A long-duration narrowband Pc5 pulsation

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Received 18 July 2007; revised 14 August 2008; accepted 18 November 2008; published 29 January 2009.

[1] We report on a rare event of a narrowband ULF magnetospheric pulsation that is observed at geosynchronous orbit over five consecutive days in the recovery period of a magnetospheric storm, with frequencies ranging from 5 to 9 mHz. The pulsation displays distinctive localization, being observed over several hours of local time in the noon and postnoon sectors during successive passes of GOES-8 and GOES-9. Geotail, which is traversing the outer magnetosphere a couple of R_E farther out from geosynchronous orbit at the time the pulsations are observed, shows no distinct narrowband fluctuation in the magnetic field, excluding oscillations in the solar wind as a possible source of the pulsations. On the ground, several of the IMAGE magnetometers observe pulsations with similar spectral characteristics. By performing a phase cross-spectrogram analysis on measurements from adjacent and latitudinally aligned ground stations we estimate the azimuthal mode number m of the pulsation, which we find to range between 20 and 55. Phase difference calculations indicate an eastward phase propagation of these pulsations. Density measurements from LANL spacecraft at geosynchronous orbit show evidence of a plasmasphere refilling process that is slower than usual, possibly associated with the observed slow frequency decrease and the unusually long lasting of the pulsations.


1. Introduction

[2] Narrowband, sinusoidal oscillations of the geomagnetic field are often observed in the inner magnetosphere as well as on the ground. Similarly to the definition used by Hudson et al. [2004], here we characterize as narrowband Pc5 pulsations all magnetospheric oscillations with Δf < 2 mHz at a given time, where bandwidth Δf is the full width at half maximum. Such pulsations can be attributed either to the solar wind, acting as an external driver, or to internal plasma anisotropies, and are characterized by their azimuthal wave number, m [Dungey, 1954; Green, 1976], which is often indicative of the excitation mechanism. In some cases of external generation mechanisms, the solar wind induces fast mode resonances within the magnetospheric cavity, and the observed oscillations have frequencies that are dependent upon the cavity characteristics, they are associated with small wave numbers (m < 10) and are dominantly azimuthally polarized; however recently some magnetospheric oscillations that appear both in outer space solar wind measurements as well as within the magnetosphere have been considered to be directly driven by the solar wind and to have frequencies which are preferred periodic fluctuations in the solar wind dynamic pressure [Stephenson and Walker, 2002; Kepko and Spence, 2003]. In other cases of external generation, Kelvin-Helmholtz instability at the magnetopause can launch impulses to the inner magnetosphere and Alfvén waves into the ionosphere [e.g., Rostoker and Samson, 1984]. In the case of an internal generation mechanism, the bounce-drift resonance of particles in the unstable part of a particle distribution with the resonant frequency of the local flux tube is the driver of the observed oscillations [Hasegawa, 1971; Southwood, 1976], in which case the oscillation happens at the characteristic field-line resonant frequency, which is dependent on the local magnetospheric characteristics such as the field line length, magnetic field strength and local plasma density; such internally generated oscillations have been associated with large wave numbers (m > 15) [e.g., Anderson et al., 1990; Engebretson et al., 1992].

[3] In this paper we report on a dayside, radially polarized narrowband Pc5 pulsation event that shows an unprecedented duration, being observed for five consecutive days at geosynchronous orbit over successive passages of GOES-8 and GOES-9 satellites. Long-duration pulsation events with similar phenomenology have been observed before: e.g., Takahashi et al. [1985, 1987a, 1987b] analyzed an event lasting for ~50 h; also, in a study of the interaction of long-duration ULF pulsations with energetic electrons a similar event lasting for ~2 days was reported by Sarris et al. [2007]. However, to our knowledge the event reported herein has the longest duration ever reported. The event presented is observed in the recovery phase after a magnetospheric storm (min Dst = −108 nT). The frequency of the pulsation ranges from 5 to 9 mHz during the first day of the pulsation, with frequency being higher in the prenoon region; on subsequent
days the frequency range of the pulsation narrows down, until it is centered around 5 mHz ± 0.5 mHz one day before diminishing. Geotail measurements of the outer magnetosphere, IMAGE (International Monitor for Auroral Geomagnetic Effects) ground magnetometer and LANL-MPA density measurements are utilized in order to characterize the nature of the pulsations.

2. Observations

2.1. Geosynchronous Magnetic Field Measurements

[4] Geosynchronous magnetic field measurements from satellites GOES-8 and GOES-9 and the corresponding Dynamic Power Spectra (DPS) over the five-day period that the fluctuations were observed, from 24 to 30 November 1997, are plotted in Figures 1 and 2 using a 0.512-s time resolution [Singer et al., 1996]. GOES-8 and -9 were located at geomagnetic longitudes ~75° and ~135° West at geosynchronous orbit. In order to separate the ULF field variations perpendicular to as well as along the magnetic field direction, the components of the magnetic field vector are projected in a Mean Field-Aligned (MFA) coordinate system. In this system, \( \mathbf{e}_f \) points along the average background magnetic field direction, and is obtained from a 30-min running average of the instantaneous magnetic field, centered at the data point being processed; \( \mathbf{e}_o \) is determined by \( \mathbf{e}_f \times \mathbf{r}_e \), where \( \mathbf{r}_e \) is the unit vector along the line from the earth to the instantaneous satellite position; and \( \mathbf{e}_r \) is obtained by \( \mathbf{e}_o \times \mathbf{e}_f \), completing the orthogonal system. Thus \( \mathbf{e}_o \) points in the eastward direction and \( \mathbf{e}_r \) in the meridional direction. Waves

Figure 1. The magnetic field of the pulsation measured by GOES-8 from 24 to 30 November 1997 is plotted in the Mean Field-Aligned coordinate system. The red lines correspond to local midnight crossings, at 05:00 UT every day. \( B_f \): field-aligned component, \( B_{||-B} \): the average magnetic field is subtracted from \( B_f \) to better reveal the ULF variation in the parallel component. \( B_r \): radial, \( B_o \): azimuthal. The Dynamic Power Spectra of each component are plotted in color for frequencies up to 20 mHz. The color scale corresponds to the logarithm of the power, in nT²/Hz.
in the $\hat{e}_i$, $\hat{e}_r$ and $\hat{e}_\phi$ directions are referred to as compressional, poloidal and toroidal respectively. In rotating the field components into MFA coordinates, the 30-min average acts as a high pass filter removing frequencies below 0.55 mHz.

[5] The projections of the magnetic field onto $\hat{e}_i$, $\hat{e}_r$ and $\hat{e}_\phi$ are shown in line plots marked as $B_i$, $B_r$ and $B_\phi$ in Figures 1 and 2, for GOES-8 and GOES-9 respectively; the Dynamic Power Spectra (DPS) of each component are plotted in the corresponding color plots, as denoted in each figure. The DPS calculations were performed by sliding a Hanning window through the data and performing a Fast Fourier Transform (FFT) on the subset of the signal within the window. For a 0.512-s sampling frequency, the Nyquist frequency (and hence the maximum frequency we can monitor in this data set) is 976 mHz; in order, however, to better show the fluctuations in the Pc5-range, only frequencies up to 20 mHz are shown in Figures 1 and 2.

[6] The successive passage of GOES-8 and GOES-9 satellites through the same region on each day provides a unique opportunity to study the duration, azimuthal extent and gradual frequency change of the narrowband fluctuations. On 24 November, GOES-8 observes an intense fluctuation signature in the dayside region, mainly in the radial component, $B_r$ and in the azimuthal component, $B_\phi$, at a band of frequencies that is variable through the day; GOES-9 observes noon fluctuations higher in frequency, in a narrow band around 16 mHz. On 25 November the band is centered initially on $\sim 9$ mHz in the prenoon region, around 5–7 mHz in the noon region and around 6–7 mHz in the afternoon region; the fluctuation is not evident at GOES-9 until the next day.

Figure 2. The magnetic field of the pulsation measured by GOES-9 from 24 to 30 November 1997 is plotted in the Mean Field-Aligned coordinate system. The red lines correspond to local midnight crossings, at 05:00 UT every day. $B_i$: field-aligned component, $B_r$: the average magnetic field is subtracted from $B_r$; $B_\phi$: radial, $B_\phi$: azimuthal. The Dynamic Power Spectra of each component are plotted in color for frequencies up to 20 mHz. The color scale corresponds to the logarithm of the power, in nT²/Hz.
which time density jumped from density was observed at/C24 remaining relatively constant. A second sharp increase in the storm was observed at/C24 flow speed from Wind spacecraft measurements; these measurements are presented in Figure 3. A shock associated with recovery period after a magnetospheric storm, as seen in Kyoto Dst Index, solar wind density and solar wind flow speed from spacecraft Wind are plotted from 21 to 30 November 1997.

[7] We attribute the lack of fluctuations at GOES-9 on 25–26 November to the fact that GOES-8 and GOES-9 are monitoring different L-shells. This is due to the fact that the tilted magnetic dipole of Earth lies nearly in the longitude of GOES 8, with GOES-9 being located at smaller L. This effect has been described in detail by Ossager et al. [2004], who estimated ΔL between GOES-8 and GOES-9 to vary between 0.5 and 1 in the nightside and about 0.1 in the dayside during the very quiet magnetospheric conditions that they were considering (Dst ~ −10). For the magnetospheric conditions on the first days that this event is observed at GOES-8 (Dst ~ −40), calculations of L-shell based on the T96 magnetic field model show a variation in L of ~0.3 in the dayside region.

[8] Gradually, the frequency range shrinks, until 28 November, when the fluctuations are observed only from 5 to 6 MHz. The azimuthal extent of the pulsations also varies with time: on 25 November it is found to be about 12 h of local time and it gradually shrinks until 28 November, when it is about 7 h LT. The dynamic spectra in Figures 1 and 2 show a second harmonic on most days; in particular, at the location of GOES-9 multiple harmonics can be observed on 29 and 30 November. Such harmonics of Pc5 pulsations were noted and discussed in detail in previous studies of narrowband pulsations [e.g., Higuchi et al., 1986; Takahashi et al., 1990; Southwood and Kivelson, 1997].

2.2. Solar Wind Conditions

[9] The narrowband fluctuation event occurred in the recovery period after a magnetospheric storm, as seen in measurements of the Kyoto Dst Index, solar wind density and flow speed from Wind spacecraft measurements; these measurements are presented in Figure 3. A shock associated with the storm was observed at ~0900 UT on 22 November, at which time density jumped from ~15 cm⁻³ to ~33 cm⁻³ and the flow speed from ~370 km/s to ~500 km/s. Within the shocked solar wind, density and flow speed continued to rise, reaching ~40 cm⁻³ and ~540 km/s. Around 18:00 UT the density dropped to ~5 cm⁻³ with solar wind flow speed remaining relatively constant. A second sharp increase in density was observed at ~1830 UT on 22 November, at which time density jumped from ~5 cm⁻³ to ~32 cm⁻³, with the flow speed remaining relatively high; the relation of the above features to the particular narrowband event is not known. Kyoto Dst index during this time correlated with the increases in density, gradually dropping to a minimum of ~108 nT, as seen in the top panel of Figure 3. The recovery phase following the storm lasted for approximately five days, from ~1200 UT, 23–28 November, during which time the narrowband pulsations were observed. The IMF components at Wind remained relatively low during the period after the storm, fluctuating at ~2 ± 2 nT for Bz and around ~0 ± 4 nT for Bx, and showing no indications of a strong quasi-parallel bow shock. A spectral analysis of Wind solar wind data (not shown here) for the same time period showed no indications of a narrowband fluctuation signature in the solar wind.

2.3. Outer Magnetosphere Measurements

[10] On the days that GOES-8 and −9 observed the narrowband fluctuations, Geotail was fortuitously traversing the dayside outer magnetosphere in the equatorial plane. The orbit of Geotail is plotted in Figure 4 together with the orbit of GOES-8 and −9, in the X-Y plane (left panel) and X-Z plane (right panel), in GSE coordinates. Small triangles mark the spacecraft locations every hour. The locations of Geotail at 00:00 UT on 24–26 November are marked with asterisks. GOES-8 crosses the midnight meridian (00 in LT) at 05:00 UT each day; its location at 00:00 UT every day is also marked with asterisks.

[11] The total magnetic field and individual field components from the Geotail spacecraft are plotted in the top (black and white) panels of Figure 5 with a 3-s resolution, in the Mean Field Aligned coordinate system that was described above; the spectral analysis of the field measurements is plotted in the lower (color) panel, calculated in a similar manner to GOES-8 and −9 magnetic field measurements. During the two-day passage of Geotail through the dayside magnetosphere there are distinct time intervals of intense ULF fluctuations, marked in green in the top panels of Figure 5; the spatial extent over which these fluctuations were observed along the orbit of Geotail are also marked in green in Figure 4, Geotail, GOES-8 and GOES-9 locations are plotted in the (left) XY and (right) XZ planes (GSE) from 24 to 26 November, when Geotail was traversing the dayside outer magnetosphere. Locations at 00:00 UT each day are marked with asterisks; location every hour in UT is marked with a small triangle for each of the satellites. The region where GOES-8 recorded intense narrowband fluctuations on 25 November is marked with orange; the regions over which Geotail recorded intense broadband fluctuations are marked in green.
Figure 4. From the location of the green areas in the dayside along Geotail orbit it can be concluded that these intense fluctuations correspond to Geotail crossings of the magnetopause-magnetosheath, the region which forms between the solar and terrestrial regimes, earthward of the bow shock, in which the magnetic field is usually highly disturbed. Around time 00:00 UT on 25–26 November, Geotail is located at the local times where the pulsations are observed, and would be in an ideal location to measure the narrowband pulsations, if these were extending a few RE farther out from geosynchronous orbit, or if they were related to externally produced oscillations of the bow shock caused by solar wind pressure pulses; such pulsations would be expected to propagate through the shock, sheath, and magnetopause into the inner magnetosphere, carrying similar frequency signatures from the solar wind throughout the whole region. However, no particular fluctuations are detected in the noon or postnoon region in Figure 5 that could be associated with the narrowband fluctuations in the corresponding regions at geosynchronous orbit.

2.4. Ground Measurements

[12] For the time interval that the pulsations were observed at geosynchronous orbit, ground magnetic fluctuation signatures were acquired from stations that are part of IMAGE, the International Monitor for Auroral Geomagnetic Effects. IMAGE consists of 29 stations, covering geographic latitudes from 58 to 79 degrees; the location of the stations is given in Figure 6. The IMAGE magnetometers record perturbations at 10-s resolution in geographical coordinates (X, Y, Z), where X is northward, Y is eastward and Z points vertically downward into the Earth. A spectral analysis technique similar to the analysis used in GOES-8 and GOES-9 magnetic field measurements was also applied to the IMAGE magnetometer measurements to extract the frequency characteristics of the fluctuations on the ground. No filtering has been applied to the data. On 25 November, the day GOES-8 recorded the strongest pulsations with the largest local time extent out of the five day period, multiple magnetometers of the IMAGE array observed narrowband pulsation activity on similar frequencies when they were crossing prenoon local times. The stations that observed pulsation activity are marked in yellow in Figure 6; the stations that did not observe any pulsation activity are marked in red, and the stations from which data was not available on the particular time period are marked in black.

Figure 5. A sequence of 2 days of Geotail magnetometer measurements, from 25 to 27 November 1997. Plotted are the total magnetic field and the ULF variations of the three components of the magnetic field (black and white) and the corresponding Dynamic Power Spectra (color), in units of nT^2/Hz, in the same coordinate system as in Figure 1. The green-shaded time periods in the top panels mark the regions of intense ULF fluctuations in Geotail data; the extent along Geotail’s orbit that these fluctuations were observed are also marked in green in Figure 3.

Figure 6. Locations of the magnetometers of the IMAGE array of ground stations. Stations that observed the pulsations on 25 November are marked in yellow; stations that did not are marked in red, and stations from which data was not available on that day are marked in black.
Ground measurements from 24 to 30 November 1997 are given for a sample station at Andenes (AND) in Figure 7. The red lines correspond to midnight crossings in local time. It can be seen that narrowband pulsations at frequencies from $\sim 5$ to $7$ mHz are observed from prenoon to noon local times only on 25 November, the day that GOES-8 observes the strongest pulsations, overlapping for the most part with the local time extent of the narrowband pulsations at geosynchronous orbit. Measurements on that day from two adjacent stations, AND and KIL, located at latitudes $69.02^\circ$ and $69.30^\circ$ respectively and separated by $4.76^\circ$ in longitude, are given in greater detail Figure 8. On this figure we only plot the $Y$-magnetic field component (eastward), in which the strongest fluctuations are observed. The Pc5 pulsation was also observed in the $X$-magnetic field component (northward), however the power of the pulsation was significantly lower. The appearance of a strong signal in the $Y$ component is consistent with the ionospheric screening effect on radially

Figure 7. Measurements from the ground magnetometer at Andenes (AND) for the same time period as in Figure 1. Pulsations at $\sim 5$ to $7$ mHz can be observed only on 25 November.

Figure 8. Measurements from two longitudinally aligned ground stations, AND and KIL, on 25 November.
polarized Alfvén waves in space [e.g., Hughes, 1974]. Pulsations around 5–7 mHz, close to the frequencies observed at geosynchronous orbit can clearly be distinguished. Three distinct temporal or spatial extents of the pulsations appear within the same day; other stations also observed similar structures and frequencies on that day. The coincidence of local times and frequencies of the observed pulsations on 25 November at IMAGE stations and GOES-8 lead us to conclude that the observations on the ground and at geosynchronous orbit are manifestations of the same event. Measurements from station pairs, such as shown in Figure 8 are used below in section 3.1 to calculate the azimuthal mode number, \( m \) of the fluctuations on the ground, as well as the longitudinal speed of wave propagation.

2.5. Geosynchronous Cold Plasma Measurements

Plasma density measurements for this event were acquired by the Magnetospheric Plasma Analyzer (MPA) instruments built by the Los Alamos National Laboratory (LANL) and flown on the LANL geosynchronous satellites. Plasma number density from the LoP energy channel (energies \( \sim 1 \text{eV} \) to \( 130 \text{eV} \)) of MPA on satellite LANL 1994–084 is plotted as a function of local time in Figure 9; we note here that cold plasma dominates total number density measurements. In this figure the vertical lines indicate local midnight crossings of the satellite. The dates marked correspond to the dates the satellite crosses local noon. In this figure a gradual increase in plasma density can be observed through successive LANL 1994–084 crossings, occurring gradually from 11/24 until 11/29, during the same period that the pulsations are observed. This is an indication of slow plasmaspheric refilling which is often observed during geomagnetic quiet times following a storm [Lawrence et al., 1999].

3. Discussion

The simultaneous observation of pulsations on multiple ground stations aligned across similar latitudes enables us to determine the pulsations' azimuthal mode number, \( m \) from the phase differences between the stations. Phase differences were acquired by performing cross-spectrogram phase analyses on the data time series from pairs of magnetometers. Four stations were used in this analysis: Andenes (AND), Kilpisjärvi (KIL), Masi (MAS) and Kevo (KEV), marked by yellow dots in Figure 6. The Cross-Spectrogram Phase was calculated for three station pairs: AND-KIL, AND-MAS and AND-KEV, which have progressively larger longitudinal separations, as shown in Figure 6. The largest latitudinal separation in any pair is < 0.5°; the longitudinal separations are 4.76°, 7.67° and 10.98° respectively for the three pairs. The particular longitudinal configuration, with progressively larger longitudinal separations, was selected in order to overcome the uncertainty which involves azimuthal wavelengths potentially smaller than the longitudinal separation of each station pair, in which case the results would be uncertain to within a multiple of \( 2\pi \).

In calculating the Cross-Spectrogram Phase, the Software for Waveform ANalysis (SWAN), designed for the visualization and analysis of scientific and engineering data was utilized [e.g., Lagoutte et al., 2000]. The method used is based on classical cross-spectrum estimation, in which the discrete signals are divided into segments and the overlapping among the segments is estimated by an averaging operation over time [see, e.g., Jenkins and Watts, 1969]. In the top panel of Figure 10 the phase difference for each of the station pairs is plotted as a function of time and frequency, for 25 November 1997. A threshold has been used to reveal only the frequencies and time periods of maximum cross-correlation between the two signals; the threshold has been set at 0.2, meaning that data of cross-spectrogram phase were displayed for 20 percent of the total cross-spectrogram power [see Lagoutte et al., 2000, p. 105]. The color scale corresponds to the phase differences in degrees. It can be seen that there is a distinct phase difference corresponding to the time intervals in Figure 8 that the \( \sim 5–7 \) mHz fluctuations are observed.

In the middle panel of Figure 10 the values of phase differences between 5 and 7 mHz for fluctuations of the eastward component Y are plotted as a function of time for each of the station pairs; phase differences are plotted with triangles for the pair AND-KIL, with X-s for the pair AND-MAS and with squares for the pair AND-KEV. The distinct ensembles of cross-phases indicate time intervals of particular behavior, with similar trends observed simultaneously in all station pairs. The distinct ensembles are averaged together and connected by lines, to point out trends in the temporal development of the fluctuation on that day. The solid line corresponds to the average of cross-phases in time for the pair AND-KIL, the dashed line to the pair AND-MAS and the dashed-dotted line to the pair AND-KEV. It can be seen that a larger separation between the stations of each pair corresponds to larger phase difference, consistently for the three station pairs.
In the lower panel of Figure 10 the phase differences are used to calculate the azimuthal mode number $m$ as a function of time, by using:

$$m = \frac{\Delta \phi}{\Delta \lambda}$$

where $\Delta \phi$ is the phase difference in the fluctuations between the two stations of each of the station pairs, as plotted in the middle panel of Figure 10, and $\Delta \lambda$ is the separation in longitude between the stations. A similar approach was used by Thomson and Kivelson [2001] to estimate the azimuthal mode number of magnetospheric giant pulsations (PGs). As indicated in the survey of Thomson and Kivelson, in general there is an ambiguity of $2\pi N$ associated with the phase difference between any station pair; however the use of three station pairs and the linear increase that is observed in the phase differences as longitudinal separation increases confirms that $N = 0$ in this event. From the lower panel of Figure 10 it can be seen that the azimuthal mode number starts initially at a value of $\approx20$, increases to 30, further increases to a value with greater ambiguity ranging between 35 and 55, and returns to 30. These variations are either spatial (azimuthal) structures that the stations successively monitor as they scan the dayside magnetosphere or a temporal development of the event; however this cannot be distinguished in the analysis performed.

As it can be seen in Figure 10, the phase of the fluctuations at ground station AND consistently leads the phase at stations KIL, MAS and KEV, all located eastward of AND at approximately the same latitude, by $\approx65^\circ$, $130^\circ$ and $190^\circ$ respectively, indicating eastward propagation. These phase differences correspond to a delay in the signal from AND to each of the three stations KIL, MAS and KEV by 30s, 60s and 88s respectively for the given fluctuations. A simple calculation based on the longitudinal separation of the stations (AND-KIL: $\approx190$ km; AND-MAS: $\approx300$ km; AND-KEV: $\approx430$ km) gives a longitudinal speed of wave that is, on average, $\approx5$ km/s.

The lack of narrowband pulsations or other magnetospheric activity in the dayside outer magnetosphere, as examined through measurements from Geotail, excludes the possibility that the solar wind is a direct driver for the observed pulsations, inherently fluctuating and inducing the pulsations on the magnetopause, which would subsequently propagate through the magnetospheric cavity, creating field line resonances. The lack of activity at ground stations monitoring $L = 9.7$ and above supports this observation. This
was expected, as an external driver that remains localized and persistent over so many days is highly unlikely.

[21] The magnetic local time of the four ground stations during the times that the pulsations are observed on the ground spans from early morning to noon; thus the eastward propagation velocity of the pulsations as observed in the prenoon region on the ground is not consistent with the Kelvin-Helmholtz wave generation theory, as the vast majority of waves generated by the Kelvin-Helmholtz instability have a westward propagation direction in the morning region and an eastward propagation direction in the afternoon region [e.g., Samson et al., 1971]. Eastward propagation of the pulsations is also inconsistent with an ion drift-bounce resonant interaction, as in this case the pulsations are expected to follow ions in their westward motion. However, it is possible that the waves appear to propagate eastward but actually propagate westward in the plasma rest frame, similarly to a case study presented by Takahashi et al. [1987a, 1987b]; in that study, AMPTE/CCE recorded a compressional Pc5 wave event at ~8 RE in the dawn region that similarly exhibited an eastward (or sunward) propagation, opposite to most previous measurements at geosynchronous orbit; Takahashi et al. [1987a, 1987b] proposed that this propagation was caused by a dawn-dusk dc electric field which conveys the plasma sunward. According to that description, the wave, probably propagating westward in the plasma rest frame, appears to propagate eastward because the electric field drift velocity is larger than the wave phase velocity. In a statistical study by Takahashi et al. [1990] several similar such events were investigated.

[22] Of particular importance for the damping or growth of the standing Alfvén waves is the energization state of the local ion distribution: as described by Southwood et al. [1969], if the distribution is stable, i.e., monotonic in energy, then \( df/dW < 0 \), and the particles can damp the wave; on the other hand, if the distribution is unstable, i.e., it is described by “bumps” in the energy distribution function, then \( df/dW > 0 \), and the particles might contain a sufficient amount of free energy to drift-bounce resonate with and lead to the growth of the waves. Internal excitations of pulsations based on the free energy content of particle distributions have been investigated in studies by Hughes et al. [1978], Engebretson and Cahill [1981], Allan et al. [1982, 1983] and Baddeley et al. [2004], who have attributed dayside (mostly postnoon) pulsations to enhancements in the ring current as a result of newly injected plasma from the magnetotail. Through this excitation mechanism the pulsations derive their energy by a drift resonant wave-particle interaction with tens-keV protons. In particular, Baddeley et al. [2004] presented a statistical study of the unstable proton populations containing “free energy” required to drive small-scale poloidal mode ULF waves in the magnetosphere between L-shell locations of 6 and 9 and also indicated that in the postnoon sector there are populations of 10–50 keV ions which contain significant free energy to drive a resonant mode and create Pc5 pulsations.

[23] As cold plasma density affects significantly the occurrence and frequency characteristics of magnetospheric pulsations, we also investigated MPA ion data in the energy range 1–130 eV from LANL 1994–084 in order to determine if there is a causal relationship between the longevity of the observed pulsations and cold plasma. These measurements show a gradual increase in cold plasma density occurring from 11/24 until 11/29, during the same period that the pulsations are observed. These measurements indicate that the plasmasphere is refilling more slowly than usual following the storm of 22 November, so that the ring current ions remain, though Dst returns to greater than –20 nT by 28 November, the last day that the pulsations are observed. The gradual increase in cold plasma density during this period is also possibly associated with the gradual reduction in wave frequency that is observed in the magnetic field measurements: for a field-line resonance the wave period is directly proportional to the square root of the density along a flux tube. Therefore, the higher the density, the longer the period of the pulsations. A plasma refilling process and the associated increase of cold plasma density is thus expected to result in a gradual decrease in the FLR frequency, which is what is observed particularly in Figure 1 over the five days that the pulsations last.

4. Summary and Conclusions

[24] A pulsation event of remarkably long duration, 4–5 days, was presented through measurements on the ground and in the magnetosphere. To our knowledge this is the longest Pc5 pulsation event ever observed. At geosynchronous orbit, GOES-8 and GOES-9 measured pulsation signatures with frequencies from 5 to 9 mHz and a direction of polarization that is transverse to the magnetic field direction, primarily in the radial component. After each successive passage a gradual decay in amplitude is observed, together with a narrowing of the frequency range and a decrease in local time extent. On the ground a pulsation signature was observed on 25 November, the day of strongest fluctuations, at magnetometers of the IMAGE array of stations. The stations that observed pulsations at ~5–7 mHz were located across a narrow range of latitudes, ranging from 67.8° to at least 69.8°; stations north of 74.5° did not observe pulsation signatures. A cross-spectrogram phase analysis was performed on data from pairs of ground magnetometers that observed pulsations and were latitudinally aligned; the analysis has revealed an eastward propagation of the waves in the prenoon region, and a mode number \( m \) ranging from 20 to 55, as calculated from a phase difference that was changing consistently for various station pairs. The analysis of phase differences between station pairs also revealed an azimuthal propagation in the eastward direction with a speed of ~5 km/s. A fortuitous crossing of the dayside outer magnetosphere by spacecraft Geotail occurred on the days of maximum fluctuation, right after Geotail crossed into the magnetosphere through the bow shock and magnetopause; the lack of narrowband pulsation observations throughout Geotail’s traversal showed that the pulsation does not extend to 10 RE. We can thus exclude the solar wind as a potential energy source that could directly drive the observed pulsations. Density measurements at geosynchronous orbit from LANL satellite 1994–084 show a slow plasmasphere refilling process taking place that could be associated with the long duration of the pulsations, and could explain the gradual decrease in frequency over time.

[25] In summary, even though we provide some evidence against: (1) an external—solar wind source of the pulsations, as supported by GEOTAIL observations, (2) the generation of the pulsations by the Kelvin-Helmholtz instability, as
supported by the eastward motion in the prenoon region and (3) an ion drift-bounce generation mechanism, as supported also by the eastward motion of the waves, we can provide no conclusive evidence in favor of a particular generation mechanism. However, in a manner similar to the description of Takahashi et al. [1987a, 1987b, 1990], it is possible that the wave actually propagates westward in the plasma rest frame, and appears to propagate eastward because the electric field drift velocity is larger than the wave phase velocity.

Furthermore, we believe that these pulsations are very localized radially, as suggested by the localization of the ground observations in latitude; in support of the radial localization are also the very different signatures between observations at GOES-8 and GOES-9, and the fact that observations were observed at GOES-8 throughout the whole 5-day period, but were observed at GOES-9 after a few days, even though GOES-8 and GOES-9 were located in similar L-shells (separation in L between the two spacecraft was less than 1). Such radially polarized Pc5 pulsations have been observed before: similar to the phenomenology of this event, they have been reported to occur primarily inside of L = 7 on the dayside magnetosphere [Anderson et al., 1990] and to be localized in L shell, having radial extents between 0.2 and 1.6 R\(_e\) [Singer et al., 1982]. However, all previous events were of limited duration, most often being observed for a single spacecraft crossing; to our knowledge this is the longest lasting Pc5 pulsation ever observed.

Acknowledgments. We thank Andrew Wright, Anthony Chan, and Jan Mann for fruitful discussions. We thank D. Lagoutte and his colleagues from LPCE/CNRS in Orleans for providing the SWAN software used in the cross-spectrogram phase analysis. We thank the institutes who maintain the IMAGE Magnetometer Array. We thank the LANL-MPA team for providing the LANL-MPA data. We are also thankful for the reviewers’ constructive comments and suggestions, which made this paper concise and clear.

Zuyin Pu thanks William Allan and two other reviewers for their assistance in evaluating this paper.

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