Evidence for a discrete spectrum of persistent magnetospheric fluctuations below 1 mHz

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[1] Ultralow-frequency waves in the magnetosphere have been observed and widely reported in the literature. One important class of such waves includes field-line resonances, having fundamental frequencies as low as ~1.3 mHz. Fluctuations below this frequency have been reported infrequently, although a few studies note oscillations with periods of approximately 30 min. The nature of these waves is especially interesting because the expected wavelength that would be associated with them should be larger than the scale size of the magnetosphere. In fact, the majority of these observations have been acquired using satellites located in the fairly distant magnetotail. In one of these studies, the only one which finds a discrete spectrum, data was obtained between $X_{GSM} = -8$ and $-18R_E$. In this paper, we show evidence for the existence of a discrete spectrum of oscillations within the magnetosphere that can persist for up to 2 days and perhaps longer. These observations were acquired at geosynchronous orbit and were observed at all local times simultaneously with a signature that is clearest in energetic electron data but can also be seen in the GOES magnetometer data. These facts suggest that a global-scale magnetic fluctuation, perhaps one that originates in the magnetotail, resonates with energetic electron drift orbits via an $\mathbf{E} \times \mathbf{B}$ force. *INDEX TERMS:* 2740 Magnetospheric Physics: Magnetospheric configuration and dynamics; 2730 Magnetospheric Physics: Magnetosphere—inner; 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; 2720 Magnetospheric Physics: Energetic particles, trapped; 2756 Magnetospheric Physics: Planetary magnetospheres (5443, 5737, 6030); *KEYWORDS:* narrow band fluctuations, radiation belts, energetic particles, low-frequency fluctuations

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1. Introduction

[2] Of the lowest frequency waves that are observed in space and on the ground, perhaps the most important class are field-line resonances, having fundamental frequencies as low as ~1.3 mHz [*Xu et al.*, 1993; *Walker et al.*, 1992; *Samson et al.*, 1991; *Ruohoniemi et al.*, 1991]. Because the wave frequency is controlled by the "length" of the field line as well as the integrated Alfvén speed along that field line, it is representative, in a sense, of the scale size of the magnetosphere. That is, the lowest possible frequency that should be observable in the magnetosphere should be one that is associated with a half-wave standing between the northern and southern ionospheres.

[3] While this is true in principle, observations of frequencies somewhat below 1 mHz have been occasionally reported. *Chen and Kivelson* [1991] used magnetometer data from ISEE 2, located in the tail between approximately $X_{GSM} = -10$ and $-20R_E$, to record statistics of fluctuations between 0.26 and 1 mHz and showed that the largest amplitude waves in this band occurred at ~0.3 mHz, although amplitudes of only 0.3 nT were typical. They also noted that in several of the events they studied, narrow-band fluctuations at ~0.48 mHz were observed and suggested that they may be related to an eigenmode of the magnetotail. *Siscoe et al.* [1994] used data acquired by GEOTAIL, located near $100R_E$ deep in the tail, and noted the existence of plasma fluctuations with nominal periods of ~100 minutes that persisted for days. They attributed these fluctuations to a "breathing" of the magnetotail but did not report other spectral components or suggest the existence of a discrete spectrum.

[4] Other observations of fluctuations in the magnetotail were presented by *Nikutowski et al.* [1996], who used data from the Prognoz-8 satellite when it was located between

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$X_{GSM} = -8$ and $-18R_E$ to show the existence of fluctuations with a discrete set of frequencies nominally near 0.49, 0.79 and 1.0 mHz, which they attributed to an unspecified global effect.

[5] At much lower altitudes, similar fluctuations have also been observed. *Rinnert* [1996] showed ionospheric observations of 40–60 min quasi-periodic enhancements of E-region electron density using EISCAT data. *Lessard et al.* [1999] used data from several platforms to show that fluctuations with a 45 min period occurred over global scales and persisted for several hours. More recently, *Huang et al.* [2001] used ground-based magnetometer and HF radar data to show the existence of fluctuations with a 50–60 min period. These fluctuations were also observed by the GOES 8 magnetometer.

[6] The work presented here was initiated as a continuation of *Lessard et al.* [1999], which led to the suggestion that these events were global magnetospheric fluctuations. The commonality of the various studies listed here is far from clear, although it may be the case that they are all observations of the same phenomena. In this work, we present data showing the existence of a persistent, discrete spectrum of fluctuations using energetic electron flux data.

2. Data and Analysis

[7] Energetic particle data used in this study were recorded by the Charged Particle Analyzer (CPA) and Synchronous Orbit Particle Analyzer (SOPA) instruments on the suite of geosynchronous satellites maintained by the Los Alamos National Laboratory [*Reeves et al.*, 1997]. These satellites have their spin axis pointing Earthward, with spin periods of approximately 10 s. The data used were averaged over the spin period, so these data contain no information regarding pitch angles. In this study, only energetic electrons from 50 keV to 500 keV were studied. Five events were selected for analysis, based on the presence of visible sinusoidal fluctuations in the survey data. Table 1 lists the dates, times, satellite name and the observed frequencies, although typically not all of these frequencies were observed during the entire time interval listed. For the sake of brevity, the table lists the time ranges where any of the listed frequencies were observed. Figure 1 shows the data for one of these events (on 11 April 1991), presented as differential particle fluxes, as it might be in a typical survey format. Only one event is discussed in detail here, although the results discussed below are based on data from all of the events.

[8] Figure 2 shows data from the 1989–046 satellite acquired on 11 April 1991 and provides an example of the type of event we considered. In order to examine the sinusoidal fluctuations, the particle data were treated as wave data in the sense that it was first detrended and then dynamic Fourier transforms were calculated. Detrending for all channels was accomplished by subtracting a sliding boxcar average of 1080 data points (equivalent to subtracting a 3-hour average). For each transform, segments of data containing 4096 samples (11.3 hours of data) were used in order to obtain high spectral resolution and transforms were calculated every 6.7 min. In Figure 2, each colored panel shows the dynamic spectra of the particle fluctuations within a particular energy range (listed on the plot) with the detrended particle data plotted beneath the spectra.

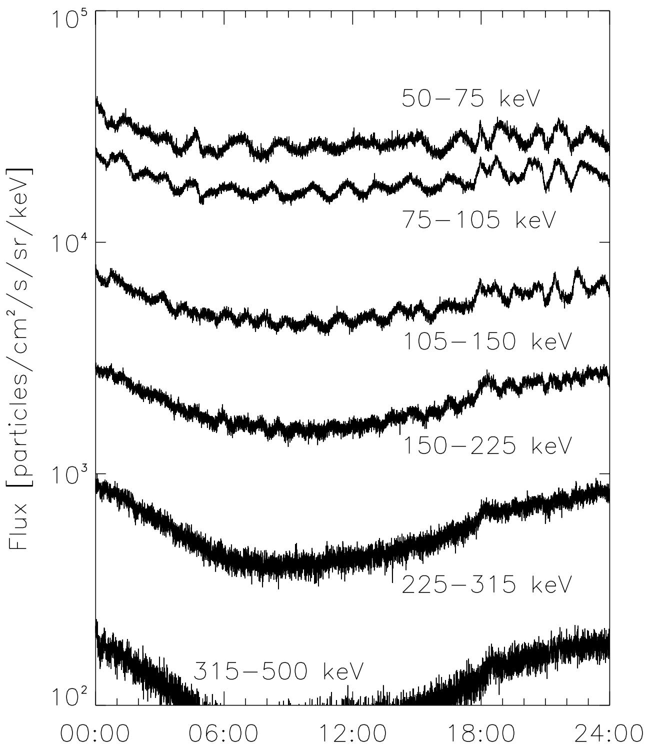

Figure 1. Differential particle fluxes observed by the Los Alamos 1989–046 satellite, on 11 April 1991. Sinusoidal oscillations are clearly visible in the particle fluxes, with the signature being more pronounced at the lower energies.

[9] Striking characteristics of these events include the narrow spectral width of the fluctuations and the persistence of the event. Note that these oscillations do not have the character of drift echoes that result from substorm injections [*Lanzerotti et al.*, 1967; *Arnoldy and Chan*, 1969; *Pfitzer and Winckler*, 1969; *Reeves et al.*, 1990]. Substorm-injected particles appear with a distinct onset and an abrupt increase in count rate, followed by a relatively gradual decrease in count rate. Echoes resulting from gradient-curvature drift motion usually follow the injection, but velocity dispersion results in any subsequent peaks having decreased amplitude and a broadening of the signature with each echo. In contrast, the oscillations discussed here have nearly constant amplitudes and remain coherent for several hours (show no signs of velocity dispersion). This characteristic suggests that a stationary driving mechanism likely is responsible for their generation.

[10] In the upper four panels of Figure 2, sinusoidal oscillations can clearly be seen in the detrended data as well as the dynamic spectra, which in general show that the spectral content of the fluctuations is confined to very narrow bands. The energy response of the instrument is not narrow and, in fact, is considered to be uniform across the range specified for each channel in order to measure the energy spectrum uniformly. In the 50–75 keV and 75–105 keV channels, fluctuations near 0.18 mHz are present from approximately 0300 UT to 1800 UT. In the 105–150 keV channel, fluctuations at ~0.32 mHz also begin near 0300 UT, fade during the middle of the day, but return to end finally near 1700 UT. In the 150–225 keV channel, distinct

Table 1. Event List

Date/Time, UT	Satellite	Frequency, mHz	K_p range
19910411/0000–19910411/2150	1987–097	.15, .32	1 to 2–
19910411/0000–19910411/1800	1989–046	.18, .32	1 to 2–
19910423/0240–19910423/2110	1990–095	.41, .55	1 to 3+
19910518/0500–19910518/1900	1987–097	.18, .31, .51	0+ to 2
19910518/0000–19910518/1900	1989–046	.13	0+ to 2
19910106/0000–19910106/1545	1987–097	.21, .30, .40, .53	0+ to 2–
19910105/2100–19910106/1600	1989–046	.21, .41, .52	0+ to 2
19960509/1210–19960510/1445	1990–095	.21, .31, .55	1– to 2
19960509/1305–19960510/1700	1994–084	.20, .45	1– to 2

fluctuations at ~0.32 mHz begin at 0600 UT and persist until 1700 UT. The point here is that particle flux oscillations occur at two discrete frequencies but only in certain energy channels.

[11] Data from the 1987–097 satellite, located approximately 12 hours away from 1989–046, are shown in Figure 3 and show similar characteristics. Particle fluxes measured in the 45–65 keV channel show fluctuations near 0.16 mHz that extend from 0000 UT to beyond 1800 UT. Both the 95–140 keV and 140–200 keV channels show fluctuations at ~0.32 mHz that begin near 0400 UT and remain until 1700 UT.

[12] These data show that energetic electron flux oscillations with approximately the same spectral content are observed by two satellites simultaneously while located on opposite sides of the Earth. The discrete spectrum and global nature of these oscillations are common to all five events considered in this study, as is tendency for the events to persist for many hours. In some cases (not shown), the oscillations persist for a day or more. Below, we present GOES magnetic field data showing magnetometer observations of one event that persisted for nearly two days, coincident with observations of particle flux oscillations.

[13] The fluctuations are observed with frequencies near 0.16 or 0.18 mHz in the instrument channels that measure electrons with energy ranges from 50–75 keV, 75–105 keV, and 45–65 keV. Fluctuations at ~0.32 mHz are observed in the 105–150 keV, 150–225 keV, 95–140 keV, and 140–200 keV channels. The apparent dependence of the oscillation frequency on particle energy suggests a possible connection to particle drift orbits. *Schulz and Lanzerotti* [1974] show the result of drift orbit calculations in a dipole field (see their Figure 6), which indicate that the oscillating particle fluxes in our data occur at energies whose drift periods are similar to the period of the oscillation. We investigated this possibility more closely by calculating the energy of the particle whose drift frequency matches the frequency of the observed oscillation and determining which energy channel of the instrument would detect the fluctuations. Figure 4 shows an example of the results, applied to the SOPA instrument on 1989–046. The vertical axis in the figure corresponds to particle energy. The alternating gray and white bars represent the energy response of the various channels in the instrument. The red, blue, and black traces show the energies of particles whose drift frequencies, in three empirical magnetic field models, are 0.18 and 0.32 mHz. The horizontal axis shows the dependence on L shell. For example, the upper red, blue, and black traces show that electrons with drift frequencies of 0.32 mHz would have energies such that they would be detected primarily by the 105–150 keV channel but perhaps by the 150–225 keV channel as well. Likewise, the figure also shows that electrons with drift frequencies of 0.18 mHz would have energies that would place them in either the 50–75 keV or 75–105 keV channels.

[14] This technique was applied to each of the oscillation periods observed in the five events and consistently showed that the periods of the fluctuations matched the drift periods of electrons with energies that fell within the energy range of the instrument channel where the fluctuations were observed. Figure 5 shows the results of the calculations. Using the mean energy of the bin containing the largest amplitude oscillations, we calculated the corresponding drift period and plotted the calculated drift period versus the observed periods of fluctuation, clearly showing that the two quantities are well correlated.

[15] The sinusoidal oscillation of particle flux data is evidence of phase bunching of particles as they drift in orbit around the Earth. The strong correlation between the phase-bunching drift period with the particles' drift period suggests the presence of a driver with this period, or one of its harmonics, although a closer examination of the data implies that the driver is at the same period as the drift period (i.e., that the fluctuations have an azimuthal wave number of m = 1). Figure 6 show the detrended data of two satellites (1989–046 and 1987–097) located 12 hours apart on 11 April 1991. The upper two panels of the figure show particle fluxes from in the 50–75 keV channel of 1989–046 and the 45–65 keV channel of 1987–097, respectively. The lower two panels show fluxes in the 75–105 keV channel of 1989–046 and the 65–95 keV channel of 1987–097. Although the energy responses of the instruments on the different satellites are not quite the same, the oscillations can still be seen to be in antiphase, implying that only a single "bunch" of particles is present. This type of analysis was completed for all five events and in all cases, showed that phase differences in the particle fluctuations observed by two or three spatially separated satellites were consistent the existence of a single "bunch" of particles.

[16] Bunching as described here might occur if an oscillating radial electric field (of global scale) with a period that matched the particle drift period were imposed on the drifting particles, resulting in an $\mathbf{E} \times \mathbf{B}$ force that would resonate with the particle drift motion and cause the bunching. Such an electric field would result from Faraday induction associated with a magnetic disturbance in the azimuthal and compressional directions. As discussed above, however, the frequencies observed in these data are much lower than the lowest frequencies (~2 mHz) that have been associated with field-line resonances, suggesting that some structure larger than the magnetosphere proper (such as the magnetotail) must be supporting these waves.

[17] With this motivation, magnetic field data from the GOES satellite were examined for each of the events. Typically, each event showed fluctuations having a bursty character with frequencies comparable to those observed in the energetic particle data. In some cases, the fluctuations in the particle data were well-correlated with those in the magnetic field data, although the magnetic field fluctuations were often weak.

[18] Figure 7 shows dynamic spectra of magnetic field data from the GOES 7 satellite on 5–6 January 1991. These

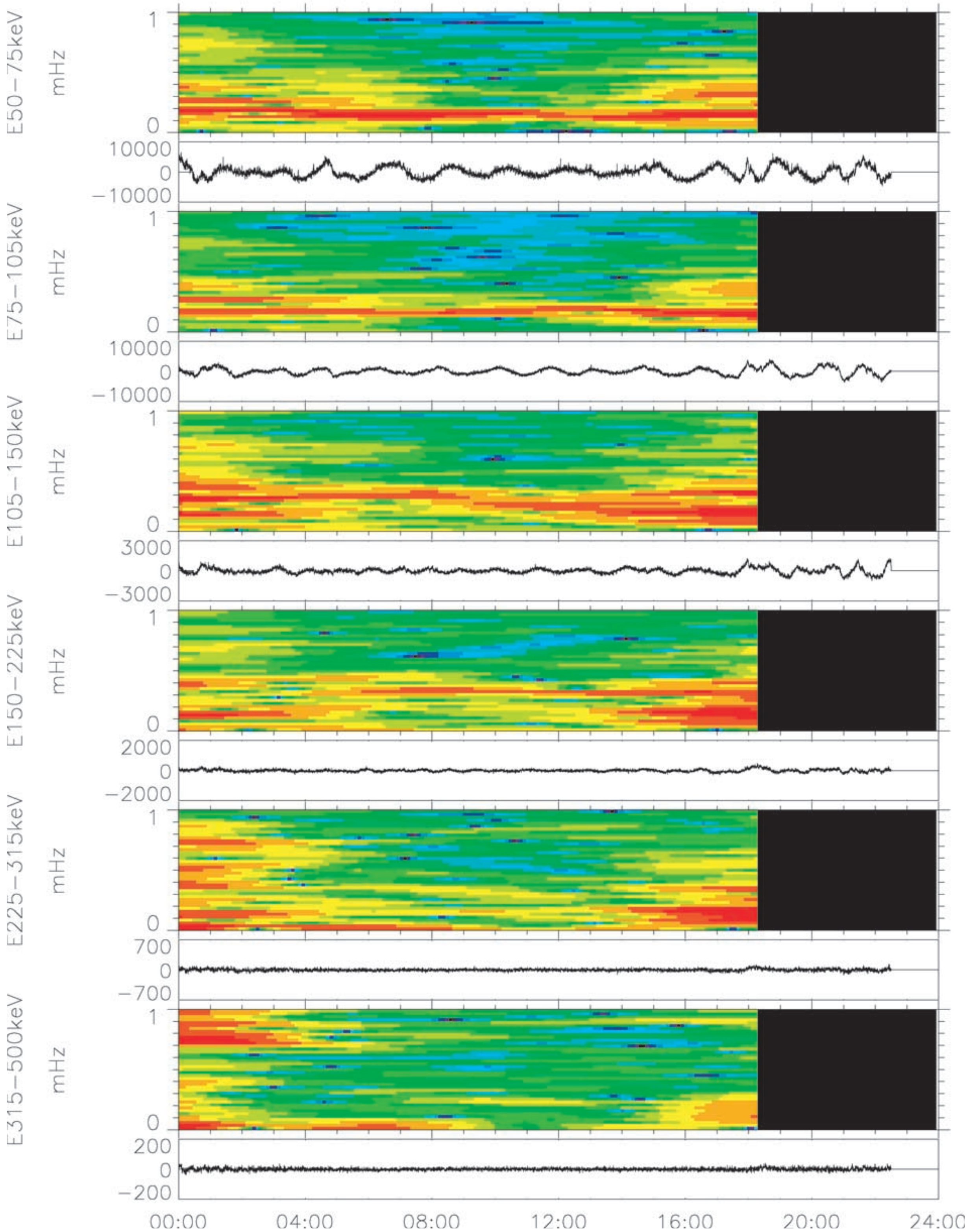

Figure 2. Dynamic spectra of energetic particle fluxes measured by the Los Alamos 1989−046 satellite acquired on 11 April 1991. Quasi-periodic oscillations near 0.18 mHz appear in the 50−75 keV and 75−105 keV channels, as well as those at ∼0.32 mHz in the 150−225 keV channel.

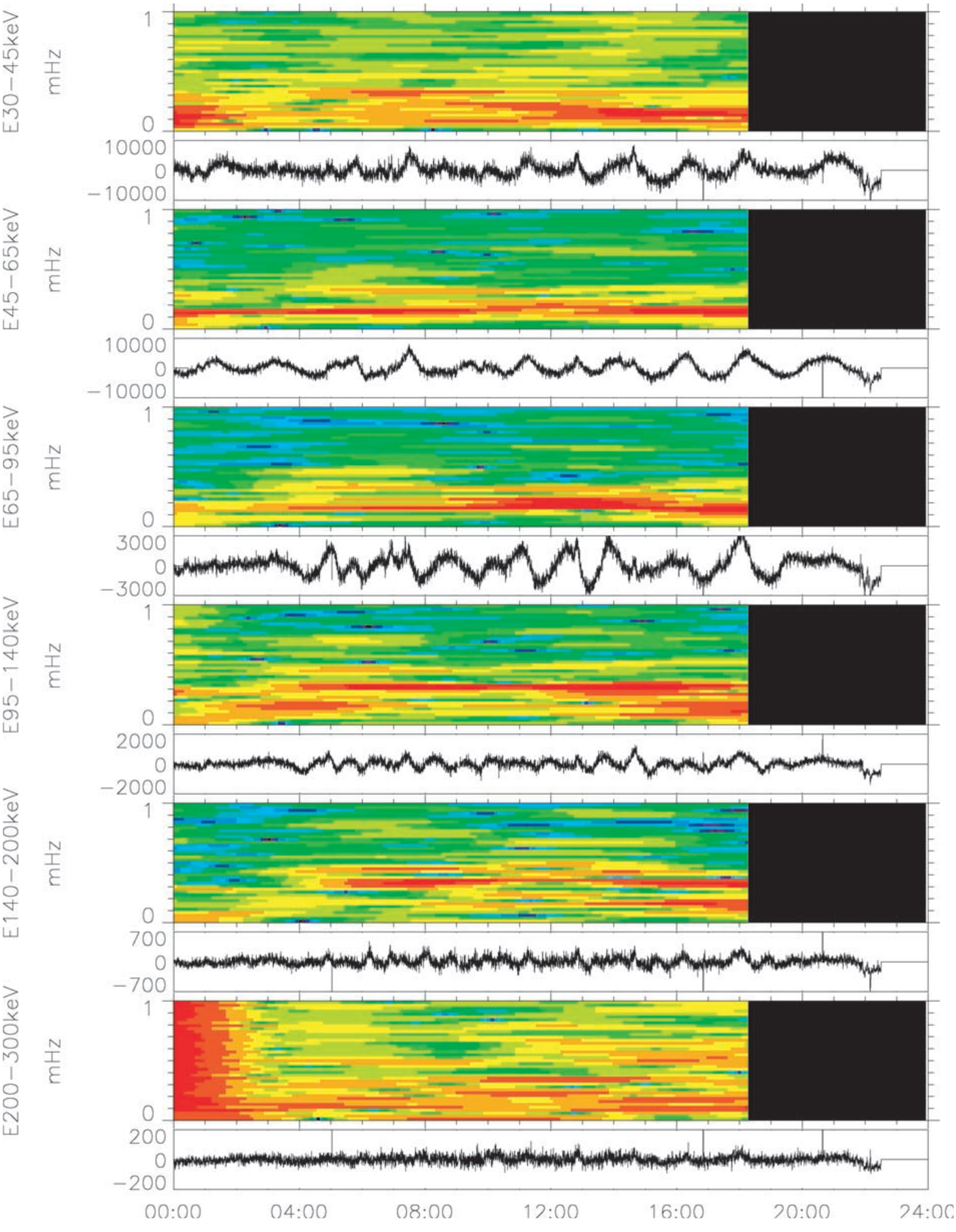

Figure 3. Dynamic spectra of energetic particle fluxes measured by the Los Alamos 1987–097 satellite. Quasi-periodic oscillations near 0.16 mHz appear in the 45–65 keV channel, as well as those at ~0.32 mHz in the 95–140 keV and 140–200 keV channels.

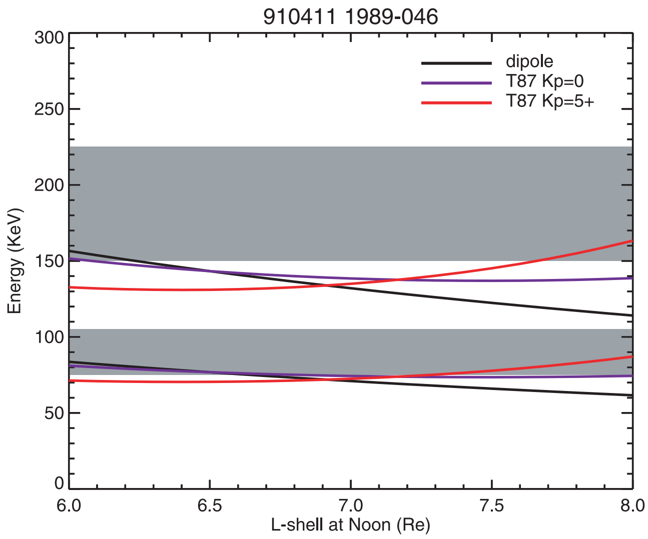

Figure 4. Using the frequencies of the observed fluctuations shown in Figure 2, electron energies whose drift frequencies matched those of the observations were calculated using various magnetic field models. This figure shows which bins (represented by alternating gray and white bars) would detect particles with these energies. The upper traces show the calculated values for 0.32 mHz and the lower traces show the same information for 0.18 mHz. In both cases, the calculated values place these particles in precisely the bins where the fluctuations are observed.

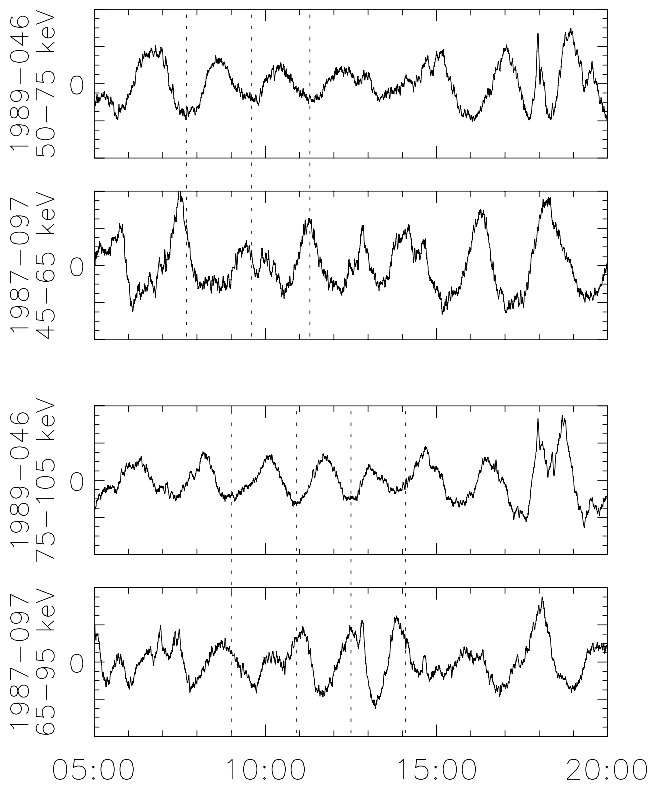

Figure 6. Detrended particle fluxes observed by two satellites, located 12 hours apart on 11 April 1991. The upper two panels of the figure show particle fluxes from in the 50–75 keV channel of 1989–046 and the 45–65 keV channel of 1987–097 respectively. The lower two panels show fluxes in the 75–105 keV channel of 1989–046 and the 65–95 keV channel of 1987–097. Vertical dashed lines highlight times when the anti-phase character of the oscillations is especially pronounced.

data were obtained during one of the events used in this study and are presented here because they most clearly show the presence of persistent, narrow band fluctuations in the magnetic field data, which occur at frequencies comparable to the sinusoidal oscillations observed in the particle flux data. Near 0600 UT on 5 January, oscillations with a ~2 hour period are present in the radial and parallel components. Although the power at this frequency (~.14 mHz) is dominant throughout the 2-day interval, faint spectral peaks that persist throughout the period can also be seen in the eastward component near 0.55 and 0.88 mHz; power at 0.55 mHz can also be seen in the parallel component. Note especially that as was the case with the particle flux data, spectral power in the magnetic field fluctuations is dominated by lower frequencies.

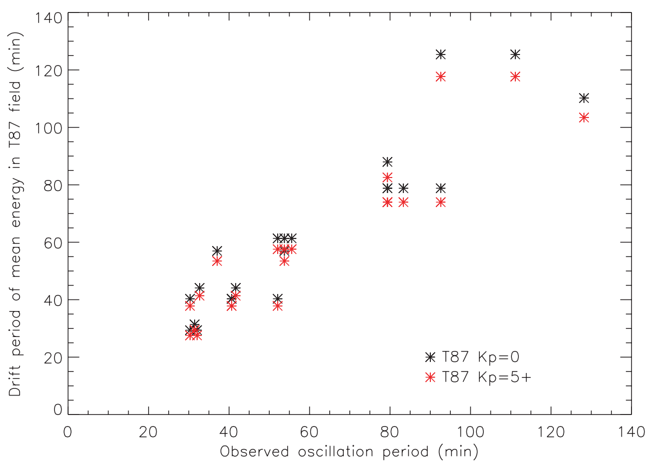

Figure 5. A plot of calculated drift periods versus observed periods of fluctuations. These results provide strong evidence that the observed periods of oscillation match the particles' drift periods.

3. Statistical Properties

[19] During the early stages of this work, we sought to characterize the spectral content of these fluctuations in order to perhaps understand their discrete nature. The occurrence distribution of observed frequencies for all five events were compiled, encompassing a total of 170 hours of observations. Two important features emerged from this step. The first is that the observed frequencies tended to cluster around 0.13 to 0.2 mHz, 0.32 mHz, and 0.53 mHz. The second is that lower frequencies were observed more frequently than higher ones.

[20] In a more complete study, however, the tendency to cluster around particular frequencies was not observed, although the more common occurrences of low frequencies was confirmed. Figure 8 shows the results of the study,

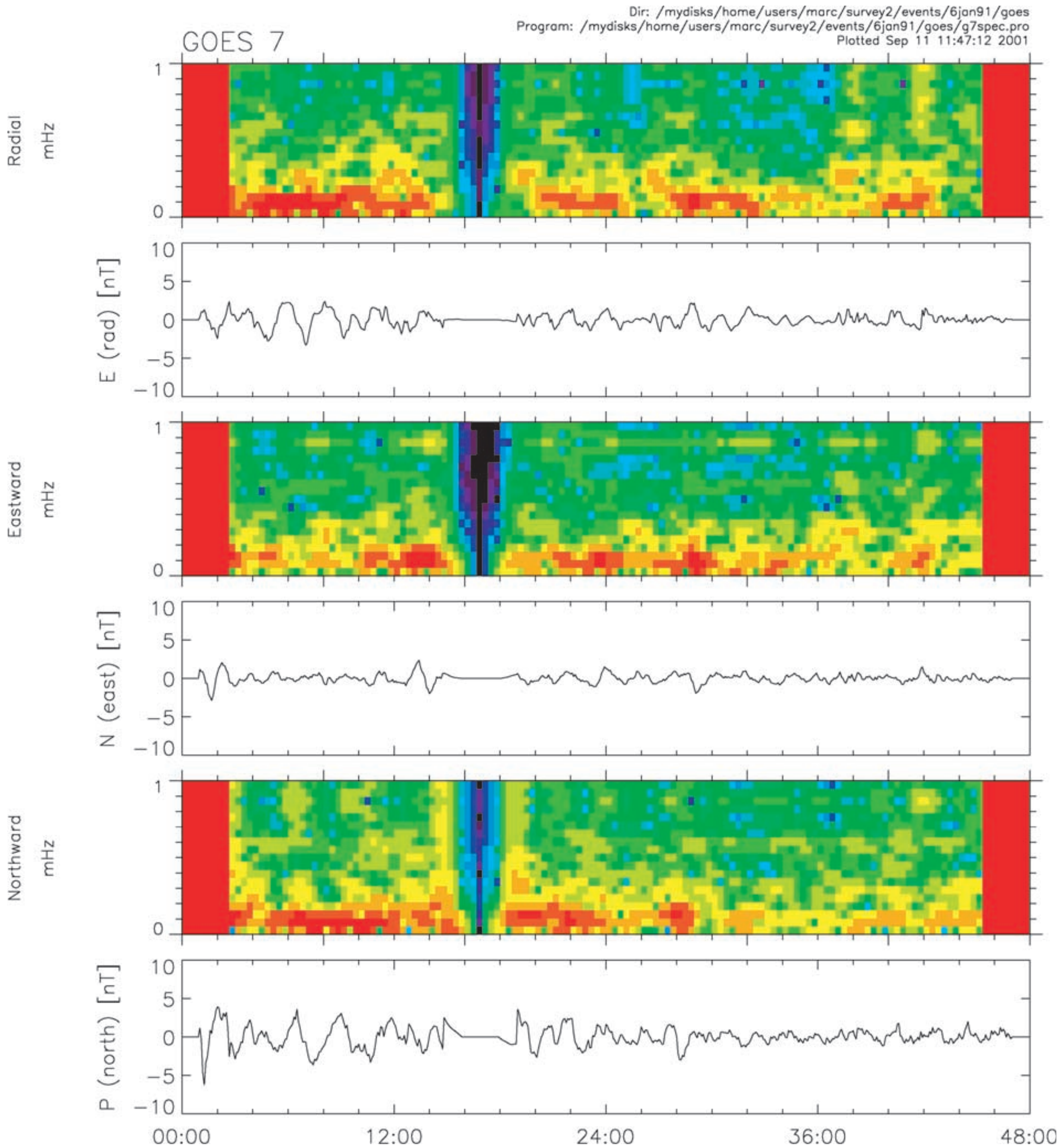

Figure 7. Dynamic spectra of GOES 7 magnetometer data acquired on 5–6 January 1991. From top to bottom, components radial, eastward and northward. For each component, detrended data is plotted below the dynamic spectra, which show the spectral power of oscillations below 1 mHz. The intensity scale is arbitrary in order to highlight the spectral content of each component.

which examined energetic electron data (50 keV to greater than 1.5 MeV) from the 1990–095 satellite acquired between November 1990 and March 1991. Over this period, a number of data gaps and bad data segments reduced the total number of hours of reliable data to ~1,200. Occurrence rates were determined by summing the observation time of any particular frequency (in any energy channel) and normalizing by the total observation time. The figure clearly shows that the more commonly observed frequencies fall between 0.1 and 0.5 mHz (there were no observations of oscillations below ~0.1 mHz).

[21] Perhaps more importantly, the figure shows that the observed frequencies do not tend to cluster around any specific value. That is, individual occurrences of these events have very narrow spectral features. On the other hand, the particular frequencies that are observed vary from

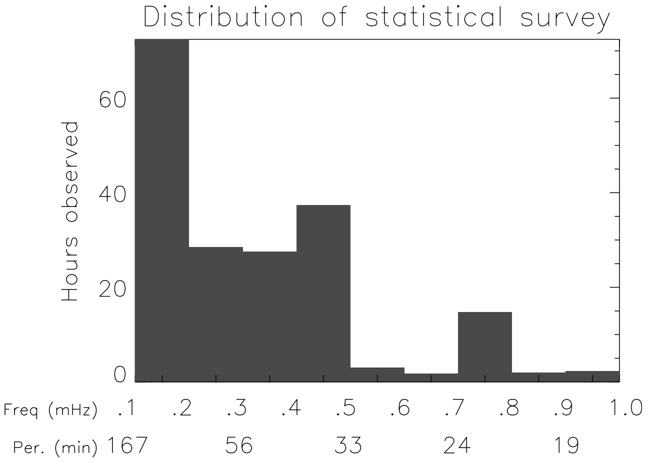

Figure 8. The occurrence distribution of observed frequencies. Note that lower frequencies were observed more frequently than higher ones but that no tendency to cluster around specific frequencies can be seen.

one event to the next. Implications are discussed in the following section.

[22] Finally, we note that the occurrence rate for these events is very low, amounting to only ~6% for the most commonly observed frequencies. In part, this may be due to the fact that their amplitude is very low. Certainly, these events could not be detected during a magnetic storm, although the mechanism may in fact be present and functioning.

4. Summary and Discussion

[23] The observations can be summarized as follows:

1. Data are presented that show persistent (for tens of hours), narrow band oscillations in energetic electron fluxes. Five events are studied in detail; only some of the data are shown here.
2. Using various magnetic field models, we show that the frequencies of the flux oscillations match the drift frequencies of these particles in three empirical magnetic field models.
3. Comparison of the phase of the oscillations observed simultaneously by different satellites suggest that bunching occurs in a single region (i.e., that the azimuthal wave number of the bunching is m = 1).
4. For each of the five events, GOES magnetic field data show bursty power in the compressional component, at ~0.1–0.2 mHz, consistent with the particle flux observations, where this was the most commonly observed frequency range.
5. In one event, GOES magnetic field data show a discrete spectrum of fluctuations that persists for at least 2 days. Observed frequencies in this case are 0.14, 0.55, and 0.88 mHz.

[24] The observations show that waves having a discrete spectrum with frequencies below 1 mHz are sometimes excited in the magnetosphere. These waves can be detected by the GOES magnetometer, although the fluctuations can be very weak (less than 1 nT). Through some mechanism perhaps involving $\mathbf{E} \times \mathbf{B}$ forces, these waves can also be observed as sinusoidal oscillations in energetic particle flux data. Important properties of these waves are that they occur on global scales and can persist for several hours or even days.

[25] The fact that these frequencies are observed globally and are below the fundamental frequencies of field-line resonances at these L shells suggests one of two processes is responsible for their occurrence. Either the fluctuations are being driven by similar fluctuations in the solar wind and energy couples through the magnetopause, or wave power at these frequencies is present in the magnetotail and propagates Sunward. *Rinnert* [1996] report fluctuations in E-region electron density with periods between 40 and 60 min. They also note that the observed frequencies fall below what has been observed within the magnetosphere proper and consider the possibility that the oscillations are generated in the magnetotail, a scenario considered theoretically by previous authors [*Patel*, 1968a, 1968b; *McClay and Radoski*, 1967]. However, the propagation of wave energy Sunward remains an open question and, in particular, it seems unlikely that wave power at these low frequencies could propagate Sunward and couple energy at global scales.

[26] At this point, it is worth noting that the discrete frequencies discussed in this paper are not very different than those of discretely driven field-line resonances, typically 1.3, 1.9, 2.6–2.7, and 3.2–3.3 mHz, and most often observed in the vicinity of $L = \sim 6.7$ which maps very close to geosynchronous orbit [*Samson and Harrold*, 1992; *Fenrich et al.*, 1995; *Ziesolleck and McDiarmid*, 1994]. Both discretely driven field-line resonances and the oscillations reported here have the characteristic that any given event exhibits very narrow-band features, but the specific frequencies observed can vary from one event to the next. Clearly, the frequencies reported here are lower, but their "spectral proximity" suggests that they may have the same origin. For example, if we merge the list of frequencies observed in the event presented in Figure 2 with those of field-line resonances, the combined spectrum has peaks at 0.18, 0.32, 1.3, 1.9, 2.6, and 3.2 mHz (note that frequencies near 0.8 mHz were often observed in our study as well). The fact that frequencies below 1 mHz are observed much less often than those above 1 mHz might just be a result of the inability of the lower frequencies to couple their energy to a field-line resonance. In other words, frequencies above 1 mHz might be observable because the efficient transfer of energy associated with resonant coupling results in an increased wave amplitude. This scenario is consistent with a suggestion that the spectral power is contained in the solar wind.

[27] Recently, *Kepko et al.* [2002] presented data correlating fluctuations in the solar wind number density with GOES magnetic field fluctuations at frequencies similar to those discussed here. They suggest that the magnetospheric oscillations are driven by solar wind oscillations via a coupling mechanism involving slowly changing magnetospheric currents.

[28] *Thomson et al.* [1995] present an analysis of solar wind magnetic field data that shows the presence of fluctuations with frequencies similar to those discussed here and attribute their presence to helioseismic *p*-modes, acoustic fluctuations within the Sun that are driven by pressure gradients. These authors do not consider whether these modes (in the solar wind) can transfer their energy to the

magnetosphere. The information is presented here for reference only, and we do not necessarily suggest that the ultimate source of the fluctuations reported here is helioseismic activity.

5. Conclusions

[29] The particle and magnetic field data presented above both show the presence of a discrete spectrum of oscillations below 1 mHz, observed on a global scale and persisting for several hours or more, perhaps up to 2 days or more. The oscillations are clearly visible in the particle flux data and less obvious in the magnetic field data, although we suspect that the magnetic field oscillations may be providing the driver for the particle flux oscillations. Because these frequencies are lower than the lowest frequencies expected to be observed within the magnetosphere, we conclude that they are likely driven by solar wind fluctuations.

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References

Arnoldy, R. L., and K. W. Chan, Particle substorms observed at geostationary orbit, *J. Geophys. Res.*, *74*, 5019, 1969.

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.

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

Huang, C., et al., Long-period magnetospheric-ionospheric perturbations during northward interplanetary magnetic field, *J. Geophys. Res.*, *106*, 13,091, 2001.

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.

Lanzerotti, L. J., C. S. Roberts, and W. L. Brown, Temporal variations in the electron flux at synchronous altitudes, *J. Geophys. Res.*, *72*, 5893, 1967.

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.

McClay, J. F., and H. R. Radoski, Hydromagnetic propagation in the theta-model geomagnetic tail, *J. Geophys. Res.*, *72*, 4525, 1967.

Nikutowski, B., J. Büchner, 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*(8), 55, 1996.

Patel, V. L., Origin of long-period micropulsations, *Nature*, *218*, 857, 1968a.

Patel, V. L., Magnetospheric tail as a hydromagnetic waveguide, *Phys. Lett.*, *26A*, 596, 1968b.

Pfitzer, K. A., and J. R. Winckler, Intensity correlations and substorm electron drift effects in the outer radiation belt measured with the OGO-3 and ATS-1 satellites, *J. Geophys. Res.*, *74*, 5005, 1969.

Reeves, G. D., T. A. Fritz, T. E. Cayton, and R. D. Belian, Multi-satellite measurements of the substorm injection region, *Geophys. Res. Lett.*, *17*, 2015, 1990.

Reeves, G. D., R. D. Belian, T. C. Cayton, M. G. Henderson, R. A. Christensen, P. S. McLachlan, and J. C. Ingraham, Using Los Alamos geosynchronous energetic particle data in support of other missions, in *Satellite-Ground Based Coordination Source Book*, edited by M. Lockwood, et al., pp. 263–272, Eur. Space Agency, Paris, 1997.

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., and B. G. Harrold, Field line resonances associated with MHD waveguides in the magnetosphere, *Geophys. Res. Lett.*, *19*, 441, 1992.

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.

Schulz, M., and L. Lanzerotti, *Particle Diffusion in the Radiation Belts*, Springer-Verlag, New York, 1974.

Siscoe, G. L., L. A. Frank, K. L. Ackerson, and W. R. Paterson, Irregular, long-period boundary oscillations beyond $\sim$100 R_e: GEOTAIL plasma observations, *Geophys. Res. Lett.*, *21*, 2979, 1994.

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

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.

Xu, B. L., J. C. Samson, W. W. Liu, F. Creutzberg, and T. J. Hughes, Observations of optical aurora modulated by resonant Alfvén waves, *J. Geophys. Res.*, *98*, 11,531, 1993.

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

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