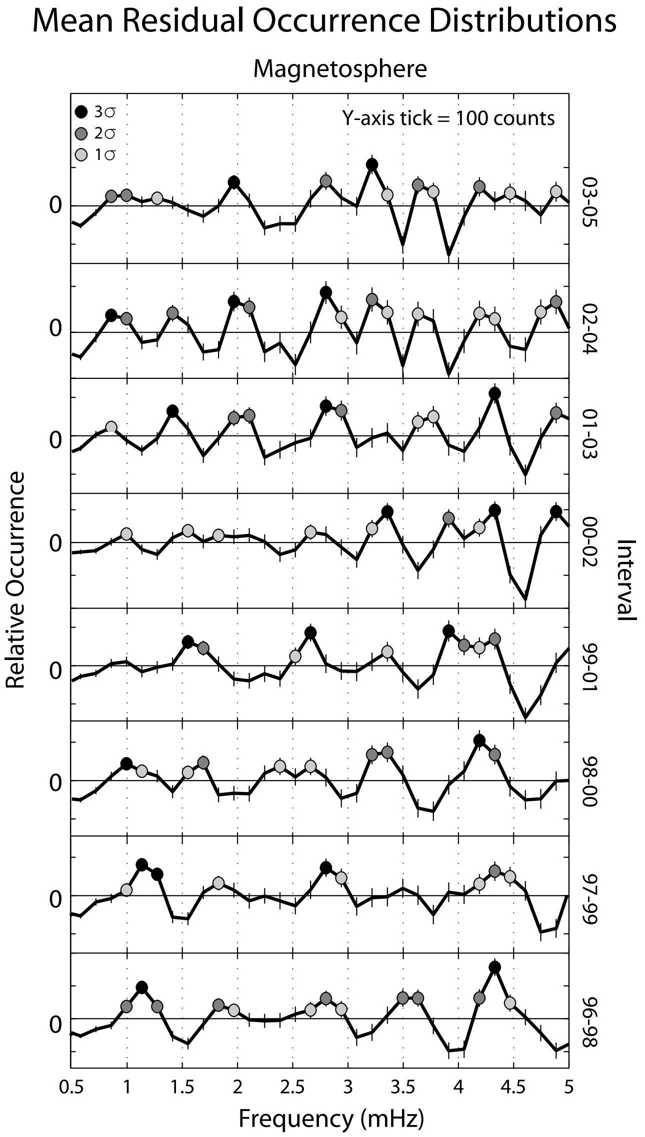

Figure 5. Mean residuals of 3-year occurrence distributions of discrete frequencies found in the dayside magnetosphere from 1996 to 2005. Vertical lines at each frequency indicate ±1 standard deviation of the residual at that frequency, and dots indicate statistically significant occurrence enhancements at the 1 (light gray), 2 (dark gray), and 3 (black) standard deviation thresholds. y axis tick marks indicate 100 counts. The horizontal line indicates a mean residual value of zero.

[22] There is consistency in the frequencies at which there are occurrence enhancements across all 11 years of solar wind data. For example, occurrence enhancements near f = 0.7, 1.4, 2.0, and 4.8 mHz are statistically significant at greater than or equal to the three-sigma level for the majority of the nine intervals. There is also consistency in the frequencies at which there are occurrence enhancements across all 10 years of magnetospheric data analyzed. For example, occurrence enhancements near f = 1.0, 1.5, 1.9, 2.8, 3.3 and 4.4 mHz are statistically significant in a majority of the eight intervals. For both studies, the widths of the enhancements are a few tenths of mHz wide. Although both studies exhibit enhancements that persist through most of the analyzed intervals, both the solar wind and magnetosphere results also exhibit some gradual evolution through the 11(10) years examined, possibly due to a solar cycle dependence. This feature is consistent with the results of *Viall et al.* [2008], which found that the enhance-

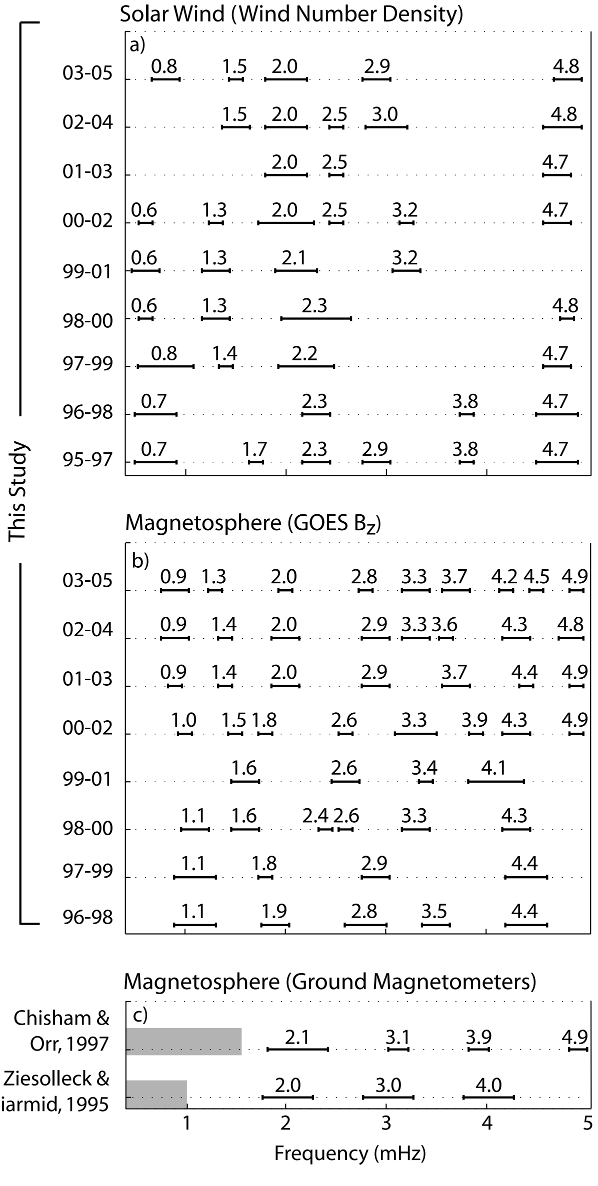

Figure 6. Summary of the statistically significant occurrence distribution enhancements shown in Figures 4 and 5 and comparison of our frequency occurrence enhancements with previously published statistical results for magnetospheric oscillations. (a) Enhancements in the occurrence distribution of the solar wind frequencies for 3-year intervals at the three-sigma threshold. (b) Enhancements in the occurrence distribution of the magnetospheric oscillations for 3-year intervals at the one-sigma threshold. Bar width beneath each occurrence enhancement value represents the approximate width of the frequency band enhancement. (c) (as shown in Figure 2b).

Table 2. Statistics of the Direct Wind-GOES Comparison[a]

Total number of segments analyzed	32,532
SW, $\geq$1 significant frequency	28,445
SW, $\geq$1 significant frequency, magnetosphere, $\geq$1 significant frequency, $\geq$1 match	15,500
SW, $\geq$1 significant frequency, magnetosphere, $\geq$1 significant frequency, 0 matches	11,529

[a] See text for details.

ments in the occurrence distribution of the statistically significant periodic length scales evolved gradually over the 11 years. As the length scales shift, they will correspond with different apparent frequencies observed in Earth's reference frame. Additionally, the velocity distribution in the solar wind, which determines which frequencies the length scales will appear at most often, is well known to be dependent on solar cycle. Both likely contribute to the gradual evolution of the observed frequencies in the solar wind, and therefore the frequencies that directly drive magnetospheric oscillations.

[23] Two of the occurrence enhancements ($f \sim 1.5$ and 1.9 mHz) are observed in a majority of both the magnetosphere and the solar wind results. Two of the enhancements observed in the majority of magnetospheric occurrence distributions ($f \sim 2.3$ and 3.3 mHz) are the same as two of the three-sigma enhancements that occur in the solar wind distributions, although they are only present in a few of the solar wind distributions. The $f = 0.7$ mHz enhancement identified in the solar wind results is broad, and its center shifts some from year to year, often encompassing $f = 0.9$ and 1.0 mHz, where an occurrence enhancement is located for the magnetosphere. Additionally, there is a 4.9 mHz occurrence enhancement in the magnetosphere in four of the distributions, which may correspond to the 4.8 mHz enhancement in the solar wind. However, while the $f \sim 4.8$ mHz enhancement persists throughout most of the solar wind occurrence distributions, it is present in only the last four magnetosphere intervals (2000–2002, 2001–2003, 2002–2004, and 2003–2005). The absence of an occurrence enhancement near $f \sim 4.8$ mHz in the magnetosphere in the first few magnetosphere intervals means that the magnetosphere oscillated at $f \sim 4.8$ mHz less often than it oscillated at other nearby frequencies. It does not mean that the magnetosphere was not being directly driven at 4.8 mHz. Unlike the enhancements in the magnetosphere that saw a solar wind counterpart, the 4.4 mHz occurrence enhancement in the magnetosphere does not seem to have a counterpart in the solar wind. The magnetosphere oscillates at discrete frequencies in the millihertz range through multiple physical processes, one of which is direct driving by the discrete frequencies in the solar wind density. The results discussed above suggest that solar wind number density structures often directly drive the magnetosphere to oscillate at repeatable, discrete frequencies, but that a subset of repeatable frequencies are observed in the magnetosphere due to other physical processes, as expected.

[24] While the analysis presented above demonstrates similarity in enhancements in the occurrence distributions of spectral peaks, and suggests a physical relationship between the frequencies observed in the solar wind number density and those observed in the magnetosphere, it does not demonstrate causality. To make that important connection, we next estimate how often the solar wind directly drives discrete oscillations in the magnetosphere. We began with all of the Wind data segments that we analyzed between 1996 and 2005. Using the position of the Wind spacecraft and the mean solar wind velocity calculated over the 6-hour segment, we ballistically propagated each segment to the dayside magnetosphere. We kept intervals that were within 35 R_E of the x axis upon reaching the magnetosphere, and excluded intervals that were not. In order to affirm a magnetospheric response to the propagated solar wind driver, we determined if a GOES spacecraft was located within three hours of local noon at the center of the time period. If no GOES spacecraft met this dayside criterion, we did not include that event in our analysis. If more than one spacecraft met that criterion, then we used data from the GOES satellite closest to local noon.

[25] For all of the segments that passed the above criteria, we perform spectral analysis in the same manner discussed in section 2. For the direct comparison, our goal for each segment is to identify similar spectral peaks in both data sets. We lower the threshold from 95% to 90% and fit both the solar wind and the magnetospheric spectra with a median smoothed spectra. For the solar wind, we find that this fit allows more frequencies to pass the amplitude test. The additional requirement that the frequencies are observed in both data sets compensates for this. Additionally, we still employ the strong requirement that a spectral peak passes both the F test and the narrow band test simultaneously. For each solar wind segment in which at least one statistically significant frequency between $f = 0.5$ and 5.0 mHz was identified at the 90% confidence level, we looked for the same spectral peak(s) in the corresponding magnetospheric segment. We defined two spectral peaks as the same if they were within $6\Delta f$ (0.3 mHz) of each other. Table 2 summarizes the results of this analysis. It includes the total number of segments analyzed, the number of segments where at least one frequency in the solar wind time series was significant and the number of those segments in which at least one of the same frequencies was statistically significant in the magnetosphere time series. Of the segments analyzed in which a spectral peak was identified in the solar wind data, 54% of the corresponding magnetospheric segments had at least one of the same significant spectral peaks. We estimate the uncertainty in this estimate using the bootstrap method, and find that the standard deviation in our estimate is 0.3%. This confirms that the solar wind often directly drives magnetospheric oscillations at the same discrete frequencies.

5. Conclusion

[26] Our statistical results in both the solar wind (Figure 6a) and the magnetosphere (Figure 6b) confirm that, while discrete frequencies across the entire analyzed range ($f = 0.5$–5.0 mHz) occur, certain sets occur more often than others. This result is in agreement with our earlier work [*Viall et al.*, 2008] that found that periodic solar wind number density structures occur more often at particular radial length scales. The general conclusion that particular

frequencies occur more often than others is also consistent with the statistical results of both *Ziesolleck and McDiarmid* [1995] and of *Chisham and Orr* [1997]. Furthermore, we find occurrence enhancements near $f = 2$, 3 and 4.8 mHz in the majority of both our solar wind and our magnetospheric occurrence distributions, which is consistent with the occurrence enhancements that both research groups found.

[27] In 54% of the solar wind segments within 35 R_E of the x axis, in which we identified a spectral peak at the 90% confidence threshold, at least one of the same discrete frequencies was statistically significant in the corresponding magnetospheric data segment. In other words, discrete magnetospheric oscillations in the $f = 0.5-5.0$ mHz range are directly driven by periodic solar wind number density structures 54% of the time that the solar wind contains periodic number density structures. These periodic number density structures occur at particular discrete radial length scales [*Viall et al.*, 2008], and appear in Earth's reference frame at particular discrete apparent frequencies. The particular apparent frequencies observed in the solar wind number density are due to the particular length scales coupled with the bimodal solar wind velocity distribution. The outstanding question is determining the mechanism that causes these periodic number density structures in the solar wind to occur at particular length scales. We briefly discussed possible source mechanisms of *Viall et al.* [2008]; research is underway to address this question further.

[28] **Acknowledgments.** This work was supported by National Science Foundation Grant 0436138. We thank Keith Ogilvie and the Wind SWE investigation for the solar wind data and Justin Kasper for helpful discussion about those data. We acknowledge H. Singer and CDAWeb for the GOES magnetometer data.

[29] Zuyin Pu thanks the reviewers for their assistance in evaluating this paper.

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