AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2014GL060755

Key Points:

- Use global auroral images to measure ULF waves
- Provide evidence for global cavity mode in the magnetosphere
- Identify compressional waves to be the candidate for the auroral Pc5 pulsations

Correspondence to:
K. Liou,
kan.liou@jhuap.edu

Citation:
Liou, K., and D. G. Sibeck (2014), Study of a global auroral Pc5 pulsation event with concurrent ULF waves, *Geophys. Res. Lett.*, *41*, 6547–6555, doi:10.1002/2014GL060755.

Received 2 JUN 2014
Accepted 27 JUN 2014
Accepted article online 3 JUL 2014
Published online 14 OCT 2014

Study of a global auroral Pc5 pulsation event with concurrent ULF waves

Kan Liou[1] and David G. Sibeck[2]

[1]Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, USA, [2]NASA GSFC, Greenbelt, Maryland, USA

Abstract We present results from a study of concurrent, periodic variations in auroral luminosity (auroral pulsations) and in magnetospheric plasma/magnetic field data. This event occurred on 10 March 2010 from ~13 to 17 UT during an extended southward interplanetary magnetic field and was probably triggered by a slow shock. The auroral pulsations, as measured by the Ultraviolet Imager on board the Polar satellite, were long lasting (~2.5 h), monochromatic (~2.5 mHz), large scale, and appeared in the night sector auroral zone with a latitudinal extent comparable to the latitudinal width of the oval. There was no phase shift between the auroral pulsations observed at different local times, indicating a stationary structure. Particle data from the Defense Meteorological Satellite Program Special Sensor Precipitating Electron and Ion Spectrometer indicate that the pulsations were diffuse originating from the central plasma sheet. During this time, Geotail was in the dawn sector plasma sheet and observed a ULF wave with the same frequency as the auroral pulsations last ~35 min. The ULF wave had large radial and compressional components, and the plasma density and total magnetic field were anticorrelated. These two observations strongly suggest that the observed ULF wave was associated with an standing ULF poloidal mode. The wave compressional component may be able to change the loss cone, resulting in periodic auroral precipitating.

1. Introduction

In contrast to the well-known pulsating aurora, which results from modulations of precipitating electron flux with VLF waves (predominately oscillating at 2–4 Hz [e.g., *Royrvik and Davis*, 1977]), auroral pulsations are fluctuations in auroral luminosities at ULF (1 mHz–1 Hz) frequencies. Modulations of auroras at Pc5 (2–7 mHz) wave frequencies have been observed mostly from the ground. For example, *Xu et al*. [1993] and *Samson et al*. [1996] reported that some optical auroral arcs are modulated by Pc5 magnetic pulsations. They demonstrated that the latitudinal phase structure of the auroral pulsations is consistent with model predictions for field line resonant shear Alfvén waves. *Saga et al*. [2014] observed modulation of arcs by a Pc5 wave in the dawn sector following a substorm onset. The intensity of diffuse auroras can also oscillate in phase with concurrent geomagnetic Pc5 pulsations [*Oguti*, 1963]. Such events occur predominantly in the dawn sector [*Yamamoto et al*., 1988]. Modulations of riometer signals, associated with 10–100 keV electron precipitations, with Pc4 and Pc5 ULF micropulsations have also been reported [e.g., *Olson et al*., 1980, and references therein]. It is generally believed that particle precipitations are controlled by magnetospheric dynamics, while modulations of precipitations are controlled by ULF waves [e.g., *Lanzerotti et al*., 1980].

Reports of auroral pulsations over a large spatial scale, particularly those in the Pc5 frequency range, are still rare because the limited field of view of ground-based cameras prohibits observations of the large-scale and long-period auroral phenomenon. In order to understand and verify the excitation mechanism of pulsations, simultaneous observations of large-scale auroral pulsations and conjugate magnetospheric ULF waves are required. Using space-based global auroral images acquired by Polar Ultraviolet Imager (UVI) [*Torr et al*., 1995], *Liou et al*. [2008] were able to study auroral pulsations on a global scale (but with less detail than ground-based all-sky imagers). Their event study demonstrated that tailward moving auroral pulsations (1–3 mHz) were produced by solar wind pressure disturbances at similar frequencies that sweep through the magnetosphere. More recently, *Liou and Takahashi* [2013] used Polar UVI, GOES, and ground magnetometers to show that Pc5 auroral pulsations in the premidnight sector, presumably produced by substorm dipolarization, are associated with field line resonances (FLRs).

This letter reports a fortuitous event with simultaneous Polar UVI auroral pulsations and Geotail ULF wave observations in the plasma sheet conjugate to the auroral pulsations. The main objective of the study is to determine the magnetospheric wave modes responsible for optical auroral pulsations.

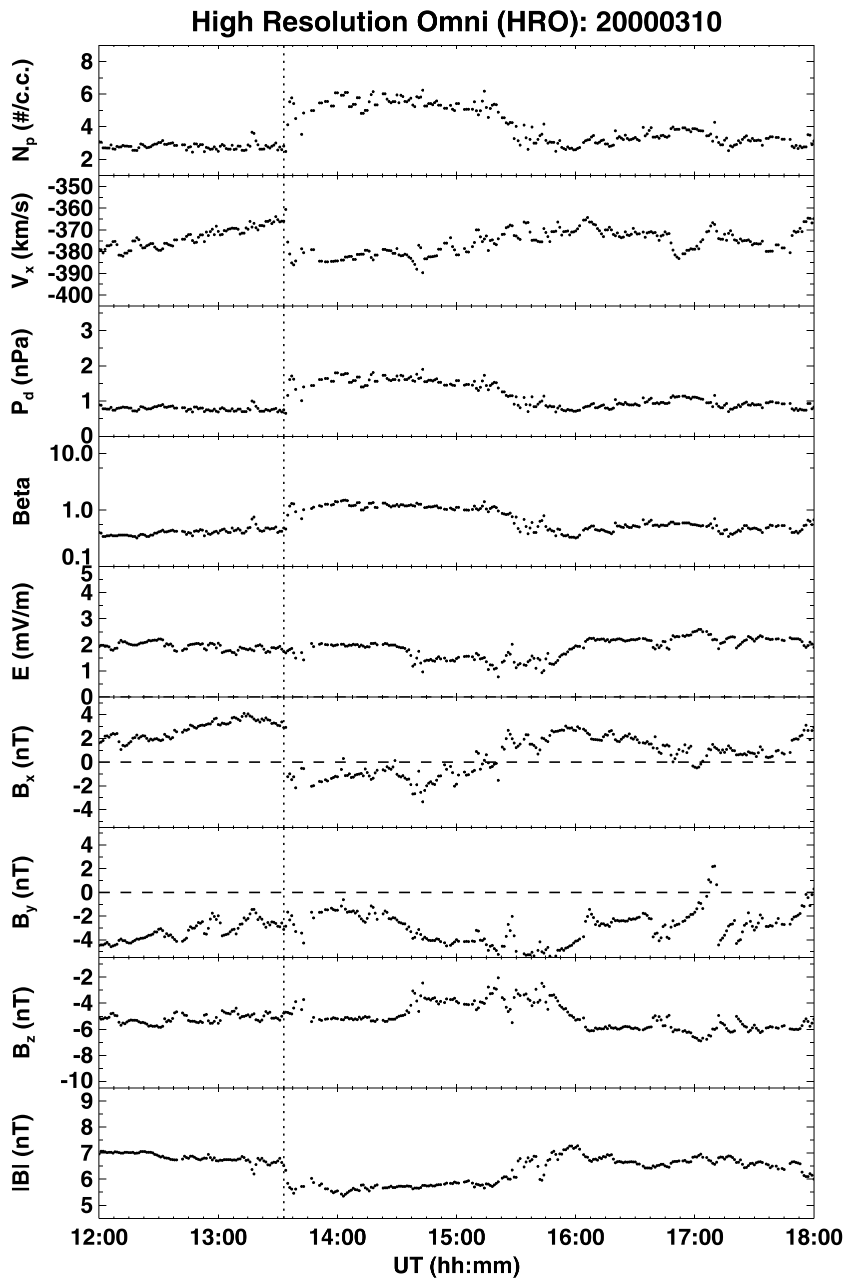

Figure 1. Panels from top to bottom are solar wind plasma density (N_p), x component of velocity (V_x), dynamic pressure (P_d), plasma beta, convection electric field (E), three components (B_x, B_y, and B_z), and the total ($|B|$) magnetic field upstream of the subsolar bow shock.

2. Observations

2.1. Solar Wind Parameters

The auroral pulsation event occurred on 10 March 2000, from ~13:00 UT to 17:00 UT. Figure 1 shows the solar wind plasma and magnetic field data with a 1 min time resolution from the NASA's Space Physics Data Facility high-resolution OMNIWeb. Plasma and magnetic field measurements made upstream from the Earth's bow shock by Wind, IMP-8, and ACE spacecraft are propagated to the nose of the bow shock using minimum variance techniques developed by *Weimer et al*. [2003]. A slow shock, as indicated by a sudden increase in the plasma density, speed, and temperature and a sudden decrease in the total magnetic field, appeared in the lagged data at ~13:35 UT. The shock hit at the magnetosphere at ~13:48 UT,

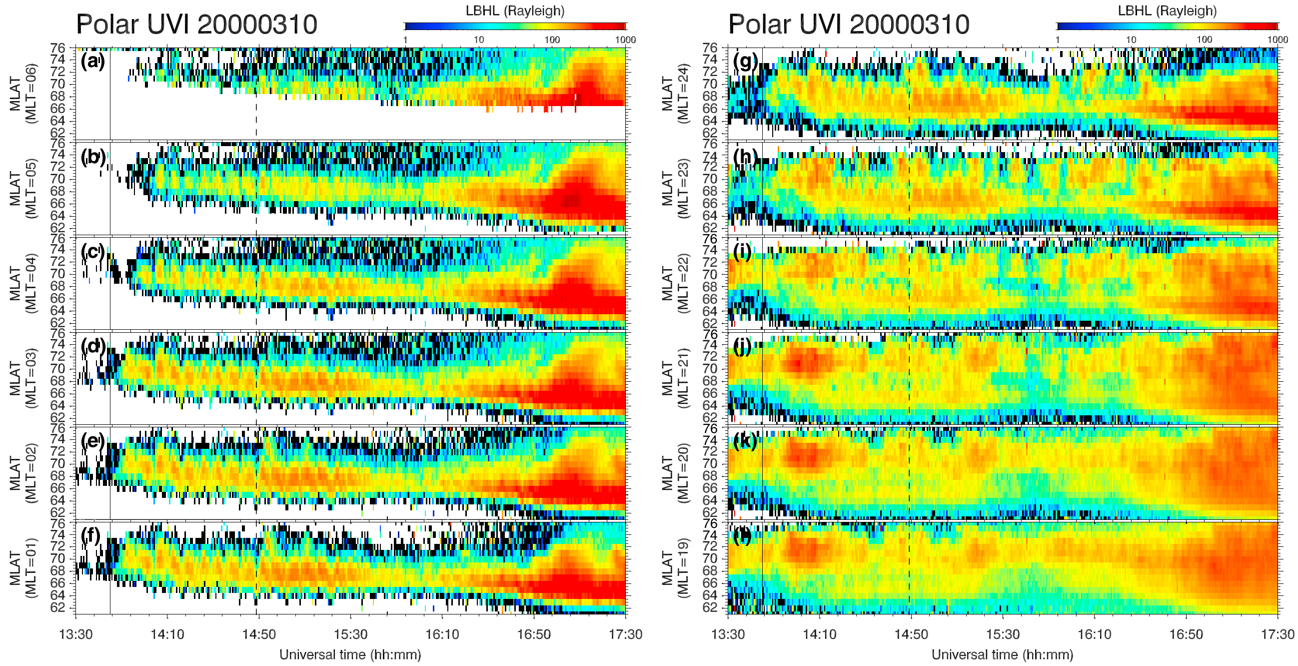

Figure 2. Auroral keograms at fixed magnetic local times (left: 01–06 MLT and right: 19–24 MLT) derived from the Polar UVI images. The unit for the *y* axis is magnetic latitudes. There are two vertical lines: the solid line marks 13:45 UT, the shock impact time, and the dashed line (~14:50 UT) shows the coherence of the pulsations at different local times.

as indicated by an *SI* in the *SYM-H* data (not shown). The interplanetary magnetic field (IMF) was generally southward (~−3–−6 nT) both upstream and downstream of the shock. The plasma density increased from ~3 cm^{-3} upstream of the shock to ~6 cm^{-3} downstream of the shock. There are no obvious long-period (minutes) perturbations in the solar wind parameters either upstream or downstream of the shock.

2.2. Polar UVI Observations

Figure 2 shows auroral keograms derived from Polar UVI images between 13:30 and 17:30 UT for the postmidnight (left) and premidnight (right) sectors. Dayside data are not presented because most of the dayside auroral region was outside the field of view of the UVI during this time period. Clear variations in the auroral luminosity occur after ~13:42 UT (marked by a vertical line). Before this time, the aurora was generally weak except the region of 19–22 magnetic local time (MLT), and the auroral oval was located at higher latitudes (e.g., ~67°–73° at 01 h MLT). After this time, the aurora intermittently brightened (referred to as "auroral pulsations" thereafter) throughout almost the entire night sector. The period of the pulsations is estimated to be ~6.7 min, corresponding to a frequency of ~2.5 mHz. The onset of the auroral brightenings/pulsations seemed to start at midnight, a few minutes after the magnetospheric impact of the shock. After the onset, the brightening moved to lower latitudes (e.g., 64°–70° at 01 h MLT) and expanded to the dawn and dusk flanks. An important feature of the auroral pulsations is that there is little phase difference at different local times, as indicated by a dashed line in Figure 2. This means that they do not propagate in the longitudinal direction. In other words, the aurora brightened and faded globally as a whole.

The auroral pulsations occupied nearly the entire postmidnight oval. In the premidnight sector, the auroral pulsations were located on the lower latitude (e.g., ~64°–68° at 22 h MLT) part of the oval, coexisting with some short-term auroral activations at higher latitudes greater than ~70° magnetic latitude (MLAT). The postmidnight auroral pulsations lasted for ~3 h until ~16:50 UT when aurora enhanced throughout the entire nightside. In the premidnight sector, the auroral pulsations ended sooner at ~15:30 UT. After ~15:30 UT, the aurora started to fade at all local times, which corresponds to the decrease in the solar wind dynamic pressure.

During this period, the oval in the postmidnight sector gradually shifted equatorward, consistent with the dominant southward IMF condition. On the other hand, an equatorward shift of the oval is not as obvious in the premidnight sector.

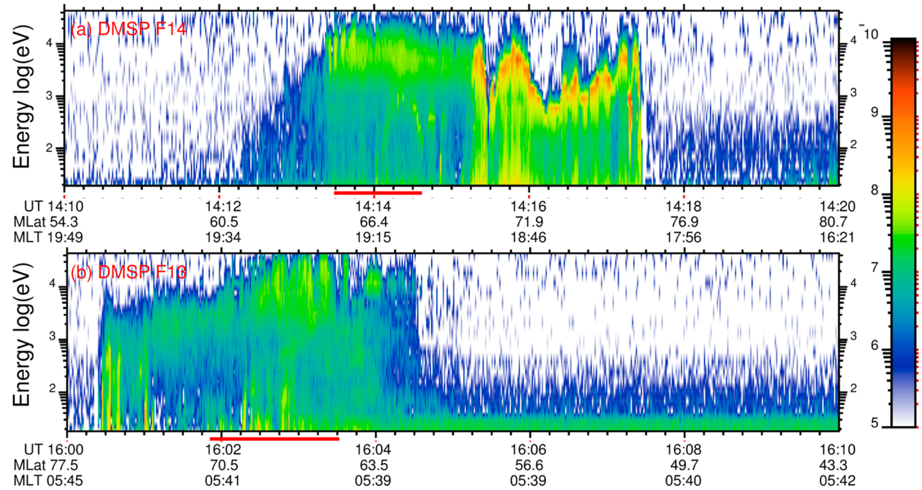

Figure 3. Electron differential energy flux (eV/cm^2 s sr eV) from SSJ/4 on (a) DMSP F14 and (b) DMSP F13 during the oval passes.

2.3. DMSP Particle Measurements

Information about the magnetospheric source of precipitating electrons/protons that produce auroral pulsations can provide insight into the pulsation-associated wave. Figure 3 shows particle spectrograms from the Special Sensor Precipitating Electron and Ion Spectrometer (SSJ/4) Particle Analyzer on board the Defense Meteorological Satellite Program (DMSP) F13 and F14. As shown in Figure 3a, DMSP F14 was northbound and traversed the northern oval at ~19:30 MLT after ~14:12 UT. During this pass, there are two different types of precipitation spectra. At lower latitudes, the electron precipitation is characterized by stable, structureless precipitating electrons, presumably originating from the central plasma sheet (CPS), with the peak flux energy greater than a few keV. On the other hand, at higher latitudes, the precipitation is characterized by monoenergetic electrons with varying energies ranging from slightly below 1 keV up to ~7 keV. These two types of electron population are separated at ~69.8° MLAT. This is roughly consistent with the Polar UVI measurements (Figure 2l), which show that the brighter aurora (presumably associated with discrete arcs) was located poleward of ~70° MLAT at the time of the DMSP F14 pass. This suggests that the auroral pulsations are associated with enhanced CPS precipitating electrons (marked as a horizontal red line in the time axis of Figure 3a).

Figure 3b shows the electron differential energy flux from the DMSP F13 dawn (~05:40 MLT) oval pass at ~16:00 UT. At this particular time of the pass, the spectra of precipitating electrons were of the diffuse type for the entire crossing, except at the poleward edge (~2° wide) where weak broadband electrons can be seen. The auroral pulsations during this time seen by UVI roughly correspond to ~65°–71° MLAT and are associated with intense precipitating electrons.

2.4. Geotail Magnetosphere Observations

Figure 4 shows the in situ measurements of plasma by the low-energy particle (LEP) experiment [*Mukai et al.*, 1994] and magnetic field by magnetic field (MGF) experiment [*Kokubun et al.*, 1994] on Geotail. During the auroral pulsations, Geotail was in the dawn sector of the southern magnetospheric midtail region moving sunward from (−7.8, −14.3, −0.6) R_E at 13:00 UT to (−2.8, −13.1, −3.0) R_E at 17:00 UT in the geocentric solar magnetospheric (GSM) coordinate system. The plasma density was in the range of 0.1–0.3 cm^{-3}, and the ion temperature was a few keV (see Figures 4a and 4d). These values are typical of the plasma sheet region. The large (~100 km/s) x component of the plasma velocity over the entire time period suggests that this is a period of steady magnetospheric convection and is consistent with the observed steady large negative IMF B_z component. The impact of the shock on the magnetosphere probably induced the large transient fluctuation in the plasma flow and the pressure pulse at Geotail at ~13:57 UT (see Figures 4b and 4e). Magnetic field measurements from MGF indicate dominant B_z and B_y components. The large (negative) B_y component and the small (negative) B_x component also suggest that Geotail was located at the southern hemispheric predawn sector. According to the T96 model field [*Tsyganenko*, 1995] with P_d = 1.54 nPa, Dst = −17,

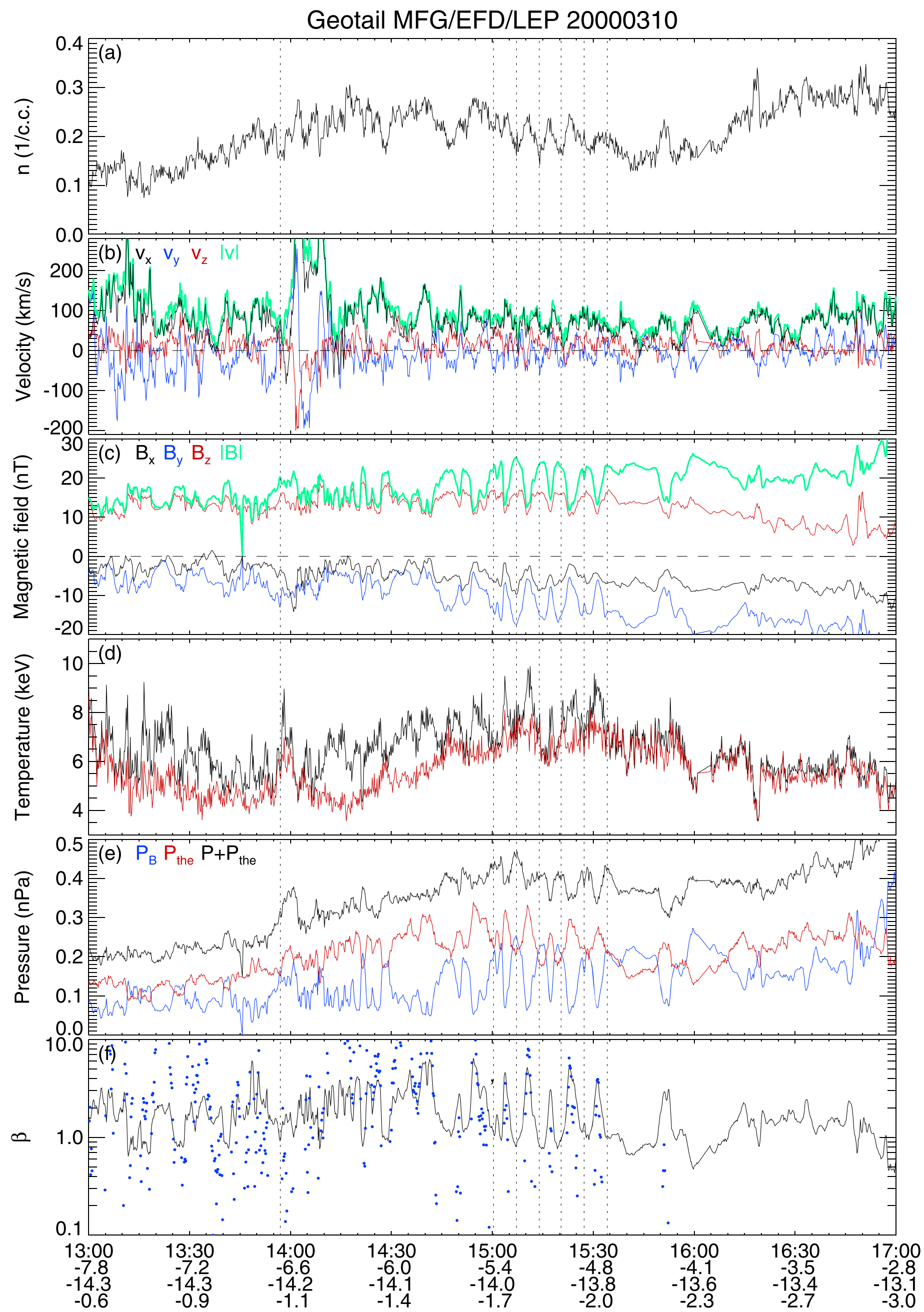

Figure 4. Plasma and magnetic field measurements from Geotail on 10 March 2010 from 13 to 17 UT. (a) Plasma density, (b) three components of plasma velocity (v_x in black, v_y in blue, and v_z in red) and plasma flow speed $|v|$ (green), (c) three components of the magnetic field (B_x in black, B_y in blue, and B_z in red) and the magnitude of magnetic field $|B|$ (green), (d) ion temperature ($T\perp$ in black and $T_{\parallel}$ in red), (e) sum of magnetic (blue) and thermal (red) pressure, and (f) plasma beta (black) and regions (marked by blue dots) that favor mirror wave instability (see text for detail).

$B_y = -4.16$ nT, and $B_z = -3.94$ nT, the magnetic foot point of Geotail at 15:00 UT was ~4.1 MLT and 73.0° MLAT in the Altitude Adjusted Corrected Geomagnetic Coordinates [*Baker and Wing*, 1989]. This places Geotail roughly on the northern edge of the auroral oval (see Figure 2c).

Between 13:00 and 15:00 UT, the magnetotail was moderately active ($AE >$ ~500 and $Dst > -21$). Starting ~15:00 UT, AE slowly decreased to ~200 at 16:00 UT. There are clear quasi-monochromatic perturbations in the density and all the three components of the magnetic field measurements between 15:00 and 15:35 UT.

The frequency of the oscillations is ~2.5 mHz, which is the same frequency as that observed in the auroral data. The magnetic field oscillation (or the ULF wave) is large ($\delta|B|$~10 nT) and consists of both transverse and longitudinal components (see Figure 4c). Since Geotail was located at the dawn sector close to the magnetic equator, the *z* component of the magnetic field is approximately parallel to the local magnetic field. During this time period, Geotail was in the predawn sector (-5.4, 14.0, and -1.7 R_E) in GSM. Estimating from the observed field, it is found that the *x* component to the *y* component ratio of the mean field is 0.47 ± 0.09, which is close to the expected value (~0.4) from the International Geomagnetic Reference Field dipole field model. Therefore, the transverse component of the field oscillation is mainly in the radial direction. The slightly larger ratio is probably due to the fact that the magnetotail is stretched. The ratio of longitudinal to transverse component of field oscillation is estimated to be ~0.5. Because Geotail was near the magnetic equator, the compressional component of the field perturbations can result from poloidal mode oscillations.

As shown in Figures 4a and 4c, there is a clear antiphase relationship between the density and the total magnetic field strength. This suggests that the oscillation could be either a magnetosonic slow or mirror mode wave. The plasma temperature shown in Figure 4d clearly shows anisotropy with perpendicular temperature greater than the parallel temperature from ~13:00 UT to 15:30 UT. Figure 4f shows the plasma beta β (ratio of plasma thermal pressure to magnetic pressure, $2\mu nT/B^2$). The plasma beta is greater than 1 throughout most of the region. We also calculated the conditions for the fluid limit of mirror mode, $\beta\perp(T\perp/T_{\|} - 1) - 1 > 0$ [e.g., *Hasegawa*, 1969]. All regions marked by blue dots satisfy the condition.

3. Discussion and Conclusions

We have analyzed the 10 March 2000 auroral pulsation event. There are many more auroral pulsation events that we have identified with the Polar UVI data. However, this particular event is the only one that occurred, while Geotail was in the magnetotail conjugate to the aurora, thus allowing us to study the ULF wave mode responsible for the auroral pulsations. During this event, GOES 8 and GOES 10 were in the morning and near the dawn sector, respectively. We did not present their data because they neither show ULF waves in the relevant frequency band nor because of lack of coverage in these local time sectors from the Polar UVI.

The main features of the auroral pulsation event can be summarized as the following: (1) the auroral pulsations were global (except the dawn-to-noon quadrant not covered by UVI at the time), nonpropagating (standing), oscillations in the meridional direction; (2) the pulsations were monochromatic with a period of ~6.7 min ($f = 2.5$ mHz) and lasted for more than 3 h; and (3) the pulsations were associated with ULF waves at the same frequency in the predawn sector observed by Geotail. Based on the Geotail data, the magnetic field perturbations observed at 15:00–15:35 UT had a large radial component. We interpret the ULF wave as a poloidal mode oscillation with a substantial compressional component.

One of the most important findings from this study is the global feature of the monochromatic auroral pulsations, which provides the first direct evidence for the existence of magnetospheric cavity mode. Pc5 pulsations of the same frequency are common in ground arrays that cover a wide range of high latitudes [e.g., *Samson and Rostoker*, 1972]. *Kivelson et al*. [1984] reported compressional oscillations with nearly constant periods (<8 min) within the magnetosphere at L ~5–10 near local noon from ISEE 1. Although these measurements were made in a small local time region, they are considered global and are interpreted as FLRs excited by fast mode waves trapped between an inner (inside the magnetosphere) reflecting point and an outer reflecting boundary such as the magnetopause [e.g., *Kivelson and Southwood*, 1985, 1986] or the bow shock [*Harrold and Samson*, 1992]. Unfortunately, we cannot tell if the global Pc5 pulsations were also present on the ground. We have checked the nighttime magnetometer data from the 210° magnetic meridian chain stations: Kotel'nyy (69.9° MLAT), Tixie (65.7° MLAT), and Chokurdakh (64.7° MLAT). Although there were large magnetic field perturbations at those sites starting at ~12 UT (not shown), we did not find field perturbations at the similar frequencies as the aurora. This could be due to the fact that the auroral pulsations are associated with diffuse auroras, which carry little field-aligned current. To understand the auroral pulsations, one will have to understand the generation mechanism(s) of ULF waves. In the remaining section, we will discuss a number of possible generation mechanisms for the ULF waves and auroral pulsations.

The Kelvin-Helmholtz instability (KHI) at the magnetopause has often been considered the source of geomagnetic pulsations [e.g., *Dungey*, 1954]. Under this scenario, large-amplitude magnetopause surface waves excited by a KHI can launch fast mode waves that propagate earthward across field lines to couple to shear mode Alfvén waves through mode conversion [*Southwood*, 1974; *Chen and Hasegawa*, 1974]. There is a plenty of evidence indicating that the occurrence and intensity of Pc5 ULF waves increase with increasing solar wind speed [e.g., *Kokubun et al*., 1989; *Anderson et al*., 1991], and this increased power is attributed to the KHI at the outer boundary of the magnetosphere [e.g., *Southwood*, 1979]. Based on the solar wind data, the present event is associated with only a very small increase (~20 km/s) in the solar wind speed at the shock, from ~370 km/s upstream of the shock to ~390 km/s downstream of the shock. We doubt that a KHI can arise for such a slow solar wind, as compared to the average solar wind speed of ~430 km/s at the Earth's orbit. Furthermore, magnetopause surface waves arisen from KHIs are more likely toroidal rather than poloidal mode as observed by Geotail in this event.

Buffeting of the magnetopause by solar wind pressure pulses has also been considered a good candidate for the generation of Pc5 ULF waves. Using coordinated satellite (in the solar wind, magnetosheath, and magnetosphere) and ground-based data, *Sibeck et al*. [1989] and *Korotova and Sibeck* [1995] clearly showed a connection between the solar wind pressure pulses and the Pc5 ULF waves. It has also been shown that periodic changes in the solar wind dynamic pressure can also drive auroral Pc5 pulsations at the same frequency in the dawn and dusk flanks [*Liou et al*., 2008]. Because the response of the auroral intensity to solar wind pressure pulses is prompt and one to one [*Liou et al*., 2013], compression and decompression of the magnetosphere can cause the auroral intensity to increase and decrease, respectively [*Liou et al*., 2006, 2007]. However, we do not find any obvious periodic structures in the solar wind at the same frequencies as the pulsations. Moreover, auroral Pc5 pulsations driven by solar wind structures will move tailward as solar wind structures sweep over the magnetosphere [*Liou et al*., 2008]. In constrast, the auroral pulsations in this event do not appear to be propagating azimuthally. Dynamic pressure-driven events often occur on the dayside [e.g., *Kepko and Spence*, 2003]. During this event, both GOES 8 and 10 were in the morning sector but did not observe ULF waves at similar Pc5 frequencies. Therefore, we can rule out the effect of magnetospheric buffeting.

It has been known for a long time that the sudden commencements, often associated with interplanetary shocks, can trigger geomagnetic pulsations (2.5–10 min) [*Wilson and Sugiura*, 1961]. The shock impact to the dayside magnetopause provides a broadband energy in the form of compressional pulses that can propagate across the field lines, azimuthally away from the site of impact. Theoretical studies have shown that coupling of the compressional waves with magnetic field lines through field line resonances can occur and produce cavity mode oscillations [*Kivelson and Southwood*, 1986; *Allan et al*., 1986]. However, evidence that supports the existence of the cavity mode is still rare [*Goldstein et al*., 1999]. In the event studied here, the expected compressional pulse was observed by the Geotail. However, we did not find monochromatic Pc5 ULF waves following the compressional pulse until ~1 h later. Although auroral pulsations did occur right after the shock impact on the magnetosphere, the UVI data suggest that the auroral pulsations started at midnight, not consistent with the dayside solar wind source scenario.

The observed ULF wave at Geotail exhibited an ~180° out of phase relationship between the field and density perturbations. There are two fundamental MHD waves predicting such an antiphase relationship: the mirror and slow modes. Slow modes are frequently observed in the magnetosheath but not in the magnetospheric plasma sheet. On the other hand, mirror modes are commonly observed in the magnetosphere and are considered the source of nighttime compressional ULF waves [e.g., *Woch et al*., 1990]. In situ plasma and field data from Geotail suggest that the conditions favor the mirror instability: large plasma β and temperature anisotropy ($\beta_\perp[T_\perp/T_\parallel - 1] > 1$) [e.g., *Hasegawa*, 1969]. It has been suggested that the relative size of perturbations can be used to distinguish between slow mode and mirror mode waves. In the mirror mode, the fractional change in the magnetic field should exceed that in the density [*Gary*, 1992], whereas in the slow mode, the opposite is true [*Gary and Winske*, 1992]. From Figures 4a and 4c, we estimate the fractional change in density perturbation ($\delta n/n$) ~0.07/0.2 = 0.35 and in magnetic field strength perturbation ($\delta B/B$) ~11/18 = 0.61. The fractional change in the magnetic field is twice with that of the density perturbations, suggesting a mirror mode wave. The antiphase relationship between the density perturbations and the magnetic perturbations and between the thermal pressure perturbations and the magnetic pressure perturbations also supports the mirror mode scenario. The compression of the magnetosphere by the large dynamic pressure downstream of the shock may be able to accelerate particles increasing the anisotropy ($T_\perp/T_\parallel$) of the plasma if the first adiabatic invariant is conserved. In this scenario, the shock compression probably did not trigger the observed ULF waves but set up a condition for the mirror instability to grow. However, mirror waves are observed often in association with storm time ring currents [*Barfield et al*., 1972] and to propagate in plasma gradients and curvature fields [e.g., *Walker et al*., 1983]. This is not consistent with the standing oscillations seen in the auroral data. Further, the mirror mode is not consistent with an ionosphere that simultaneously brightens at all local time. Instead, there should be a pronounced azimuthal structure around the oval.

Clearly, no single generation mechanism discussed above can explain the observed event. The auroral data suggest a global standing wave, whereas the in situ plasma and field data suggest a drift mirror mode. Any successful theory must be able to explain the two basic features of the pulsations.

In conclusion, we have identified the auroral Pc5 pulsations to be associated with a poloidal mode with a strong compression component. While we are not able to address the question about how the ULF waves were produced, we have pointed out a few possibilities. The present work suggests that the compressional mode of ULF can play an important role in particle precipitations that produce auroras. The large (~60%) magnetic field compression and decompression associated with the ULF waves in the magnetospheric equator can change the mirror ratio and modify the loss cone in a periodic fashion. When the mirror ratio increases, precipitation increases, and when the mirror ratio decreases, so does precipitation. This increase-decrease pattern results in auroral pulsations.

Acknowledgments

We acknowledge the use of the NASA/GSFC's Space Physics Data Facility's OMNIWeb (or CDAWeb or ftp) service and OMNI data. G.K. Parks was the PI for the Polar UVI, which was built by M. Torr. The Geotail IMF data were provided by S. Kokubun (PI of MGF) through DARTS, and the Geotail solar wind data were courtesy of T. Mukai (PI of LEP). JHUAPL provided the DMSP particle spectrograms, which are made possible by P.T. Newell and T. Sotirelis. The DMSP SSJ/4 particle detectors were designed and calibrated by Dave Hardy, Fred Rich, and colleagues at AFRL at Hanscom AFB in Boston. The U.S. Air Force has publicly released these data. Most of it was obtained through WDC-A (NOAA) in Boulder, with generous supplements from AFRL. This work was supported by the NSF grant AGS-0964396 to the Johns Hopkins University Applied Physics Laboratory.

The Editor thanks W. Jeffrey Hughes and Colin Waters for their assistance in evaluating this paper.

References

Allan, W., S. P. White, and E. M. Poulter (1986), Impulse-excited hydromagnetic cavity and field-line resonances in the magnetosphere, *Planet. Space Sci.*, *34*(4), 371.

Anderson, B. J., S. A. Fuselier, and D. Murr (1991), Electromagnetic ion cyclotron waves observed in the plasma depletion layer, *Geophys. Res. Lett.*, *18*(11), 1955–1958, doi:10.1029/91GL02238.

Baker, K. B., and S. Wing (1989), A new magnetic coordinate system for conjugate studies at high latitudes, *J. Geophys. Res.*, *94*(A7), 9139–9143, doi:10.1029/JA094iA07p09139.

Barfield, J. N., R. L. McPherron, P. J. Coleman Jr., and D. J. Southwood (1972), Storm-associated Pc 5 micropulsation events observed at the synchronous equatorial orbit, *J. Geophys. Res.*, *77*(1), 143–158, doi:10.1029/JA077i001p00143.

Chen, L., and A. Hasegawa (1974), A theory of long-period magnetic pulsations: 1. Steady state excitation of field line resonance, *J. Geophys. Res.*, *79*(7), 1024–1032, doi:10.1029/JA079i007p01024.

Dungey, J. W. (1954), Electrodynamics of the outer atmospheres, *Tech. Rep. 69*, Ions. Res. Lab. Pa. State Univ., University Park, Pa.

Gary, S. P. (1992), The mirror and ion cyclotron anisotropy instabilities, *J. Geophys. Res.*, *97*(A6), 8519–8529, doi:10.1029/92JA00299.

Gary, S. P., and D. Winske (1992), Correlation function ratios and the identification of space plasma instabilities, *J. Geophys. Res.*, *97*(A3), 3103–3111, doi:10.1029/91JA02752.

Goldstein, J., M. K. Hudson, and W. Lotko (1999), Possible evidence of damped cavity mode oscillations stimulated by the January 1997 magnetic cloud event, *Geophys. Res. Lett.*, *26*(24), 3589–3592, doi:10.1029/1999GL003636.

Harrold, B. G., and J. C. Samson (1992), Standing ULF modes of the magnetosphere: A theory, *Geophys. Res. Lett.*, *19*(18), 1811–1814, doi:10.1029/92GL01802.

Hasegawa, A. (1969), Drift mirror instability in the magnetosphere, *Phys. Fluids*, *12*, 2642–2650.

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

Kivelson, M. G., and D. J. Southwood (1985), Resonant ULF waves: A new interpretation, *Geophys. Res. Lett.*, *12*(1), 49–52, doi:10.1029/GL012i001p00049.

Kivelson, M. G., and D. J. Southwood (1986), Coupling of global magnetospheric MHD eigenmodes to field line resonances, *J. Geophys. Res.*, *91*(A4), 4345–4351, doi:10.1029/JA091iA04p04345.

Kivelson, M. G., J. Etcheto, and J. G. Trotignon (1984), Global compressional oscillations of the terrestrial magnetosphere: The evidence and a model, *J. Geophys. Res.*, *89*(A11), 9851–9856, doi:10.1029/JA089iA11p09851.

Kokubun, S., K. N. Erickson, T. A. Fritz, and R. L. McPherron (1989), Local time asymmetry of Pc 4-5 pulsations and associated particle modulations at synchronous orbit, *J. Geophys. Res.*, *94*(A6), 6607–6625, doi:10.1029/JA094iA06p06607.

Kokubun, S., T. Yamamoto, M. H. Acuna, K. Hayashi, K. Shiokawa, and H. Kawano (1994), The GEOTAIL magnetic field experiment, *J. Geomagn. Geoelec.*, *46*, 7–21.

Korotova, G. I., and D. G. Sibeck (1995), A case study of transient event motion in the magnetosphere and in the ionosphere, *J. Geophys. Res.*, *100*(A1), 35–46, doi:10.1029/94JA02296.

Lanzerotti, L., C. Maclennan, and T. Rosenberg (1980), Hydromagnetic wave modulation of substorm particle precipitation at L ~ 4, *J. Geophys. Res.*, *85*(A7), 3447–3452, doi:10.1029/JA085iA07p03447.

Liou, K., and K. Takahashi (2013), Observations of field line resonance with global auroral images, *J. Atmos. Sol. Terr. Phys.*, *105-106*, 152–159.

Liou, K., P. T. Newell, T. Sotirelis, and C.-I. Meng (2006), Global auroral response to negative pressure impulses, *Geophys. Res. Lett.*, *33*, L11103, doi:10.1029/2006GL025933.

Liou, K., P. T. Newell, J.-H. Shue, C.-I. Meng, Y. Miyashita, H. Kojima, and H. Matsumoto (2007), "Compression aurora": Particle precipitation driven by long-duration high solar wind ram pressure, *J. Geophys. Res.*, *112*, A11216, doi:10.1029/2007JA012443.

Liou, K., K. Takahashi, P. T. Newell, and K. Yumoto (2008), Polar Ultraviolet Imager observations of solar wind-driven ULF auroral pulsations, *Geophys. Res. Lett.*, *35*, L16101, doi:10.1029/2008GL034953.

Liou, K., D. Han, and H. Yang (2013), Ionospheric response to solar wind pressure pulses under northward IMF conditions, *Terr. Atmos. Ocean. Sci.*, *24*(2), 183–195, doi:10.3319/TAO.2012.09.11.01(SEC).

Mukai, T., M. Hirahara, Y. Saito, T. Terasawa, and A. Nishida (1994), Geotail observation of cold ion streams in the medium distance magnetotail lobe in the course of a substorm, *Geophys. Res. Lett.*, *21*, 1023–1026, doi:10.1029/93GL02424.

Oguti, T. (1963), Inter-relations among the upper atmosphere disturbance phenomena in the auroral zone, *JARE Sci. Rep., Ser. A, No. 1*, Polar Section, Natl. Sci. Mus., Tokyo, Japan.

Olson, J., G. Rostoker, and G. Olchowy (1980), A study of concurrent riometer and magnetometer variations in the PC 4–5 pulsation band, *J. Geophys. Res.*, *85*(A4), 1695–1702, doi:10.1029/JA085iA04p01695.

Royrvik, O., and T. N. Davis (1977), Pulsating aurora: Local and global morphology, *J. Geophys. Res.*, *82*(29), 4720–4740, doi:10.1029/JA082i029p04720.

Saga, O., K. Hayashi, D. Y. Klimushkin, and P. N. Mager (2014), Modulation of auroras by Pc5 pulsations in the dawn sector in association with reappearance of energetic particles at geosynchronous orbit, *J. Atmos. Sol. Terr. Phys.*, *110-111*, 1–8.

Samson, J. C., and G. Rostoker (1972), Latitude-dependent characteristics of high-latitude Pc 4 and Pc 5 micropulsations, *J. Geophys. Res.*, *77*(31), 6133–6144, doi:10.1029/JA077i031p06133.

Samson, J. C., L. L. Cogger, and Q. Pao (1996), Observations of field line resonances, auroral arcs, and auroral vortex structures, *J. Geophys. Res.*, *101*(A8), 17,373–17,383, doi:10.1029/96JA01086.

Sibeck, D. G., et al. (1989), The magnetospheric response to 8-minute period strong-amplitude upstream pressure variations, *J. Geophys. Res.*, *94*(A3), 2505–2519, doi:10.1029/JA094iA03p02505.

Southwood, D. J. (1974), Some features of field line resonances in the magnetosphere, *Planet. Space Sci.*, *22*, 483–491.

Southwood, D. J. (1979), Magnetopause Kelvin-Helmholtz instability, in *ESA Magnetospheric Boundary Layers*, pp. 357–364, ESA, Paris, France.

Torr, M. R., et al. (1995), A far ultraviolet imager for the international solar terrestrial physics mission, *Space Sci. Rev.*, *71*, 329.

Tsyganenko, N. A. (1995), Modeling the Earth's magnetospheric magnetic field confined within a realistic magnetopause, *J. Geophys. Res.*, *100*(A4), 5599–5612, doi:10.1029/94JA03193.

Walker, A. D. M., H. Junginger, and O. H. Bauer (1983), GEOS 2 plasma drift velocity measurements associated with a storm time Pc5 pulsation, *Geophys. Res. Lett.*, *10*(8), 757–760, doi:10.1029/GL010i008p00757.

Weimer, D. R., D. M. Ober, N. C. Maynard, M. R. Collier, D. J. McComas, N. F. Ness, C. W. Smith, and J. Watermann (2003), Predicting interplanetary magnetic field (IMF) propagation delay times using the minimum variance technique, *J. Geophys. Res.*, *108*(A1), 1026, doi:10.1029/2002JA009405.

Wilson, C. R., and M. Sugiura (1961), Hydromagnetic interpretation of sudden commencements of magnetic storms, *J. Geophys. Res.*, *66*(12), 4097–4111, doi:10.1029/JZ066i012p04097.

Woch, J., G. Kremser, and A. Korth (1990), A comprehensive investigation of compressional ULF waves observed in the ring current, *J. Geophys. Res.*, *95*(A9), 15,113–15,132, doi:10.1029/JA095iA09p15113.

Xu, B.-L., J. C. Samson, W. W. Liu, F. Creutzberg, and T. J. Hughes (1993), Observations of optical aurora modulated by resonant Alfvén waves, *J. Geophys. Res.*, *98*(A7), 11,531–11,541, doi:10.1029/93JA00435.

Yamamoto, T., K. Hayashi, S. Kokubun, T. Oguti, and T. Ogawa (1988), Auroral activities and long-period geomagnetic pulsations: 1. Pc5 Pulsations and concurrent auroras in the dawn sector, *J. Geomagn. Geoelec.*, *40*, 553–569.