Research Paper
J. Astron. Space Sci. 32(4), 305-310 (2015)
http://dx.doi.org/10.5140/JASS.2015.32.4.305

JASS Journal of Astronomy and Space Sciences

Morningside Pi2 Pulsation Observed in Space and on the Ground

Essam Ghamry†
National Research Institute of Astronomy and Geophysics (NRIAG), Helwan, Cairo 11421, Egypt

In this study, we examined a morningside Pi2 pulsation, with a non-substorm signature, that occurred in very quiet geomagnetic conditions (*Kp* = 0) at 05:38 UT on December 8, 2012, using data obtained by Van Allen Probes A and B (VAP-A and VAP-B, respectively) and at a ground station. Using 1 sec resolution vector magnetic field data, we measured the X-component of the pulsation from the Abu Simbel ground station (*L* = 1.07, LT = UT +2 hr, where LT represents local time) in Egypt. At the time of the Pi2 event, Abu Simbel and VAP-A (*L* = 3.3) were in the morning sector (07:38 LT and 07:59 MLT, respectively, where MLT represents magnetic local time), and VAP-B was in the postmidnight sector (04:18 MLT and *L* = 5.7). VAP-A and VAP-B observed oscillations in the compressional magnetic field component (*Bz*), which were in close agreement with the *X*-component measurements of the Pi2 pulsation that were made at Abu Simbel. The oscillations observed by the satellites and on the ground were in phase. Thus, we concluded that the observed morningside Pi2 pulsation was caused by the cavity resonance mode rather than by ionospheric current systems.

Keywords: Van Allen Probes, Pi2 pulsation, cavity mode resonance

1. INTRODUCTION

The irregular pulsations with relatively low frequencies that occur in connection with magnetospheric substorms are called Pi2 pulsations and have periods ranging from 40 sec to 150 sec (Saito 1969). Pi2 pulsations have many important characteristics: (1) they can be observed at almost all local times in the nightside region and even in the dayside region (Sutcliffe & Yumoto 1989, 1991), (2) they are almost compressional wave events (Lee 1998), and (3) they are frequently observed in low-latitude regions in both ground- and satellite-based measurements (Lee 1998).

The excitation and propagation mechanisms of Pi2 pulsations are still important subjects in the area of magnetospheric ultra-low-frequency waves. Keiling & Takahashi (2011) introduced generation mechanisms for Pi2 pulsations separated by a source region; these mechanisms comprise the inner- and outer-magnetospheric models. The inner-magnetosphere model consists of three mechanisms: Plasmaspheric Cavity Resonance (PCR), Plasmaspheric Virtual Resonance (PVR), and the plasmapause surface mode phenomenon. PCR waves are defined as fast mode waves trapped between the plasmapause and the ionosphere. In this model, the plasmapause, as the outer boundary, acts as a perfect reflector with a sharp inward density gradient (Allan et al. 1986; Zhu & Kivelson 1989; Lee 1996; Ghamry et al. 2011, 2012; Jun et al. 2013; Ghamry & Fathy 2015; Hamada et al. 2015). Lee (1998) developed an analytic PVR model by modifying the model used to analyze quantum mechanical potentials. Some simulations and observational studies were subsequently reported about PVR (Lee & Kim 1999; Lee & Lysak 1999; Takahashi et al. 2003; Kim et al. 2005; Lee & Takahashi 2006; Ghamry et al. 2015).

In addition to Pi2 pulsations that are associated with substorms, Sutcliffe (1998, 2010) studied Pi2 pulsations that occurred in the absence of substorms. Lyons et al. (1999) showed that Poleward Boundary Intensifications (PBIs) occurred without substorm signatures and that each PBI accompanied Pi2 activity enhancement. Nose et al. (2003) investigated a morningside Pi2 pulsation that occurred

Received Oct 23, 2015 **Revised** Nov 25, 2015 **Accepted** Nov 27, 2015

†**Corresponding Author**
E-mail: essamgh@nriag.sci.eg, ORCID: 0000-0003-1556-2172
Tel: +20-2554-9780, Fax: +20-2554-8020

in the presence of a clear substorm. They concluded that plasmaspheric cavity mode resonance was the source of this pulsation.

In this paper, we discuss a morningside Pi2 pulsation that occurred in the absence of a substorm in very quiet geomagnetic conditions ($Kp = 0$). We focus on the event that occurred at 05:38 UT on December 8, 2012, which was observed by Van Allen Probes A and B (VAP-A and VAP-B, respectively) and the low-latitude ground station at Abu Simbel in Egypt. The organization of this paper is as follows. In section 2, the data sets are described. The observations are presented in section 3 and discussed in section 4. Section 5 gives the conclusions.

2. DATA SETS

We used the electric and magnetic field data from VAP-A and VAP-B. These twin spacecraft, which were launched on August 30, 2012, have near-equatorial orbits with apogees near $L \sim 6$ and contain comprehensive suites of particle and field sensors designed to study the Earth's radiation environment (Mauk et al. 2013). They have identical triaxial fluxgate magnetometers capable of measuring 64 vectors per second (Kletzing et al. 2013). Their ~9 hr orbits are also nearly identical, and the slight differences between their orbits allow them to overlap with one another and vary the distance between the two spacecraft.

The Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS) instrument (Kletzing et al. 2013) is used to obtain magnetic field data. The EMFISIS magnetic field data are rotated from the Geocentric Solar Magnetospheric (GSM) coordinate system into a mean field-aligned coordinate system. This decomposition allows the dominant magnetic field wave polarization to be identified as toroidal (azimuthal), poloidal (radial), or compressional (parallel). In this system, ez is in the direction of the mean magnetic field, ey (eastward) is parallel to $ez \times r$, where r is the position vector of the satellite relative to the center of the Earth; and ex (radial) is given by $ex = ey \times ez$. The parallel magnetic field component δBz is defined as Bz (1 sec) minus Bz (5 min average) and is the high–pass filtered compressional component.

Magnetic field measurements from the Abu Simbel magnetic observatory are used to detect low-latitude Pi2 pulsations. The time resolution of the magnetic fields measured both at Abu Simbel and by VAP-A and VAP-B is 1 sec. The provisional auroral electrojet indices AE and AL are measured with 1 min resolution and are used to determine whether low-latitude Pi2 pulsations are associated with substorm activity.

3. OBSERVATIONS

In order to examine the geomagnetic activity and the low-latitude magnetic field variations at the onset of the Pi2 pulsation, we plotted AE and AL and the ground magnetometer data from Abu Simbel, as shown in Figs. 1(a) and 1(b), respectively, from 05:00 UT until 07:00 UT on December 8, 2012. Fig. 1(d) shows the X-component of the dynamic spectrum measured at Abu Simbel. The dynamic spectrum was obtained by first differencing the 5 sec time series. The Fourier transform was calculated using a time window of 10 min and shifting it by 25% in successive steps. The spectrum was smoothed in the frequency domain by using five-point averages of the raw spectral estimates.

Although AL becomes negative near 05:38 UT, its magnitude remains very small (<35 nT), significantly less than that during a typical substorm. During this time, the X-component of the Pi2 pulsation measured at Abu Simbel also becomes slightly negative. Therefore, a substorm current wedge did not form during the Pi2 event (Clauer & McPherron 1974). Based on these observations, we suggest that the Pi2 pulsation presented in Fig. 1 occurred in the absence of substorms.

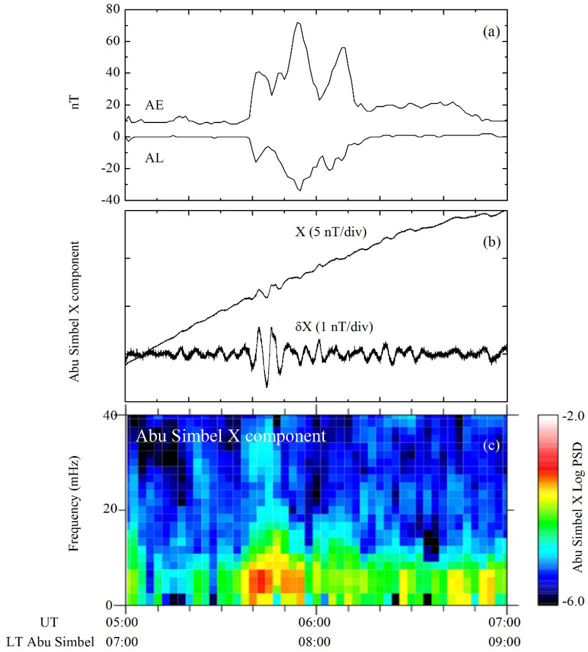

Fig. 1. (a) Auroral electrojet indices AE and AL and (b) *X*-component measured at Abu Simbel from 05:30 UT until 06:00 UT on December 8, 2012. (c) Frequency–time display of Power Spectral Density (PSD) of *X*-component measured at Abu Simbel. LT indicates local time.

Fig. 2 shows the locations of the VAPs and the Abu Simbel ground station in the *L*–MLT plan at the onset of the abrupt decreasing/increasing of AL/AE, that is, at 05:38 UT on December 8, 2012. At this time, both VAP-A and VAP-B were in the plasmasphere (L = 3.3 and 5.7, respectively) and south of the magnetic equator (MLAT = -8.96° and -3.22°, respectively). Both Abu Simbel and VAP-A were on the morning side (07:59 MLT and 07:38 MLT, respectively), while VAP-B was on the postmidnight side (04:18 MLT). Abu Simbel and VAP-A had a very small local time separation (less than 20 min) during the Pi2 event.

Fig. 3(a) displays the high-pass *X*-component at Abu Simbel during the interval from 05:30 UT to 06:00 UT. The δBz data obtained by VAP-B and VAP-A are plotted in Figs. 3(b) and 3(c), respectively. To facilitate visual inspection of the phase delay, vertical dashed lines are drawn in Figs. 3(a)–3(c) through the peak of the Abu Simbel *X*-component. We found that the poloidal magnetic field and δBz variations observed by both VAP-A and VAP-B were nearly identical to the *X*-component oscillations measured at Abu Simbel, indicating that the pulsations observed in space and on the ground were excited by a common source. The δBz oscillations measured by VAP-A and VAP-B are nearly in phase with those measured on the ground, suggesting that the poloidal wave was radially standing (Kim & Takahashi 1999; Takahashi et al. 2001, 2003). The amplitude of the δBz oscillations measured by VAP-B is larger than that measured by VAP-A, though the oscillations have the same wave packet structures. The amplitude difference could have resulted from the fact that VAP-B was closer to the node of the fundamental δBz perturbation mode.

Figs. 4(a)-4(c) show the power densities of δX at Abu Simbel, δBz at VAP-A, and δBz at VAP-B, respectively, for the time interval from 05:30 UT to 06:00 UT. The spectral parameters were computed using five-point smoothing in the frequency domain. All three power spectra are strongly enhanced in the 6–15 mHz frequency band, with the peak enhancements occurring at ~12 mHz.

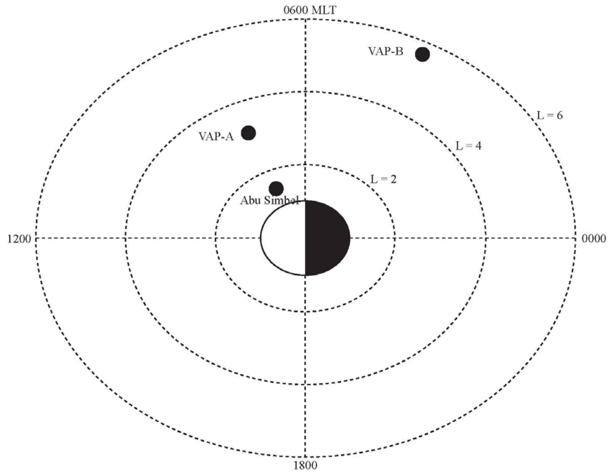

Fig. 2. *L*–MLT plot of locations of VAP-A, VAP-B, and Abu Simbel low-latitude ground station at Pi2 onset time.

4. DISCUSSION AND CONCLUSION

All previous studies have concluded that dayside Pi2 pulsations are common phenomena at low latitudes. Dayside Pi2s were first studied by Yanagihara & Shimizu (1966). Sutcliffe & Yumoto (1989) reported that 83% of nightside Pi2s can be concurrently identified on the dayside at low latitudes but that the occurrence dramatically decreases at midlatitudes on the dayside. Sastry et al. (1983) and Shinohara et al. (1997) reported equatorial enhancement of dayside Pi2s.

Sutcliffe & Yumoto (1991) confirmed that the spectra of dayside and nightside Pi2s are almost identical. They concluded that dayside Pi2s originate from plasmaspheric cavity modes. Shinohara et al. (1997) found that the

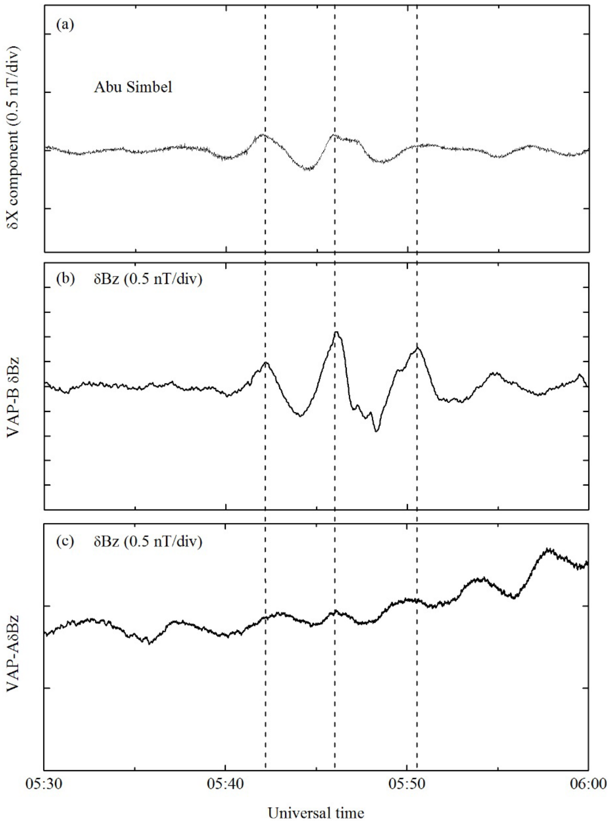

Fig. 3. Comparison of (a) *X*-component measured at Abu Simbel station, (b) δBz measured by VAP-B, and (c) δBz measured by VAP-A from 05:30 UT to 06:00 UT on December 8, 2012.

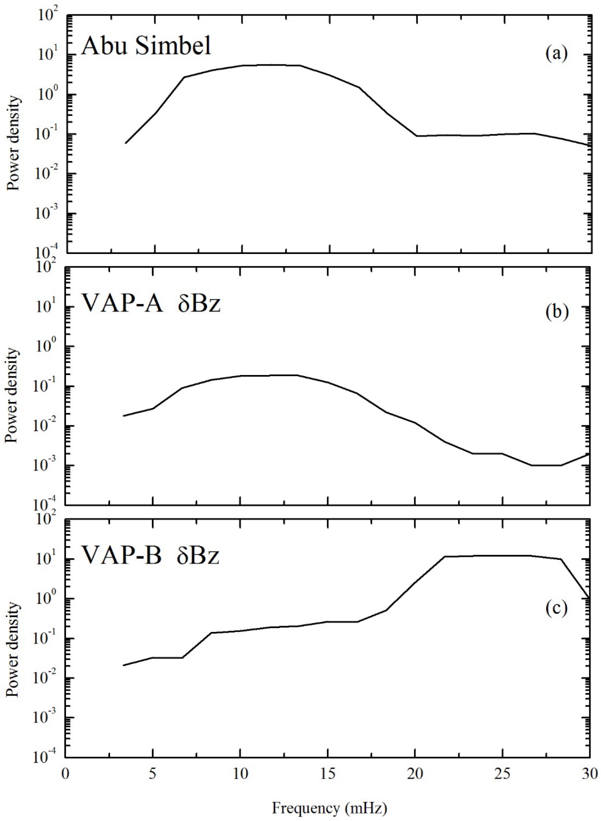

Fig. 4. Power spectra for (a) *X*-component measured at Abu Simbel, (b) δBz measured by VAP-A, and (c) δBz measured by VAP-B.

amplitudes of Pi2s are enhanced during the daytime at the dip equator. They suggested that dayside and nightside Pi2s in equatorial and low-latitude regions could be explained by instantaneous penetration of electric field variations from the nightside polar ionosphere to the dayside equatorial ionosphere and direct incidence of compressional oscillations from the nightside inner magnetosphere, respectively.

Two scenarios have been proposed as possible sources of low-latitude dayside Pi2 pulsations (Ohnishi & Araki 1992). The first is the global cavity mode, in which the magnetospheric signal propagates as a fast-mode wave, so the oscillations observed on the ground and by low-altitude satellites will be in phase. The second is propagation of electric field oscillations through the ionosphere-ground waveguide. In this case, the electric field drives currents in the ionosphere, and the magnetic field perturbations produced by the currents will oscillate out of phase when observed below and above the ionosphere (Takahashi et al. 1999).

Pc4 pulsations, whose periods (45–150 sec) have nearly the same range as that of Pi2 periods (40–150 sec), generally exit in the dayside magnetosphere. Thus, Pc4 pulsations mask Pi2 activities and cause difficulty in identifying dayside Pi2 pulsations. Yumoto (1986) and Odera (1986) documented that dayside Pc4 pulsations depend on the solar wind speed and the cone angle of the Interplanetary Magnetic Field (IMF), where the cone angle is equal to cos^{-1} ($abs(Bx)/B$), where B is the magnetic field magnitude (Takahashi et al. 2005). Fig. 5 presents the solar wind data for the period 04:00–07:00 UT on December 8, 2012. From top to bottom, the solar wind speed; *X*, *Y*, and *Z* components of the IMF; total IMF; and IMF cone angle are shown. Between 05:30 UT and 06:00 UT (the period of the investigated Pi2 event), the solar wind speed is around 275 km/s, which is slower than the average solar wind speed of 400–450 km/s. The IMF cone angle is around 130°. These conditions (i.e., slow solar wind and large IMF cone angle) are unlikely to excite Pc4 pulsations (Takahashi et al. 2005). Therefore, it can be concluded that the pulsation detected in space and on the ground on the morning side on December 8, 2012 was a Pi2 pulsation.

Nose et al. (2003) reported for the first time that plasmaspheric cavity mode resonance resulting from Pi2 pulsations caused by substorms can exit on the morning side. In this paper, we report for the first time the existence of plasmaspheric cavity mode resonance on the morning side resulting from a non-substorm Pi2 pulsation. We investigated the Pi2 pulsation that occurred at 05:38 UT on December 8, 2012 using data obtained by VAP-A and VAP-B and at the Abu Simbel

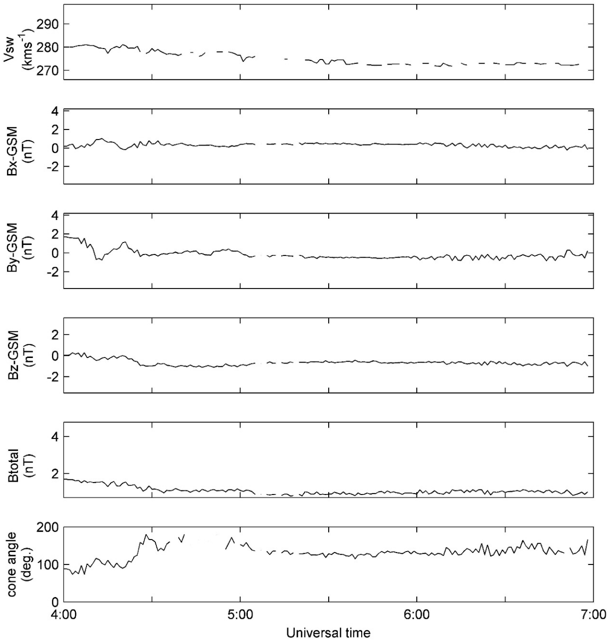

Fig. 5. Solar wind data measured from 04:00 UT until 07:00 UT on December 8, 2012. From top to bottom: solar wind speed; *X*, *Y*, and *Z* components of IMF; total IMF; and IMF cone angle.

ground station. At the time of the Pi2 event, VAP-A was in the plasmasphere, while VAP-B was outside of it. VAP-A and VAP-B observed *Bz* oscillations that were highly coherent with the X-component measurements obtained at Abu Simbel. The oscillations observed by the satellites were in phase with those measured on the ground. Therefore, we concluded that the Pi2 pulsation observed on the morning side was caused by cavity resonance mode rather than ionospheric current systems.

ACKNOWLEDGMENTS

This work was supported financially by the Science and Technology Development Fund (STDF), Egypt, Grant No. 4969. The geomagnetic indices (AE and AL) were provided by World Data Center C2 (WDC-C2) for Geomagnetism, Kyoto University (http://wdc.kugi.kyoto-u.ac.jp/index.html). The solar wind data were provided by OMNI. The Abu Simbel magnetic field data were provided by the Geomagnetism Laboratory in the National Research Institute of Astronomy and Geophysics (NRIAG), Helwan, Cairo, Egypt (http://www.nriag.sci.eg/?page_id=403).

REFERENCES

Allan W, White SP, Poulter EM, Impulse-excited hydromagnetic cavity and field-line resonances in the magnetosphere, Planet. Space Sci. 34, 371–385 (1986). http://dx.doi.org/10.1016/0032-0633(86)90144-3

Clauer CR & McPherron RL, Mapping the local time-universal time development of magnetospheric substorms using mid-latitude magnetic observations, J. Geophys. Res. 79, 2811–2820 (1974). http://dx.doi.org/10.1029/JA079i019p02811

Ghamry E, Fathy A, A new method to calculate the time delay of the Pi2 pulsations. Adv. Space Res., In Press (2015). http://dx.doi.org/10.1016/j.asr.2015.10.045

Ghamry E, Mahrous A, Yasin N, Fathy A, Yumoto K, First Investigation of Geomagnetic Micropulsation, Pi 2, in Egypt, Sun Geosph. 6, 84–87 (2011).

Ghamry E, Mahrous A, Fathy A, Salama N, Yumoto K, Signatures of the low-latitude Pi 2 pulsations in Egypt, Natl. Res. Inst. Astron. Geophys. J. Astron. Geophys. 1, 45–50 (2012). http://dx.doi.org/10.1016/j.nrjag.2012.11.005

Ghamry E, Kim KH, Kwon HJ, Lee DH, Park JS, et al., Simultaneous Pi2 observations by the Van Allen Probes inside and outside the plasmasphere, J. Geophys. Res. 120, 4567–4575 (2015). http://dx.doi.org/10.1002/2015JA021095

Hamada AM, Mahrous AM, Fathy I, Ghamry E, Groves K, et al., Tec Variations During Geomagnetic Storm/Substorm with PC5/PI2 Pulsation Signature, Adv. Space Res. 55, 2534–2542 (2015). http://dx.doi.org/10.1016/j.asr.2015.02.010

Jun CW, Kim KH, Kwon HJ, Lee DH, Lee E, et al., Statistical Analysis of Low-latitude Pi2 Pulsations Observed at Bohyun Station in Korea, J. Astron. Space Sci. 30, 25–32 (2013), http://dx.doi.org/10.5140/JASS.2013.30.1.025

Keiling A, Takahashi K, Review of Pi2 models, Space Sci. Rev. 161, 63–148 (2011), http://dx.doi.org/10.1007/s11214-011-9818-4

Kim KH, Takahashi K, Statistical analysis of compressional Pc3-4 pulsations observed by AMPTE CCE at L = 2-3 in the dayside magnetosphere, J. Geophys. Res. 104, 4539–4558 (1999). http://dx.doi.org/10.1029/1998JA900131

Kim KH, Takahashi K, Lee DH, Sutcliffe PR, Yumoto K, Pi2 pulsations associated with poleward boundary intensifications during the absence of substorms, J. Geophys. Res. 110, A01217 (2005). http://dx.doi.org/10.1029/2004JA010780

Kletzing CA, Kurth WS, Acuna M, MacDowall RJ, Torbert RB, et al., The Electric and Magnetic Field Instrument Suite an(-d Integrated Science (EMFISIS) on RBSP, Space Sci. Rev. 179, 127–181 (2013)., http://dx.doi.org/10.1007/s11214-013-9993-6

Lee DH, Dynamics of MHD wave propagation in the low-latitude magnetosphere, J. Geophys. Res. 101, 15371–15386 (1996). http://dx.doi.org/10.1029/96JA00608

Lee DH, On the generation mechanism of Pi 2 pulsations in the magnetosphere, Geophys. Res. Lett. 25, 583–586 (1998). http://dx.doi.org/10.1029/98GL50239

Lee DH, Kim K, Compressional MHD waves in the magnetosphere: A new approach, J. Geophys. Res. 104, 12379–12385 (1999). http://dx.doi.org/10.1029/1999JA900053

Lee DH, Lysak RL, MHD waves in a three-dimensional dipolar magnetic field: A search for Pi2 pulsations, J. Geophys. Res. 104, 28691–28699 (1999). http://dx.doi.org/10.1029/1999JA900377

Lee DH, Takahashi K, MHD Eigenmodes in the Inner Magnetosphere, Magnetospheric ULF Waves: Synthesis and New Directions, eds. Takahashi K, Chi PJ, Denton RE, Lysak RL (American Geophysical Union, Washington, D. C., 2006), 73–89.

Lyons LR, Nagai T, Blanchard GT, Samson JC, Yamamoto T, et al., Association between Geotail plasma flows and auroral poleward boundary intensifications observed by CANOPUS photometers, J. Geophys. Res. 104, 4485–4500 (1999). http://dx.doi.org/10.1029/1998JA900140

Mauk BH, Fox NJ, Kanekal SG, Kessel RL, Sibeck DG, et al., Science objectives and rationale for the radiation belt storm probes mission, Space Sci. Rev. 179, 3–27 (2013). http://dx.doi.org/10.1007/s11214-012-9908-y

Nose M, Takahashi K, Uozumi T, Yumoto K, Miyoshi Y, et al., Multipoint observations of a Pi2 pulsation on morningside: The 20 September 1995 event, J. Geophys. Res. 108, 1219 (2003). http://dx.doi.org/10.1029/2002JA009747

Odera TJ, Solar wind controlled pulsations: A review, Rev. Geophys. 24, 55–74 (1986). http://dx.doi.org/10.1029/RG024i001p00055

Ohnishi H, Araki T, Two-dimensional interaction between a plane hydromagnetic wave and the Earth-ionosphere system with curvature, Ann. Geophys. 10, 281–287 (1992).

Saito T, Geomagnetic pulsations, Space Sci. Rev. 10, 319–412 (1969). http://dx.doi.org/10.1007/BF00203620

Sastry TS, Sarma YS, Sarma SVS, Sanker Narayan PV, Day-time Pi pulsations at equatorial latitudes, J. Atmos. Terr. Phys. 45, 733–741 (1983).

Shinohara M, Yumoto K, Yoshikawa A, Saka O, Solovyev SI, et al., Wave characteristics of daytime and nighttime Pi2 pulsations at the equatorial and low latitudes, Geophys. Res. Lett. 18, 2279–2282 (1997). http://dx.doi.org/10.1029/97GL02146

Sutcliffe PR, Observations of Pi2 pulsations in a near ground state magnetosphere, Geophys. Res. Lett. 25, 4067–4070 (1998). http://dx.doi.org/10.1029/1998GL900092

Sutcliffe PR, Pi2 band activity at low latitudes during non–substorm intervals, J. Geophys. Lett. 37, L05101 (2010). http://dx.doi.org/10.1029/2009GL041661

Sutcliffe PR, Yumoto K, Dayside Pi 2 pulsations at low latitudes, Geophys. Res. Lett. 16, 887–890 (1989). http://dx.doi.org/10.1029/GL016i008p00887

Sutcliffe PR, Yumoto K, On the cavity mode nature of low-latitude Pi 2 pulsations, J. Geophys. Res. 96 1543–1551 (1991). http://dx.doi.org/10.1029/90JA02007

Takahashi K, Anderson BJ, Yumoto K, Upper atmosphere research satellite observation of a Pi2 pulsation, J. Geophys. Res. 104, 25035–25045 (1999). http://dx.doi.org/10.1029/1999JA900317

Takahashi K, Ohtani S, Hughes WJ, Anderson RR, CRRES observation of Pi2 pulsations: Wave mode inside and outside the plasmasphere, J. Geophys. Res. 106, 15567–15581 (2001). http://dx.doi.org/10.1029/2001JA000017

Takahashi K, Lee DH, Nosé M, Anderson RR, Hughes WJ, CRRES electric field study of the radial mode structure of Pi2 pulsations, J. Geophys. Res. 108, 1210 (2003). http://dx.doi.org/10.1029/2002JA009761

Takahashi K, Liou K, Yumoto K, Kitamura K, Nose M, et al., Source of Pc4 pulsations observed on the nightside, J. Geophys. Res. 110, A12207 (2005). http://dx.doi.org/10.1029/2005JA011093

Yanagihara K, Shimizu N, Equatorial enhancement of micropulsation pi-2, Mem. Kakioka Mag. Obs. 12, 57–63 (1966).

Yumoto K, Generation and propagation mechanisms of low-latitude magnetic pulsations – A review, J. Geophys. 60, 79–105 (1986).

Zhu X, Kivelson MG, Global mode ULF pulsations in a magnetosphere with a nonmonotonic Alfvén velocity profile, J. Geophys. Res. 94, 1479–1485 (1989). http://dx.doi.org/10.1029/JA094iA02p01479