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- Plasmaspheric virtual resonances for Pi2 pulsations
- Radial mode structure of Pi2 pulsation

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Simultaneous Pi2 observations by the Van Allen Probes inside and outside the plasmasphere

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Abstract Plasmaspheric virtual resonance (PVR) model has been proposed as one of source mechanisms for low-latitude Pi2 pulsations. Since PVR-associated Pi2 pulsations are not localized inside the plasmasphere, simultaneous multipoint observations inside and outside the plasmasphere require to test the PVR model. Until now, however, there are few studies using simultaneous multisatellite observations inside and outside the plasmasphere for understanding the radial structure of Pi2 pulsation. In this study, we focus on the Pi2 event observed at low-latitude Bohyun (BOH, $L = 1.35$) ground station in South Korea in the postmidnight sector (magnetic local time (MLT) $= 3.0$) for the interval from 1730 to 1900 UT on 12 March 2013. By using electron density derived from the frequency of the upper hybrid waves detected at Van Allen Probe-A (VAP-A) and Van Allen Probe-B (VAP-B), the plasmapause is identified. At the time of the Pi2 event, VAP-A was outside the plasmasphere near midnight (00:55 MLT and $L = \sim 6$), while VAP-B was inside the plasmasphere in the postmidnight sector (02:15 MLT and $L = \sim 5$). VAP-B observed oscillations in the compressional magnetic field component (B_z) and the dawn-to-dusk electric field component (E_y), having high coherence with the BOH Pi2 pulsation in the H component. The H-B_z and H-E_y cross phases at VAP-B inside the plasmasphere were near $-180°$ and $-90°$, respectively. These phase relationships among B_z, E_y, and H are consistent with a radially standing oscillation of the fundamental mode reported in previous studies. At VAP-A outside the plasmasphere, B_z oscillations were highly correlated with BOH Pi2 pulsations with $\sim -180°$ phase delay, and the H-E_y cross phase is near $-90°$. From these two-satellite observations, we suggest that the fundamental PVR mode is directly detected by VAP-A and VAP-B.

1. Introduction

Pi2 magnetic pulsations are transient and damped geomagnetic oscillations in the period range of 40 to 150 s [*Saito*, 1969]. Their excitation is usually associated with the impulsive change in the near-Earth magnetotail at the onset of magnetospheric substorms. However, it is not fully understood how such an impulsive energy source at the onset of a substorm produces a well-defined period and waveform of Pi2 pulsations [*Olson*, 1999; *Keiling and Takahashi*, 2011, and references therein].

It has been suggested that midlatitude/low-latitude Pi2 pulsations are generated by plasmaspheric cavity-mode resonance because they have a common period over a wide range of longitude without significant time delay [e.g., *Sutcliffe and Yumoto*, 1989; *Yeoman and Orr*, 1989]. The idea of cavity-mode resonance was first suggested by *Saito and Matushita* [1968] and has been directly confirmed from satellite observations. When Pi2 pulsations are observed in the inner ($L < 5$) magnetosphere, they exhibit properties of a radially standing compressional wave trapped inside the plasmasphere. The relationship between the electric and magnetic field perturbations clearly show the cavity-mode–type oscillation [e.g., *Takahashi et al.*, 2001, 2003; *Kim et al.*, 2010; *Kwon et al.*, 2012]. The spatial phase structure of compressional Pi2 oscillations is consistent with a radial standing wave of a cavity mode [*Takahashi et al.*, 1995]. If the radially standing compressional Pi2 waves are produced inside the plasmasphere, their frequency should depend on the plasmapause distance from Earth. *Takahashi et al.* [2003] and *Nosé* [2010] showed that Pi2 frequency decreases as the plasmapause increases. *Kwon et al.* [2013] reported that Pi2 frequencies under extremely quiet geomagnetic conditions are much lower than the typical Pi2 frequency range, and the very low Pi2 frequencies are attributed to large plasmasphere with the plasmapause located $L>6$.

The density gradient at the plasmapause plays a crucial role in determining the properties of compressional waves in the plasmasphere. *Allan et al.* [1986] discussed first the plasmaspheric effect on magnetohydrodynamic waves in the magnetosphere. In order to excite a cavity mode in the plasmasphere, the plasmapause should be a good reflector. In some numerical studies [e.g., *Fujita and Glassmeier*, 1995; *Lee*, 1996] the plasmaspheric cavity mode has been obtained by assuming that the plasmapause is a perfect boundary. Thus, the cavity-mode oscillation do not exist outside the plasmasphere. There are spacecraft observations to support apparent localization of compressional Pi2 pulsations in the plasmasphere. *Takahashi et al.* [2001] reported that fast-mode waves exhibiting high coherence with low-latitude Pi2 are trapped inside the plasmasphere. The simultaneous multispacecraft observations both inside and outside the plasmasphere using Cluster [*Collieret al.*, 2006] or Time History of Events and Macroscale Interactions during Substorms [*Luo et al.*, 2011] have provided that Pi2 pulsations are confined inside the plasmasphere.

Unlike some idealized models used in simulation, the real magnetosphere does not have perfectly reflecting boundaries. That is, a perfect boundary at the plasmapause is not a good assumption in investigating the mode structure of plasmaspheric resonances because the energy of the plasmaspheric cavity mode can escape into the magnetotail in the real magnetosphere. In order to understand how plasmaspheric resonances occur under various boundary conditions, *Lee and Kim* [1999] investigated fast-mode waves propagating into the plasmasphere and introduced the key concept of the plasmaspheric virtual resonance (PVR) mode. The authors showed that compressional pulsations inside the plasmasphere can be established as PVR by virtual trapped resonance for relatively large Alfvén speed crest or by virtual scattering resonance for relatively small Alfvén speed crest near the plasmapause [see *Lee and Kim*, 1999, Figure 1], which is considered as a soft boundary. The concept of virtual scattering resonance is different from that of “leaky” cavity mode because the scattering resonance has not required closed boundaries like cavity.

An important property of PVR mode is that the wave energy is not strictly confined in the plasmasphere because it allows the wave energy to tunnel through the plasmapause. In numerical simulations using a realistic plasmasphere [*Fujita and Glassmeier*, 1995; *Lee and Lysak*, 1999; *Fujita et al.*, 2002; *Lee and Takahashi*, 2006], it is confirmed that compressional Pi2 oscillations are strongly associated with the PVR mode in the plasmasphere and that they appear beyond the plasmapause. *Lee and Takahashi* [2006] also showed that the PVR mode is consistently excited regardless of the ambient Alfeén speed profiles and that the PVR mode can be excited even when the Alfeén speed monotonically drops in the radial direction [see *Lee and Takahashi*, 2006, Figure 5].

Observational evidence for the PVR mode has been reported from single-spacecraft observations [*Kim et al.*, 2005; *Teramoto et al.*, 2008]. Using the magnetic field data acquired by the Polar satellite, *Kim et al.* [2005] observed simultaneous occurrence of Pi2 pulsations in the compression component (B_z) outside the plasmasphere and in the H component at low-latitude Kakioka (KAK) ground station. The radial variations of the B_z-H cross phase, and the B_z to H amplitude ratio are consistent with the radial structure of the PVR mode outside the plasmasphere. *Teramoto et al.* [2008] analyzed Pi2 pulsations observed by the polar-orbiting DE 1 satellite and observed many compressional Pi2 pulsations at DE 1 located at high latitudes ($L > 8$) having high coherence with KAK H. The phase relation between B_z and H is out of phase. Assuming that a typical L of the plasmapause is ∼4–5, the authors concluded that the high-latitude compressional Pi2 pulsations are associated with the PVR mode.

There are two Pi2 studies [*Collier et al.*, 2006; *Luo et al.*, 2011], using simultaneous multipoint observations inside and outside the plasmasphere to examine the radial structure of Pi2 pulsations, to the authors' knowledge. As mentioned above, both studies reported that compressional Pi2 pulsations are confined in the plasmasphere because compressional oscillations observed outside the plasmapause are not highly correlated with low-latitude Pi2 pulsations.

Until now, there has been no simultaneous multisatellite Pi2 observations inside and out the plasmasphere to support the PVR mode. In this study we examine two low-latitude Pi2 pulsations that occurred for the interval from 1730 to 2000 UT on 12 March 2013. For the interval, Van Allen Probe-A was outside the plasmasphere near the midnight, while Van Allen Probe-B was inside the plasmasphere in the postmidnight sector. Using the magnetic and electric field data acquired from both Van Allen Probes, we discuss whether the magnetic and electric oscillations enhanced inside and outside the plasmasphere during low-latitude Pi2 intervals can be taken as the PVR mode.

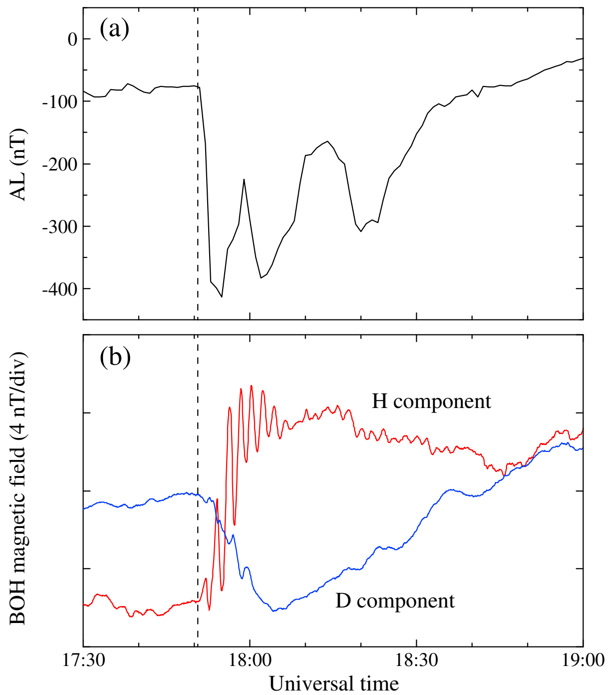

Figure 1. (a) The auroral electrojet *AL* index from 17:30 to 19:00 UT on 12 March 2013. (b) The horizontal *H* (red) and *D* (blue) components at the low-latitude Bohyun (BOH) station. The vertical dashed line indicates the onset of low-latitude Pi2 pulsation.

The organization of the paper is as follows. In section 2 we briefly describe the data sets. In section 3 we present observations and describe data analysis. In section 4 we discuss the properties of Pi2 pulsations. Section 5 gives the conclusions.

2. Data Set

In order to examine the Pi2-associated PVR mode in the inner magnetosphere, we used the magnetic and electric field data obtained from the Van Allen Probes mission consisting of two spacecraft (Van Allen Probe-A and Van Allen Probe-B) in low inclination with apogee near $L \sim 6$. Detailed descriptions of the magnetic and electric field instrumentations were given by *Kletzing et al.* [2013] and *Wygant et al.* [2013], respectively. As a reference signal to determine the relative magnetic and electric oscillations detected at the Van Allen Probes, low-latitude Pi2 pulsation observed at Bohyun (BOH, $L = \sim 1.3$) in Korea was used. The local time of BOH is approximately UT plus 9 h. To study Pi2 pulsation, we used 12 s averages of 4 s magnetic field data at the Van Allen Probes and of the original 1 s BOH magnetic field data. Approximately 11 s original electric field data at the Van Allen Probes were exactly resampled at 12 s intervals after interpolation. The magnetic field data acquired by VAP-A and VAP-B are expressed in a mean field-aligned coordinate system. The components in this system are denoted B_x (outward, perpendicular to the averaged magnetic field defined by taking the 5 min boxcar running averages of the 12 s data), B_y (eastward, perpendicular to the averaged magnetic field), and B_z (northward, along the averaged magnetic field). In this study we use only the high-pass-filtered compressional component (δB_z) defined by B_z (12 s averages) minus B_z (5 min averages). The electric field data were provided in the Modified Geocentric Solar Ecliptic coordinates. We use the dawn-to-dusk (E_y) component of the electric field. This component is nearly parallel to B_y near the midnight. The plasmapause is identified by using electron density derived from the frequency of the upper hybrid waves detected at Van Allen Probe-A (VAP-A) and Van Allen Probe-B (VAP-B) [*Kletzing et al.*, 2013]. To examine if low-latitude Pi2 pulsation is associated with a substorm activity, *AL* index was used. *AL* has a time resolution of 1 min.

3. Observations

Figures 1a and 1b show the auroral electrojet *AL* index and the horizontal components of the magnetic field *H* (northward) and *D* (eastward) at the low-latitude Bohyun (BOH) station, respectively, during the interval 17:30–19:00 UT on 12 March 2013. There is a signature of substorm onset at 17:51 UT, which is marked by a sudden decrease in *AL*, and it was accompanied by an ∼10 nT *H* increase and an ∼6 nT *D* decrease at BOH. The positive *H* and negative *D* perturbations imply that BOH was located east of the center of the substorm current wedge [*Clauer and McPherron*, 1974]. The *AL* decrease at 17:51 UT is accompanied by Pi2 oscillations at BOH. Thus, they are substorm-associated Pi2 events. The amplitude of the Pi2 oscillation in the *H* component is much larger than that in the *D* component. We will use only the *H* component data at BOH to compare low-latitude Pi2 pulsations and compressional Pi2 oscillations observed by the Van Allen Probes inside and outside the plasmasphere.

Figures 2a and 2b show the electron number density N_e derived from the frequency of the upper hybrid waves detected at VAP-A and VAP-B for the interval from 14:00 UT to 22:00 UT, respectively. The orbits of VAP-A

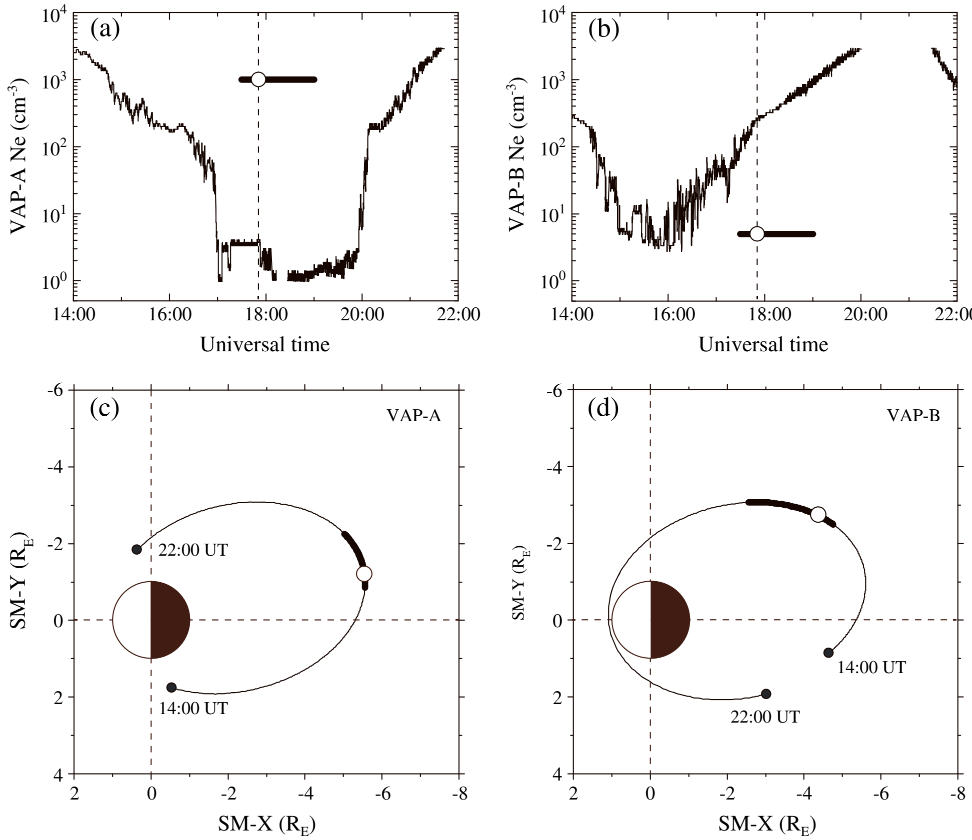

Figure 2. (a and b) Electron number density observed from VAP-A and VAP-B. (c and d) Locations of VAP-A and VAP-B orbits projected onto the solar magnetic $x-y$ plane. Thick bars in Figures 2a and 2b and thick curved lines in Figures 2c and 2d indicate the time interval of 17:30–19:00 UT shown in Figure 1. The open circles indicate the Pi2 onset time in Figures 2a and 2b and the spacecraft locations at the onset time in Figures 2c and 2d.

and VAP-B projected onto the solar magnetic $x-y$ plane for the 8 h interval are plotted in Figures 2c and 2d, respectively. The time interval from 17:30 to 19:00 UT shown in Figure 1 is indicated by a thick bar in Figures 2a and 2b and a thick curve in Figures 2c and 2d for each probe. The open circles in Figures 2a and 2b indicate the Pi2 onset at 17:51 UT, and those in Figures 2c and 2d indicate the spacecraft locations at the Pi2 onset time.

VAP-A was initially in the plasmasphere from 14:00 UT to ~16:54 UT, and then it encountered a sharp N_e decrease from ~52cm^{-3} to ~1 cm^{-3} at L = ~5.8 near midnight (00:18 MLT). This decrease in density is attributed to an outbound plasmapause crossing. VAP-A encountered a sudden N_e increase from ~3 cm^{-3} to ~180 cm^{-3}, which is due to an inbound plasmapause crossing, around 20:00 UT (L =~5 and 02:24 MLT). From these N_e data, we can confirm that VAP-A was definitely outside the plasmasphere when Pi2 pulsation was observed at the low-latitude BOH station. Around 16:00 UT VAP-B was apogee. After this time VAP-B was on the inbound leg. Between 16:00 UT and 17:40 UT VAP-B observed a gradual N_e increase from ~3 cm^{-3} to ~180 cm^{-3} with highly fluctuating N_e variations. Compared with that observed at VAP-A, the gradual N_e increase at VAP-B may have a spatial effect. That is, it is likely that VAP-B approached the Earth as skimming the plasmapause rather than crossing. At the Pi2 onset, VAP-B was near the inner edge of the plasmapause. Thus, the Pi2 event occurred when VAP-B was inside the plasmasphere.

Figure 3a displays the time series plot of δH at BOH for the Pi2 event. The magnetic field perturbations in the compressional component (δB_z) and the dawn-to-dusk electric field (E_y) component at VAP-B inside the plasmasphere and at VAP-A outside the plasmasphere are plotted in Figures 3b and 3c, respectively. δH and δB_z indicate perturbations about 300 s running averages. For visual inspection of the phase delay, the vertical dashed lines in Figures 3a–3c are drawn through the peaks of δB_z of VAP-B. The oscillations in δH are nearly identical to the oscillations in δB_z of VAP-B. The two traces show quite similar wave packet struc-

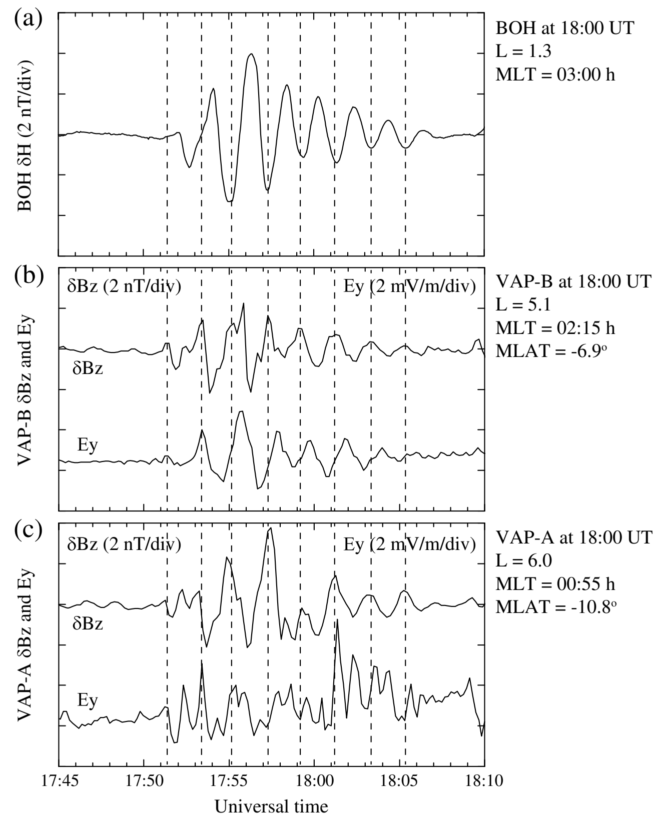

Figure 3. (a) The time series plot of δH at BOH for the Pi2 event. (b) The compressional magnetic field perturbation (δB_z) and the dawn-to-dusk electric field (E_y) at VAP-B inside the plasmasphere. (c) The format is the same as that in Figure 3b, but the field components are observed at VAP-A outside the plasmasphere.

tures, suggesting that the pulsations observed in space and on the ground are excited by a common source mechanism.

It is found that δB_z of VAP-B oscillates nearly out of phase with δH for the perturbations after 17:54 UT. Those δB_z perturbations oscillate almost in quadrature with E_y. Such a ground-space out of phase structure between δH and δB_z and the $\pm 90°$ phase delay between δB_z and E_y in space have been interpreted as a radially trapped fast mode for the compressional oscillation observed by a spacecraft outward of its nodal point of the fundamental mode [e.g., *Takahashi et al.*, 2001, 2003]. The first two perturbations in δB_z around 17:51 UT and 17:53 UT precede the first two peaks in δH at BOH and oscillate in phase with E_y, indicating that the perturbations propagate earthward. This observation is very similar to CRRES observation by *Takahashi et al.* [1999]. They reported that there is a net earthward energy flow during the first cycle of the Pi2 pulsation.

VAP-A was outside the plasmasphere and observed compressional (δB_z) oscillations when the Pi2 pulsation was observed at low-latitude BOH station. The amplitude of δB_z at VAP-A is slightly larger than that at VAP-B. This can be explained by the radial structure of a fundamental virtual resonance mode. In a dipole MHD simulation [*Lee and Lysak*, 1999; *Takahashi et al.*, 2003], the fundamental PVR node of δB_z is located very close to the plasmapause, and there is a substantial amplitude tapering off with distance from the plasmapause [see *Takahashi et al.*, 2003, Figure 12c]. If VAP-B was located just beyond the nodal point of δB_z and inside the plasmapause, VAP-B in some region outside the plasmapause would observe δB_z oscillations with amplitude larger than that at VAP-A. Like δB_z at VAP-B inside the plasmapause, there is a high degree of similarity between δB_z at VAP-A and δH at BOH with an out of phase signature. This implies that the compressional Pi2 pulsation is not confined within the plasmapause. There is no significant phase delay between δB_z at VAP-A and δB_z at VAP-B for the perturbations after 17:54 UT. This indicates that the compressional Pi2 oscillation outside the plasmapause is not in propagating mode. E_y at VAP-A exhibits oscillations starting at the onset of the Pi2 event. The waveform of E_y at VAP-A is not sinusoidal, and its oscillation is significantly different from that at VAP-B in terms of wave period and wave packet structure.

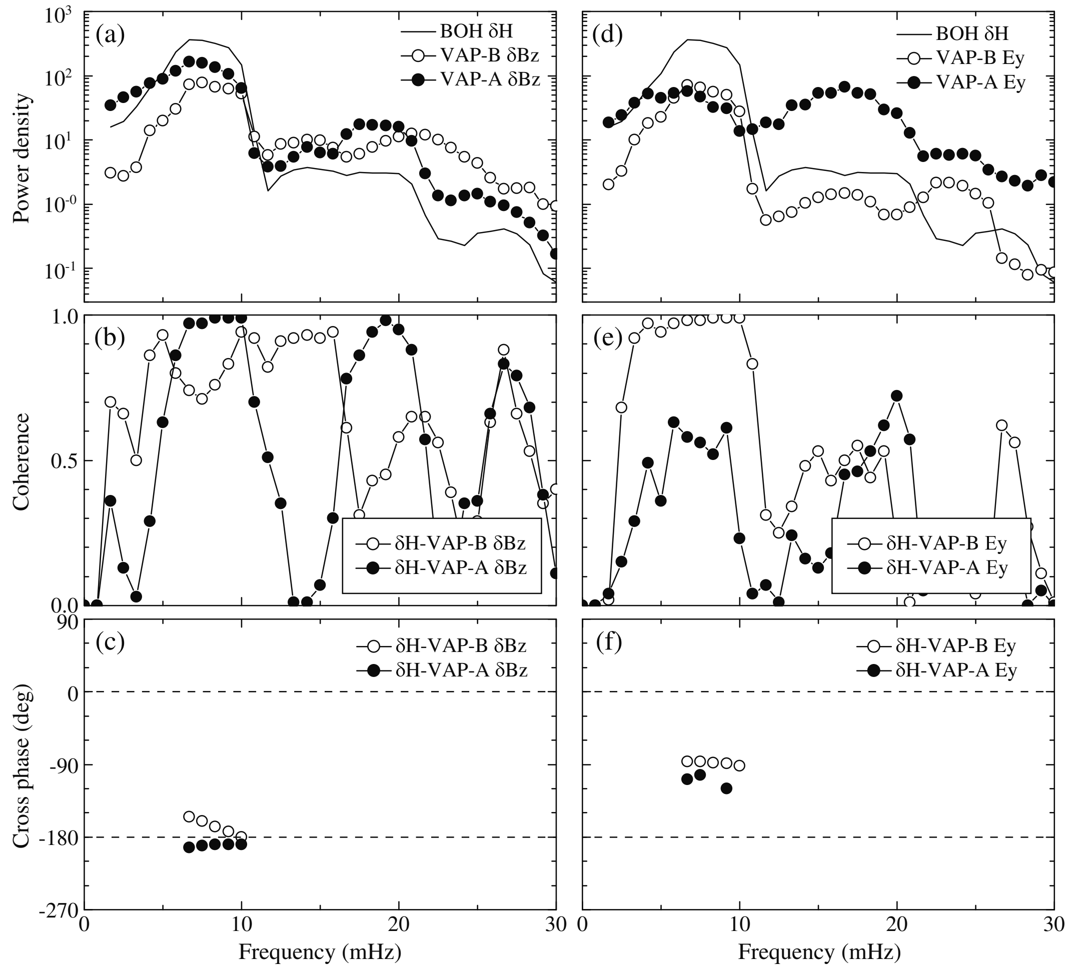

Figure 4. Spectral properties of VAP-A and VAP-B compressional (δB_z) components, the dawn-to-dusk electric field (E_y) component, and Bohyun *H* component for the Pi2 event. (a and d) Power spectra for the compressional component at VAP-A and VAP-B and *H* component at Bohyun. (b and e) Coherence. (c and f) Cross phase.

The spectral analysis for the time series shown in Figure 3 reveals the details on the frequency dependence of the coherence and cross phase between BOH δH and other components observed in space. Figures 4a–4c show the autopower spectra for δH at BOH and δB_z at VAP-A and VAP-B, and the coherence and cross phase between δH and δB_z for the time interval from 17:50 UT and 18:10 UT. The spectral parameters were computed with five-point smoothing in the frequency domain. The spectral powers of δH and both δB_z are strongly enhanced in the frequency band of ~6–10 mHz centered at ~8 mHz. δB_z inside and outside plasmasphere have high coherence (>0.6) with BOH δH in the enhanced frequency band. This indicates that the compressional Pi2 pulsations inside and outside the plasmasphere are directly related with low-latitude Pi2 pulsation. That is, the compressional Pi2 wave energy is not confined in the plasmasphere. An important property of the PVR mode is that the fast-mode wave energy is not strictly confined in the plasmasphere [*Lee and Takahashi*, 2006]. Thus, our observations can be taken as evidence of the PVR mode rather than the plasmaspheric cavity mode. As expected from the time series, the cross phases between δH and the compressional components in space are distributed near −180°.

The coherence between BOH δH and VAP-B E_y is nearly perfect in the enhanced frequency band of ~6–10 mHz, and both components exhibit near −90° phase delay, indicating a radially standing wave [e.g., *Takahashi et al.*, 2003]. Unlike VAP-B E_y inside the plasmasphere, VAP-A E_y outside the plasmasphere consists of two spectral enhancements centered at ~7 mHz and at ~17 mHz, respectively, and their powers are comparable. Due to these VAP-A E_y spectral properties, the E_y oscillations observed at VAP-A clearly differed from the low-latitude Pi2 oscillations enhanced in the frequency band of ~6–10 mHz. Since the amplitude of the higher-frequency oscillations in VAP-A E_y is enhanced after the onset of the low-latitude Pi2 pulsation, the common energy source may trigger the oscillations at ∼7 mHz and at ∼17 mHz. We suggest that the second peak of E_y at VAP-A may be associated with second harmonics of the PVR modes. Note that the shape of the first VAP-A E_y spectral peak is similar to that of BOH δH and VAP-B E_y enhanced in the frequency band 6–10 mHz. The coherence between BOH δH and VAP-A E_y is around 0.5–0.6, and their phase delay is near −100°.

4. Discussion

It has been suggested that the plasmaspheric cavity mode plays an important role in determining the spectral properties of the Pi2 pulsation in the inner magnetosphere ($L < 5$). The observational evidence for the plasmaspheric cavity mode (i.e., a radially standing fast-mode wave trapped inside the plasmasphere and/or the radial variation of the amplitude and phase of fast-mode waves) has been provided from the relationship between the electric and magnetic field perturbations and from ground-satellite statistical studies in the inner magnetosphere [e.g., *Takahashi et al.*, 1995, 2001, 2003; *Kim et al.*, 2010; *Kwon et al.*, 2012]. Using multipoint observations inside and outside the plasmasphere, *Collier et al.* [2006] and *Luo et al.* [2011] reported that fast-mode waves observed inside the plasmasphere show a high correlation with low-latitude Pi2 oscillation, while those measured outside the plasmasphere do not. From these observations, they suggested that the source of low-latitude Pi2 pulsations is confined in the plasmasphere.

In numerical studies incorporating a realistic density gradient at the plasmapause by *Lee and Lysak* [1999] and *Lee and Takahashi* [2006], the authors suggest that plasmaspheric resonances should be described as virtual resonances (i.e., PVR mode) rather than cavity resonances because the plasmapause is not a rigid boundary. Unlike plasmaspheric cavity modes requiring a perfectly reflecting plasmapause, PVR modes, which are excited in the plasmaspheric structure, are not strictly confined inside the plasmasphere. That is, finite power of the PVR-associated eigenmodes can exist outside the plasmasphere although the wave power is mostly confined inside the plasmasphere. The observational evidence for the PVR mode was reported by using data obtained from a single satellite [*Kim et al.*, 2005; *Teramoto et al.*, 2008]. *Kim et al.* [2005] observed 14 events having high coherence (>0.7) between the low-latitude Kakioka station and the Polar spacecraft outside the plasmapause. The radial amplitude and phase variations outside the plasmasphere for the high-coherence events are consistent with the radial structure of the fundamental PVR mode shown in *Takahashi et al.* [2003], which is obtained by using the simulation code of *Lee and Lysak* [1999]. *Teramoto et al.* [2008] statistically examined the coherence between low-latitude Pi2 pulsations and compressional oscillations observed by the polar-orbiting Dynamic Explorer 1 (DE 1) satellite. They reported that there are many high-coherence compressional Pi2 pulsations when DE 1 was located on the nightside at high latitude (|MLAT| > 60°) including the polar cap region. Since the radial amplitude and phase changes in the region of $L = \sim$5–7, which is outside of the estimated plasmapause, is similar to the trend expected from the fundamental PVR mode, they concluded that Pi2 pulsations might be excited by PVR mode.

Most recently, the evidence for the PVR mode was provided from simultaneous multipoint observations at the equatorial-orbiting Active Magnetospheric Particle Tracer Explorers (AMPTE)/CCE satellite and the polar-orbiting DE 1 satellite by *Teramoto et al.* [2011]. The evidence includes the radial variation of the amplitude and phase of Pi2 compressional (B_z) oscillations. That is, the B_z power was larger at AMPTE/CCE inside of the plasmapause estimated from an empirical formula than at DE 1 outside of the estimated plasmapause, and the cross phase between low-latitude Pi2 pulsation and B_z oscillation in space was ∼0° at AMPTE/CCE inside the plasmapause and ∼180° at DE 1 outside the plasmapause [see *Teramoto et al.*, 2011, Figure 16]. Although the two-satellite observations by *Teramoto et al.* [2011] provide additional evidence of PVR modes, there were no low-latitude observations of compressional Pi2 waves detected outside the estimated plasmasphere supporting PVR modes, and the real plasmapause encountered by a spacecraft (i.e., in situ observation of the plasmapause) did not provide in their study owing to lack of plasma density measurement.

In this study, we clearly identify the location of the plasmapause and examine the radial structure of δB_z and E_y oscillations in the frequency band of ∼6–10 mHz, which have high coherence with low-latitude Pi2 pulsation in the H component, observed by VAP-B inside the plasmasphere and by VAP-A outside the plasmasphere. Both spacecraft were located near the magnetic equator (|MLAT|<11°). Our two-satellite observations with low-latitude ground observation exhibited that the phase of δB_z relative to δH was near −180° for the events occurring inside and outside the plasmapause (see Figures 3 and 4). In contrast to δB_z, the cross phase between E_y and δH remained near −90° both inside and outside the plasmasphere. Our observations are consistent with the radial phase structure of the fundamental PVR mode shown in *Takahashi et al.* [2003], which is obtained using the simulation code of *Lee and Lysak* [1999] if VAP-B was located in a region between the plasmapause and the fundamental δB_z node. The simulation of the PVR mode shows that the fundamental δB_z node is located close to the inner edge of the plasmapause. As shown in Figure 2b, VAP-B observed the δB_z oscillation near the inner edge of the plasmapause. Thus, the estimated location of VAP-B relative to the δB_z nodal point is not unreasonable.

In Figure 4a, the δB_z power at VAP-A outside the plasmasphere is larger than that at VAP-B inside the plasmasphere. The fundamental PVR mode in the simulation [see *Takahashi et al.*, 2003 Figure 12] shows a peak of δB_z power outside of the δB_z node located near the inner edge of the plasmapause. It decreases rapidly toward the nodal point and gradually beyond the plasmapause. In some region outside the plasmapause, we can expect larger δB_z power than that in a region between the δB_z node and the inner edge of the plasmapause. In Figure 4d, the E_y power at VAP-B is slightly larger than that at VAP-A in the enhanced frequency band of BOH δH. This observation is also quantitatively consistent with the simulated PVR mode of E_y.

Since earthward bursty bulk flows (BBFs) have onset timing nearly identical to Pi2 onset, it has been suggested that BBFs can directly control the waveform and period of Pi2 pulsations. *Kepko and Kivelson* [1999] presented several examples of BBF-driven Pi2. If Pi2 pulsations observed at BOH are directly driven by time-modulated BBFs, the corresponding compressional oscillations in δB_z and E_y should have propagating signatures regardless of the spacecraft position relative to the plasmapause. However, δB_z and E_y at VAP-A and VAP-B did not show earthward propagating oscillations. Thus, it is unlikely that the Pi2 pulsations at BOH are directly driven by earthward BBFs.

5. Conclusions

We have studied the radial mode structure of E_y electric and δB_z magnetic field oscillations in the frequency band of ∼6–10 mHz observed by VAP-B inside the plasmasphere and VAP-A outside the plasmasphere near the midnight during a time period of Pi2 pulsations in the *H* component observed on the low-latitude BOH ground station. We confirm that the E_y and δB_z oscillations both inside and outside the plasmasphere have high coherence with low-latitude Pi2 pulsations, indicating that the Pi2 wave energy is not confined inside the plasmasphere but extends beyond the plasmapause. The phase relationships between δB_z and δH and between E_y and δH provide that the E_y and δB_z oscillations inside and outside the plasmasphere are radially standing. From these two-satellite observations, we suggest that the fundamental PVR mode is directly detected by VAP-A and VAP-B.

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