Multipoint observations of a Pi2 pulsation on morningside: The 20 September 1995 event

M. Nosé,[1] K. Takahashi,[2] T. Uozumi,[3] K. Yumoto,[3] Y. Miyoshi,[4] A. Morioka,[4] D. K. Milling,[5] P. R. Sutcliffe,[6] H. Matsumoto,[7] T. Goka,[7] and H. Nakata[8]

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[1] We investigated a Pi2 pulsation that occurred at 0538 UT on 20 September 1995, using data from ground stations and the ETS-VI and EXOS-D satellites. Since ground stations at $L = 1.45 - 12.6$ and the two satellites were located at 7–10 hours of magnetic local time (MLT), we could investigate characteristics of the morning side Pi2 pulsation in detail. We also examined geomagnetic field data from equatorial and low-latitude ($L \leq 1.5$) stations at 0200 MLT and 1500 MLT. Our findings include the following: (1) Pi2 pulsations on the morning side were observed over a wide range of L ($L < 6.1$) with almost identical period ($T \sim 70$ s) and waveforms; (2) the ETS-VI satellite located above the geomagnetic equator at $L = 6.3$ observed a Pi2 pulsation that had nearly the same period and waveforms as the ground Pi2 pulsation; (3) the Pi2 pulsation observed by ETS-VI appeared in the compressional and radial components; (4) phase lag between the compressional and radial components was $\sim 180°$ (5) the ground-to-satellite phase lag was $\sim 180°$ ($\sim 0°$) for the X component and the compressional (radial) component; (6) the EXOS-D observation placed the plasmapause location at $L = 6.8$, across which ground Pi2 pulsations changed their characteristics; and (7) no phase delay was found between low-latitude Pi2 pulsations observed around 0700 MLT, 0200 MLT, and 1500 MLT. From these results we concluded that the morning side Pi2 pulsation was caused by the plasmaspheric cavity mode resonance and that its longitudinal structure was rather uniform.
INDEX TERMS: 2752 Magnetospheric Physics: MHD waves and instabilities; 2730 Magnetospheric Physics: Magnetosphere—inner; 2768 Magnetospheric Physics: Plasmasphere; 2788 Magnetospheric Physics: Storms and substorms; *KEYWORDS:* Pi2 pulsation, cavity mode resonance, substorm, plasmasphere

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1. Introduction

[2] Recent studies have shown that when Pi2 pulsations were observed on the ground during nighttime, satellites that were inside the plasmasphere observed almost identical oscillations in the compressional and radial components of the magnetic field [*Takahashi et al.*, 1999, 2001]. Magnetic field oscillations in the Pi2 frequency band can be also seen even when satellites were outside the plasmasphere, but such oscillations were less correlated with the ground Pi2 pulsations. This indicates that the plasmaspheric cavity mode resonance is a plausible mechanism for nighttime Pi2 pulsations. The plasmaspheric cavity mode is a wave mode in which fast mode waves emitted at a substorm onset bounce back and forth between two reflecting boundaries (the ionosphere and the plasmapause) and are radially trapped in the plasmasphere. *Takahashi et al.* [1995] depicted a box model of the cavity mode resonance in the meridional plane (see their Figures 16 and 17) and concluded that ground and satellite observations of nighttime Pi2 pulsations can be mostly explained by the cavity mode. Also, by means of a two-dimensional cold MHD simulation, *Cheng et al.* [2000] and *Denton et al.* [2002] found that the plasmaspheric cavity mode resonance is feasible for excitation mechanism of nighttime Pi2 pulsations. They showed a good agreement between observations and simulation results in respect of fundamental frequency and ratios of the first three harmonic frequencies of Pi2 pulsations (i.e., f_2/f_1 and f_3/f_1).

[3] Fast mode waves radiated from a substorm onset region are expected to be trapped effectively in the plasmasphere, if the wave normal is nearly perpendicular to the reflecting boundaries (the ionosphere and the plasmapause). As a result, the plasmaspheric cavity mode resonance will

[1]Data Analysis Center for Geomagnetism and Space Magnetism, Graduate School of Science, Kyoto University, Kyoto, Japan.
[2]Applied Physics Laboratory, Johns Hopkins University, Laurel, Maryland, USA.
[3]Department of Earth and Planetary Sciences, Kyushu University, Fukuoka, Japan.
[4]Graduate School of Science, Tohoku University, Sendai, Japan.
[5]Department of Physics, University of York, York, United Kingdom.
[6]Hermanus Magnetic Observatory, Hermanus, South Africa.
[7]Office of Research and Development, National Space Development Agency of Japan, Tsukuba, Japan.
[8]Graduate School of Science and Technology, Chiba University, Japan.

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be established. This is likely to occur near the midnight meridian where substorms are thought to initiate. On the contrary we can expect that waves would not be trapped for a long time on the flanks where the waves make oblique incident on the boundaries, resulting in no appearance of Pi2 pulsations. From a statistical analysis of satellite data, *Takahashi et al.* [1995] found not only that dayside compressional power is low at substorm onset but also that the dayside compressional oscillations have low coherence with ground Pi2 pulsations. However, according to ground observations, Pi2 pulsations are global phenomena observed at local times far from local midnight [*Stuart and Barsczus*, 1980; *Yumoto et al.*, 1980; *Sutcliffe and Yumoto*, 1989, 1991; *Villante et al.*, 1992; *Nosé*, 1999]. Then we pose the following questions: Can the plasmaspheric cavity mode resonance be established even on the morningside, and what is the longitudinal structure of the cavity mode resonance?

[4] In the present study we focused on a Pi2 pulsation that occurred at 0538 UT on 20 September 1995 because two satellites (ETS-VI and EXOS-D) and ground stations located from low latitude (L = 1.45) to high latitude (L = 12.6) made observations at 0700–1000 magnetic local time (MLT). Magnetic field data from equatorial and low-latitude (L < 1.5) stations at 0200 MLT and 1500 MLT were also available. This data set provided us a unique opportunity to investigate the Pi2 pulsation on the morningside in great detail and to examine its longitudinal structure.

[5] The organization of the paper is as follows. In section 2 we present ground substorm signatures for this event at first and then display ground and ETS-VI satellite observations of Pi2 pulsations. The plasmapause location is identified by the EXOS-D data. In section 3 we discuss whether the plasmaspheric cavity mode resonance was established on the morningside. Longitudinal structure of the plasmaspheric cavity mode resonance is also discussed. Section 4 gives conclusions.

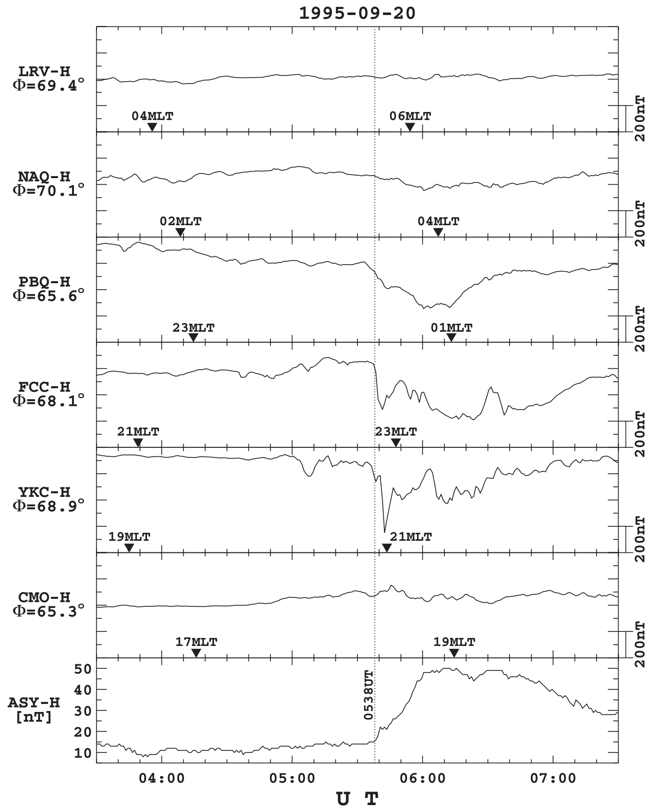

Figure 1. Ground magnetic field data for 0330–0730 UT on 20 September 1995. The top six panels show the H component of the geomagnetic field data from AE stations. Geomagnetic latitude (Φ) is indicated in the left margin of each panel. Magnetic local time is shown by triangles. The bottom panel is the H component of the longitudinally asymmetric (ASY) disturbance index. Substorm signatures are seen at 0538 UT, as indicated by a vertical dotted line.

2. Analysis of Pi2 on Morningside

2.1. Substorm Signatures

[6] In Figure 1 we display ground magnetic field data for the period 0330–0730 UT on 20 September 1995 to examine substorm signatures. The top six panels show geomagnetic field data in the H (horizontal) component from high-latitude ground stations: Leirvogur (LRV, 69.4° geomagnetic latitude (GMLAT), 71.3° geomagnetic longitude (GMLON)), Narsarsuaq (NAQ, 70.1°, 38.0°), Poste-de-la-Baleine (PBQ, 65.6°, 351.4°), Fort Churchill (FCC, 68.1°, 327.8°), Yellowknife (YKC, 68.9°, 298.8°), and College (CMO, 65.3°, 261.0°). These high-latitude ground stations are AE stations and are distributed longitudinally with MLT coverage of about 11 hours. The bottom panel is the H component of the longitudinally asymmetric (ASY) disturbance index [*Iyemori et al.*, 1992], which shows variations corresponding to a midlatitude positive bay at substorm onset [*Iyemori and Rao*, 1996].

[7] The geomagnetic field at FCC and YKC suddenly decreased by 300–400 nT at 0538 UT, which is indicated by a vertical dotted line, showing a high-latitude negative bay. At this time, FCC and YKC were around 2300 MLT and 2100 MLT, respectively. At 0538 UT, an increase of the ASY-H index (i.e., a midlatitude positive bay) was seen with an amplitude of ~40 nT. These ground signatures confirm that a substorm (not a pseudosubstorm or a minor activity) initiated at 0538 UT on 20 September 1995. Geomagnetic field at PBQ showed a gradual decrease. We think that the overall decrease was also caused by the substorm, though the decrease started earlier than 0538 UT (i.e., 0534 UT). Since there were no corresponding variations in other stations and the ASY-H index at 0534 UT, the initial decrease at 0534 UT might be due to local phenomena, which were followed by the real substorm. Note that there were no clear variations at NAQ and LRV that are on the dawnside (~0400–0600 MLT) and at CMO that are on the duskside (~1900 MLT). Thus we suggest that this substorm occurred not on the dawnside or the duskside but at premidnight (2100–2300 MLT).

2.2. Data Set

[8] We studied a Pi2 pulsation that occurred in association with the substorm described above, using geomagnetic field data from ground stations listed in Table 1. We also used the magnetic field data obtained by the triaxial fluxgate magnetometer (MAM) on board the ETS-VI satellite, which has been placed in a near-equatorial elliptical orbit having a perigee of 2.3 R_E, an apogee of 7.1 R_E, and an inclination of

Table 1. Ground Stations Used in This Study

Station Name	L	GMLAT (deg)	MLT[a] (hour)	Sampling (s)	Source[b]
		Morningside			
HOR (Hornsund)	12.6	73.7	9.5	10	IMAGE
BJN (Bear Island)	9.6	71.1	9.3	10	IMAGE
SOR (Soroya)	6.7	67.3	9.1	10	IMAGE
KIL (Kilpisjarvi)	6.1	66.2	8.9	10	IMAGE
MUO (Muonio)	5.5	64.9	8.9	10	IMAGE
PEL (Pello)	5.1	63.8	8.9	10	IMAGE
NOR (Nordli)	4.9	63.3	8.1	5	SAMNET
OUL (Oulu)	4.5	61.8	8.9	5	SAMNET
OUJ (Oulujarvi)	4.3	61.1	8.9	10	IMAGE
NUR (Nurmijarvi)	3.5	57.7	8.6	5	SAMNET
HER (Hermanus)	1.45	−33.9	6.6	1	HMO
		Nightside			
SMA (Santa Maria)	1.13	−19.5	2.1	3	KU
BLM (Belem)	1.02	8.6	2.6	3	KU
		Afternoonside			
MGD (Magadan)	2.6	51.7	15.2	3	KU
MSR (Moshiri)	1.51	35.4	15.0	3	KU
KAK (Kakioka)	1.26	26.9	14.9	1	KMO
GUA (Guam)	1.01	5.1	15.4	3	KU

[a]MLT values are at 0540 UT on 20 September 1995.
[b]HMO: Hermanus Magnetic Observatory, KU: Kyushu University, KMO: Kakioka Magnetic Observatory.

13.4° [*Nagai et al.*, 1996]. The MAM data have a time resolution of 3 s. In order to estimate plasma number density in the plasmasphere and to identify the plasmapause, we made use of plasma wave data obtained by the Plasma Wave and Sounder experiments (PWS) [*Oya et al.*, 1990] carried by the EXOS-D satellite, which was launched into a semipolar orbit with an initial perigee, apogee, and inclination of 274 km altitude, 2.6 R_E, and 75°, respectively [*Oya and Tsuruda*, 1990]. Plasma number density was estimated from the PWS observations every 8 s.

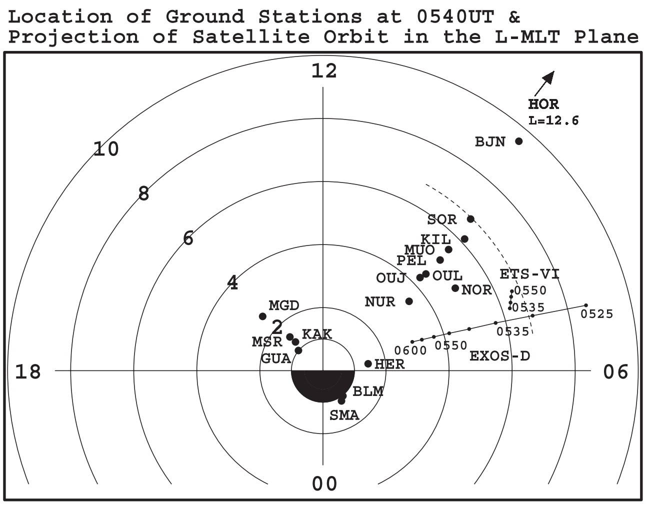

Figure 2. Location of ground stations in the L-MLT plane at 0540 UT on 20 September 1995. Orbits of the ETS-VI and EXOS-D satellites were also projected in the same plane by using the Tsyganenko 89c model for the time interval of 0535–0550 UT and 0525–0600 UT, respectively. Small dots on the orbits indicate satellite positions at 5-min intervals. A dashed arc on the morning sector is a plausible plasmapause location estimated from the EXOS-D observation.

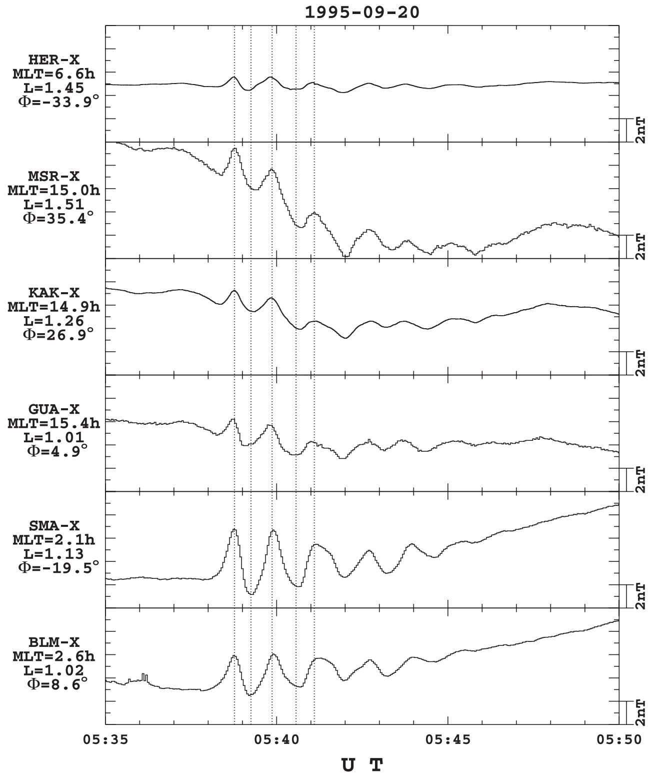

Figure 3. The X component of the geomagnetic field from equatorial and low-latitude stations for the time interval 0535–0550 UT on 20 September 1995. In the left margin, MLT, L, and the geomagnetic latitude (Φ) of each station at 0540 UT are shown.

[9] Figure 2 shows the location of ground stations in the L-MLT plane immediately after the substorm occurred, that is, at 0540 UT on 20 September 1995. Since HOR has too large L-value to be plotted in this figure, its expected location is pointed to by an arrow. Orbits of the ETS-VI and EXOS-D satellites were also projected in the same plane by using the Tsyganenko 89c model [*Tsyganenko*, 1989]. The ETS-VI orbit was shown for the interval 0535–0550 UT, while the EXOS-D orbit was shown for the interval 0525–0600 UT. Small dots on both orbits indicate satellite positions at 5-min intervals. Note that a large number of ground stations and satellites made observations on the morningside (0700–1000 MLT). Some ground stations in the equator and low-latitude were also available on postmidnight (0200 MLT) and afternoon (1500 MLT) sides in this study. A dashed arc on the morning sector, to be discussed in a later section, was found to be a plausible plasmapause location.

2.3. Observations at Equator and Low Latitude

[10] Figure 3 displays the X (northward) component of the geomagnetic field from the equator and low-latitude ground stations, HER, MSR, KAK, GUA, SMA, and BLM, for the time interval 0535–0550 UT on 20 September 1995. In the left margin, MLT, L, and Φ (geomagnetic latitude) of each station at 0540 UT were shown. Note that SMA and

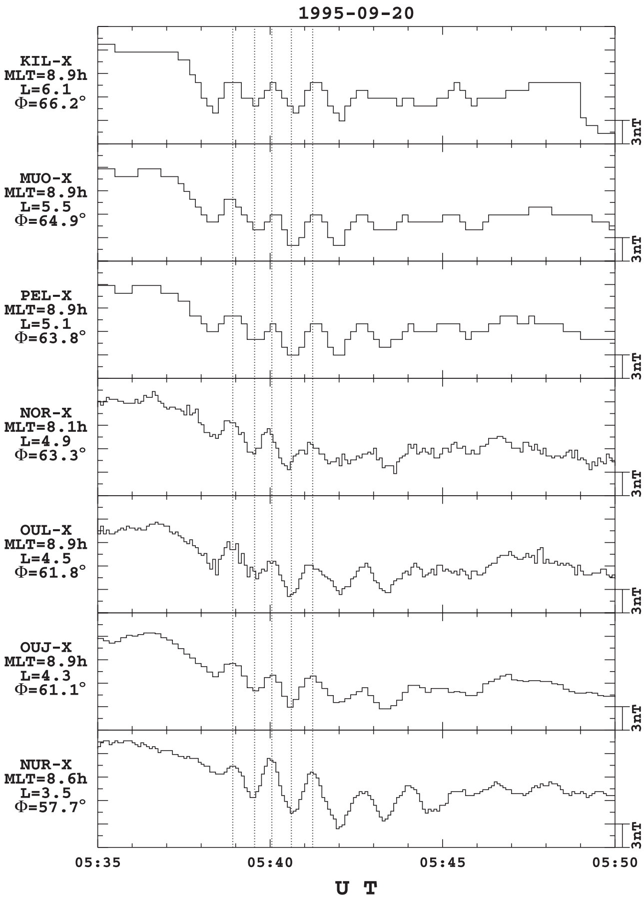

Figure 4. The X component of the geomagnetic field from mid-latitude (L = 3.5 − 6.1) stations. The format and the displayed time interval are the same as for Figure 3.

BLM were at the postmidnight sector (0200–0300 MLT), while MSR, KAK, and GUA were on the afternoon sector (~1500 MLT) and HER was on the morning sector (~0700 MLT). We found that Pi2 pulsations were observed at all of the stations with a period (T) of about 70 s. They started around 0538 UT, which corresponds to the onset time of the substorm identified from Figure 1. Vertical dashed lines indicate that this Pi2 pulsation had almost no phase lag among stations.

2.4. Observations at Midlatitude on Morningside

[11] Figure 4 shows the X component of the geomagnetic field from midlatitude (L = 3.5 − 6.1) stations located at ~0900 MLT. The format and displayed time interval are the same as those of Figure 3. The panels of Figure 4 are sorted from top to bottom in descending order of L. The mid-latitude stations also observed Pi2 pulsations starting from 0538 UT with $T \sim 70$ s. Waveforms and periods of the pulsations are similar to those at the equator and low-latitude. Vertical dashed lines are times of the peaks and troughs of the Pi2 pulsation at NUR. Inspecting these dashed lines, we concluded that Pi2 pulsations observed at NOR, OUL, and OUJ have the same waveforms as that at NUR. Since data from KIL, MUO, and PEL have a sampling time of 10 s and a magnetic field resolution of ~1 nT, it might be difficult to analyze waveforms in detail. However, the dashed lines roughly correspond to the peaks and troughs of pulsations that appeared at KIL, MUO, and PEL, suggesting that these stations also observed the same waveforms as those at the other four stations. Thus we suppose that Pi2 pulsations were observed in a wide range of L (L = 3.5 − 6.1) on the morningside with similar waveforms and no relative phase delay.

2.5. Observation by ETS-VI Satellite on Morningside

[12] We examined the magnetic field data acquired by the ETS-VI satellite. Figure 5a shows ETS-VI/MAM data for the time interval 0535–0550 UT. The magnetic field variation data were represented in the local magnetic coordinate system, in which the $\Delta B_{\parallel}$ component is the tangential direction of model magnetic field, the $\Delta B_{\perp 1}$ component is perpendicular to the model magnetic field and directed radially outward, and the $\Delta B_{\perp 2}$ component is azimuthally eastward. The field components $\Delta B_{\parallel}$, $\Delta B_{\perp 1}$, and $\Delta B_{\perp 2}$ are referred to as the compressional, radial, and azimuthal components, respectively. The ETS-VI satellite was slightly off the geomagnetic equator (7°–8° GMLAT) during the event. The satellite location is projected on the ground at $L \sim 6.3$ and MLT = 7.2 − 7.4 hours by the Tsyganenko 89c model (see Figure 2). In Figure 5b we presented the X component of the magnetic field data from NOR and NUR, which are the same as data displayed in Figure 4, for the purpose of comparison with the ETS-VI observation. In both figures we drew vertical dashed lines

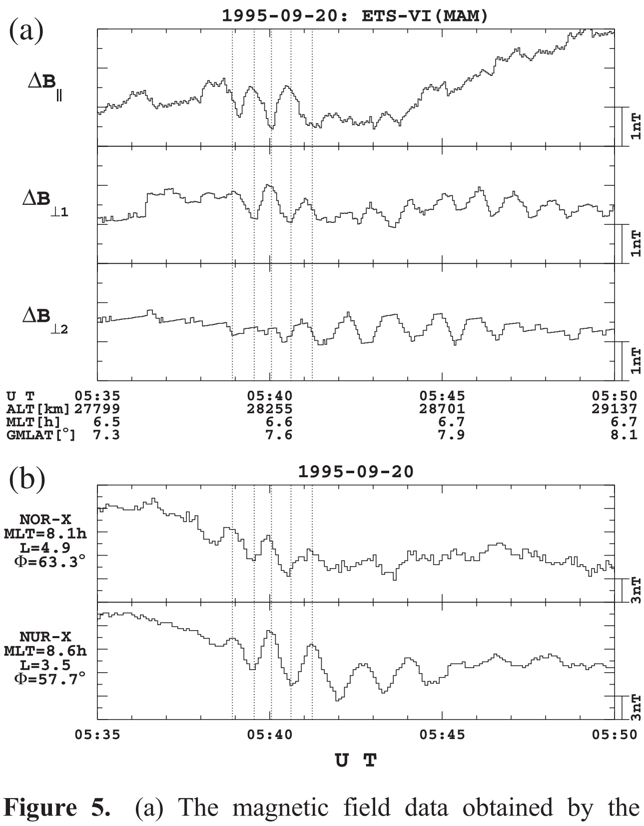

Figure 5. (a) The magnetic field data obtained by the ETS-VI/MAM instrument. The field components $\Delta B_{\parallel}$, $\Delta B_{\perp 1}$, and $\Delta B_{\perp 2}$ correspond to the compressional, radial, and azimuthal components, respectively. (b) The X component of the geomagnetic field data from NOR and NUR, which are the same as data in Figure 4.

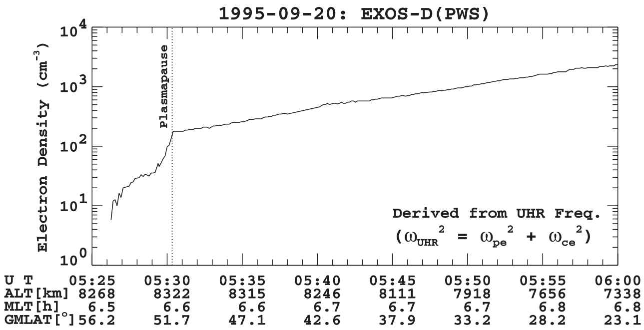

Figure 6. The electron number density along the EXOS-D orbit. The electron number density was derived from the upper hybrid resonance frequency observed by the EXOS-D/PWS instrument.

that indicate times of the positive and negative peaks of the Pi2 pulsations observed at NUR. From Figures 5a and 5b we noticed that (1) ETS-VI observed oscillations in the compressional and radial components that have a period and waveforms similar to those of ground Pi2 pulsation, indicating a fast mode wave; (2) however, there is no clear variation in the azimuthal component when Pi2 was observed on the ground (0538–0542 UT); (3) the oscillations in the compressional and radial components were out of phase; and (4) oscillations in the compressional (radial) component had the out-of-phase (in-phase) relation with those in the X component on the ground. Remember that the ETS-VI and ground stations were on the morningside (MLT = 7.2 – 9 hours) in this event. To our knowledge, this is an unprecedented observation of dayside Pi2 pulsations by satellite.

[13] We also noted that ETS-VI observed continuous oscillations in the radial and azimuthal components after 0542 UT. The oscillation period in the radial component is almost the same as that of Pi2 ($T \sim 70$ s), while the azimuthal component had a slightly longer period of $T \sim 80$ s. It seems that no corresponding oscillation was observed on the ground.

2.6. Observations by EXOS-D Satellite on Morningside (Estimation of Plasmapause Location)

[14] In the above analysis we found that the ground Pi2 pulsations at $L = 3.5 - 6.1$ and the Pi2 pulsation observed by ETS-VI at $L \sim 6.3$ had nearly identical waveforms. This implies the existence of standing waves established across a wide range of L, that is, waves radially trapped between inner and outer boundaries. The plasmapause is characterized by a steep negative gradient of the number density in the radial direction. This gradient of the number density provides a steep positive gradient of the Alfvén velocity, where fast mode waves can be reflected [*Allan et al.*, 1986; *Lee and Kim*, 1999]. Thus we expect that the plasmapause is an outer boundary and that it was located at $L > 6.3$ for this event. Using the EXOS-D/PWS data, we attempted to identify the location of the plasmapause. Figure 6 gives the profile of the electron number density along the orbit of the EXOS-D satellite. The electron number density was derived from the upper hybrid resonance frequency observed by the PWS instrument. (In the derivation the electron cyclotron frequency is required to be estimated; we calculated it using the IGRF geomagnetic field model.) From Figure 6 we determined that EXOS-D was crossing the plasmapause at 0530:20 UT, when the gradient of the electron number density changed abruptly. Projection of the EXOS-D position at 0530:20 UT into the L-MLT plane brought the plasmapause to $L \sim 6.8$. The L value of 6.8 seems to be extremely large as a plasmapause position, but we think this was probable because this day (20 September 1995) was preceded by three geomagnetically quiet days. Figure 7 shows the Kp index for 16–20 September 1995. The values of Kp in the preceding three days (17–19 September 1995) were less than or equal to 2+. As shown at the top of Figure 7, ΣKp was 12○ for the 17th, 5○ for the 18th, and 7○ for the 19th. During such enduring quiet periods, the plasmasphere is expected to expand to large L [*Taylor et al.*, 1968; *Chappell et al.*, 1970]. Assuming that the plasmapause is located in the same L shell on the morningside (see the dashed arc in Figure 2), we can conclude that ETS-VI and the midlatitude stations shown in Figure 4 were inside the plasmasphere.

2.7. Observations at Middle and High-Latitude on Morningside

[15] The X and Y (eastward) components of the geomagnetic field data at middle and high-latitude ground stations ($L = 5.1 - 12.6$) at ~0900 MLT are shown in Figure 8, where stations are ordered from high L at the top to low L at the bottom. All the stations recorded geomagnetic field variations with a sampling time of 10 s and a magnetic field resolution of ~1 nT. Solid lines indicate the X component and dash-dot lines indicate the Y component. Note that the vertical scale of the top two panels is different from that of other panels. SOR is at $L = 6.7$ and close to the plasmapause location determined from the EXOS-D measurement (see Figures 2 and 6). Thus field variations at HOR and BJN (top two panels) and at KIL, MUO, and PEL (bottom three panels) are thought to reflect phenomena outside and inside the plasmasphere, respectively. At KIL, MUO, and PEL (i.e., inside the plasmasphere), waveforms are nearly identical among them as

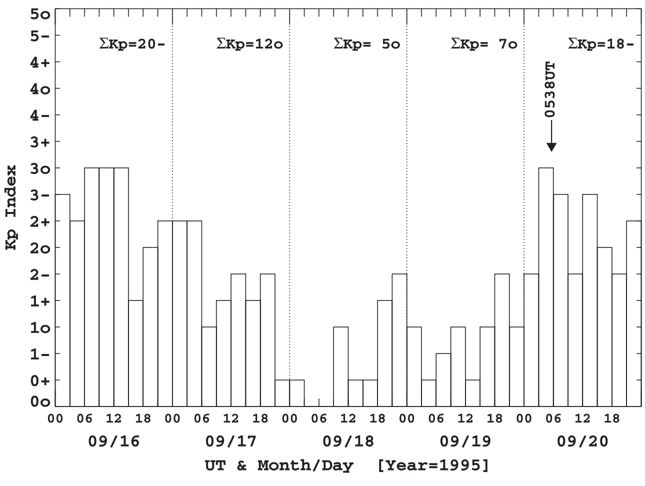

Figure 7. The Kp index for 16–20 September 1995. ΣKp for each day is shown at the top of figure. Substorm onset focused on in this study is shown by an arrow.

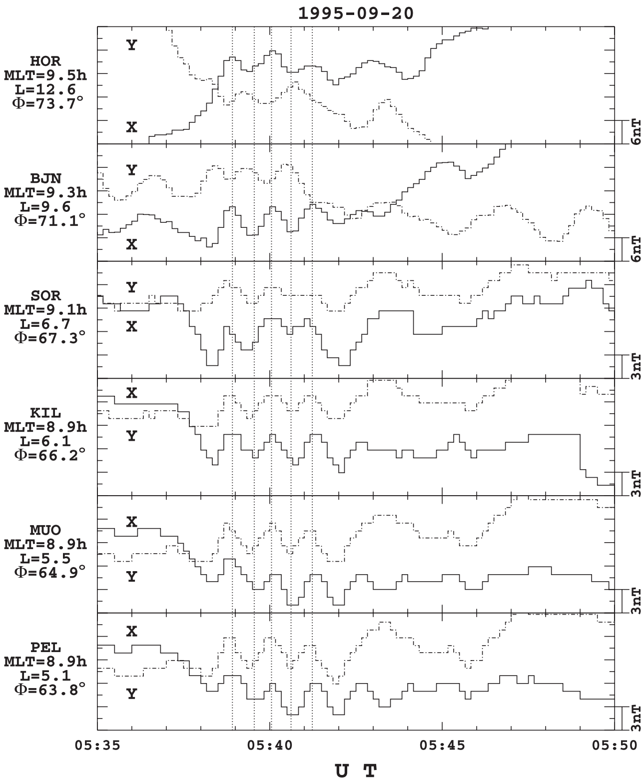

Figure 8. The X and Y components of the geomagnetic field data at mid- and high-latitude ($L = 5.1 - 12.6$) stations at ~0900 MLT. Solid and dash-dot lines are the X and Y components, respectively. The format and displayed time interval are the same as for Figure 3.

indicated by vertical dashed lines, being consistent with the result in section 2.4. However, waveforms at SOR (i.e., near the plasmapause) are slightly different from those inside the plasmapause with respect to amplitude and phase. Comparison of the X component between the top two panels (i.e., outside the plasmasphere) and bottom three panels (i.e., inside the plasmasphere) revealed that (1) oscillations are in phase and (2) the amplitude of Pi2 outside the plasmasphere is about twice as large as that inside the plasmasphere. Meanwhile, oscillations in the Y component show the out-of-phase relation between outside and inside of the plasmasphere. These observational results indicate that the wave characteristics of Pi2 change across the plasmapause.

3. Discussion

3.1. Plasmaspheric Cavity Mode Wave

[16] We have investigated the Pi2 pulsation on the morningside (0700–0900 MLT) by using ground and satellite data. Our observational results can be summarized as follows.

[17] 1. Pi2 pulsations were observed over a wide range of L ($L = 1.45$, $L = 3.5 - 6.1$) on the ground with an almost identical period ($T \sim 70$ s) and waveforms.

[18] 2. The ETS-VI satellite at $L = 6.3$ and GMLAT = $7° - 8°$ also observed a Pi2 pulsation that had nearly the same period and waveforms as the ground Pi2 pulsation.

[19] 3. The Pi2 pulsation observed by ETS-VI appeared in the compressional and radial components.

[20] 4. The phase lag between the compressional and radial components was ~180°.

[21] 5. The ground-to-satellite phase lag is ~180° (~0°) for the X component and the compressional (radial) component.

[22] 6. The EXOS-D observation placed the plasmapause location at $L = 6.8$, across which ground Pi2 pulsations changed their characteristics.

[23] From observational results 1 and 2 we supposed that this Pi2 event was caused by a fast mode wave radially trapped between two reflecting inner ($L < 1.45$) and outer ($L > 6.3$) boundaries. One might argue that dayside Pi2 pulsations are caused by penetration of the oscillating electric field from the polar ionosphere to the lower-latitude ionosphere, as proposed by *Sastry et al.* [1983] and *Shinohara et al.* [1997], resulting in simultaneous appearance of Pi2 pulsations over a wide range of L. However, we think that this mechanism is not the case for this event because the Pi2 pulsation was observed by the ETS-VI satellite. Observational result 6 implies that the outer boundary is the plasmapause at $L = 6.8$ and that the observed Pi2 pulsations were caused by a fast mode wave trapped in the plasmasphere, that is, the plasmaspheric cavity mode resonance.

[24] Previous studies have shown that nighttime Pi2 pulsations observed by satellites were dominant in the compressional and radial components, which are characteristics of fast mode waves and are consistent with the cavity mode [*Lin and Cahill*, 1975; *Sakurai and McPherron*, 1983; *Takahashi et al.*, 1992, 1995, 1999; *Kim et al.*, 2001; *Keiling et al.*, 2001]. Using the Explorer 45 data, *Lin and Cahill* [1975] reported that seven events of Pi2 pulsations near $L = 5$ were principally compressional waves. *Sakurai and McPherron* [1983] found that Pi2 pulsations observed by the ATS-6 geosynchronous satellite had a significant compressional component in most cases. From the AMPTE/CCE and CRRES observations, *Takahashi et al.* [1992, 1995, 1999] concluded that Pi2 pulsations were evident in the compressional and radial components. *Kim et al.* [2001] found that the AMPTE/CCE satellite located at $L \sim 3.9$ and 5.0 observed strongly compressional oscillations at substorm onsets. Electric and magnetic field measurements by the Polar satellite at 10°–14° MLAT and $L \sim 4$ showed two Pi2 pulsation events in the compressional component accompanied by the azimuthal component [*Keiling et al.*, 2001]. Observational result 3 is consistent with these previous results, although our observations were not made on the nightside but on the morningside.

[25] Scrutinizing nighttime Pi2 pulsations observed at Kakioka and by the AMPTE/CCE satellite, *Takahashi et al.* [1995] proposed a possible model for the standing structure of cavity mode waves (see their Figures 16 and 17). The CRRES study by *Takahashi et al.* [2001] gave strong evidence supporting this model. According to their model, Pi2 should be dominated by the compressional and radial components that oscillate out of phase with each other, if an observing satellite is located above the geomagnetic equator and near the outer boundary. The model also predicts that the phase lag between the X component

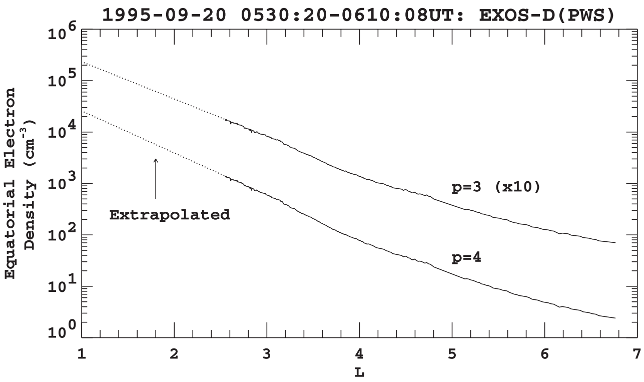

Figure 9. The equatorial electron number density (n_{eq}) estimated from Figure 6 by $n_{eq} = n(r/(L \cdot R_E))^p$, where n is the density at the EXOS-D location, r is the geocentric distance of EXOS-D, and p is the mass index. The equatorial electron density profiles of p = 3 and p = 4 are shown. The density profile of p = 3 is shifted upwards by one order to avoid being confused with that of p = 4. Dotted lines show the density that is estimated from the actual observations at L = 2.5 − 3.5 by extrapolation.

and the compressional (radial) component became ~180° (~0°). Observational results 3, 4, and 5 are commensurate with expectations from the model.

[26] The above discussion leads us to conclude that plasmaspheric cavity mode resonance can be established even on the morningside at substorm onset. We believe that this is the first report of the plasmaspheric cavity mode resonance on the morningside for Pi2 pulsations. (Although there is a report of the magnetospheric cavity mode oscillation on the morning side by *Kim et al.* [1998], that cavity oscillation explains Pc3 pulsations and its energy would be supplied by upstream waves.)

3.2. Period of Plasmaspheric Cavity Mode Wave

[27] To ensure the plasmaspheric cavity mode resonance, we compared the observed period of Pi2 pulsations ($T \sim 70$ s) with periods estimated from two different plasmaspheric models: a two-dimenstional (2-D) box-shape model and a 2-D trapezoid-shape model.

3.2.1. 2-D Box-Shape Model

[28] We used a model of the plasmasphere, in which the geomagnetic field is straight and aligned with the z axis, the x axis points radially outward, and the y axis points to the azimuthal eastward direction so that it completes the right-handed system with the x and z axes. We assumed that the model is uniform in the y direction; that is, we consider a 2-D plasmaspheric model. The strength of the geomagnetic field (B_0) and the plasma number density (n_0) vary only in the x direction. There are conducting boundaries at $x = 1\ R_E$ and $x = 6.8\ R_E$, which correspond to the equatorial ground and the plasmapause, respectively. We also set conducting boundaries at $z = \pm 4.5\ R_E$ as the northern and southern ionospheres, resulting in constant length of the magnetic field line of 9 R_E. This is because length of the dipole field line at L = 3.9, which is the middle of the plasmasphere, is found to be ~8.8 R_E. Thus the plasmasphere is considered to be box-shaped. For this 2-D box-shape plasmaspheric model we can write the linearized cold MHD equation in the following form:

$$\left(\frac{\mu_0 n_0(x) M}{B_0(x)^2}\omega^2 - k_z^2\right)E_y + \frac{d^2 E_y}{dx^2} = 0, \tag{1}$$

where μ_0 is the permeability of the vacuum, M is the mean ion mass, ω is the wave angular frequency, k_z is the parallel wave number, and E_y is the electric field in the y direction. M depends on the plasmaspheric ion composition. For example, if the plasma is 100% proton, M is equivalent to m_p (proton mass), but if the plasma consists of 90% proton and 10% oxygen, M becomes $\sim 2.5 m_p$.

[29] We took $B_0(x)$ as the strength of the dipole magnetic field at the equator and $n_0(x)$ as the electron number density given in Figure 9. Solid lines in Figure 9 trace the equatorial electron density derived from the EXOS-D/PWS observation by $n_{eq} = n(r/(L \cdot R_E))^p$, where n_{eq} is the equatorial electron density, n is the density at the EXOS-D location, r is the geocentric distance of EXOS-D, and p is the mass index. This equation has been used by several pulsation studies with the various values of p: a constant value of p = 3 [*Osaki et al.*, 1998] or p = 4 [*Takahashi and Anderson*, 1992; *Nosé et al.*, 1998], and values changing from p = 3 within the plasmasphere to p = 4 in the plasma trough [*Orr and Matthew*, 1971]. Here we showed two electron density profiles with constant values of p = 3 and p = 4. The density profile of p = 3 is shifted upward by one order to avoid being confused with that of p = 4. The lowest L value through which EXOS-D passed in the present orbit was 2.5; thus the equatorial density at L = 1 − 2.5 was calculated by extrapolating the density profile between L = 2.5 and 3.5 exponentially (dotted lines). A standing structure of waves in the z direction is expressed by $k_z = 2\pi/18\ R_E^{-1}$, which indicates the fundamental harmonics.

[30] The fourth-order Runge-Kutta method was used to solve equation (1) numerically. Fixed boundary condition are chosen, such that E_y is zero at $x = 1\ R_E$ and $x = 6.8\ R_E$. We focused on the fundamental harmonics of plasmaspheric cavity mode wave. Results of the calculation of the model period are shown in Figure 10 as a function of mean ion

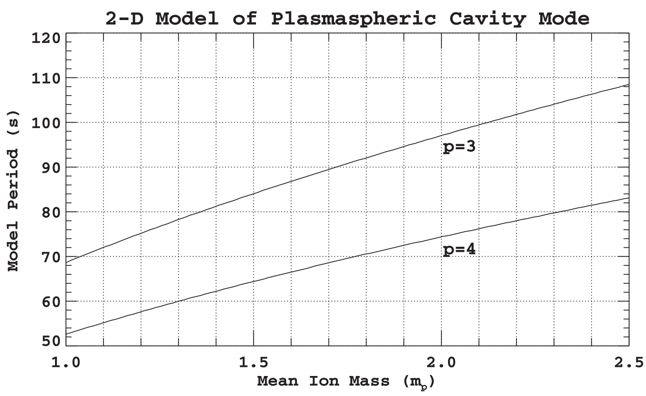

Figure 10. Model period of a two-dimensional plasmaspheric cavity mode resonance as a function of mean ion mass. Results are shown for p = 3 and p = 4.

mass in the plasmasphere. DE-1 measurements showed that the density ratios of He^+/H^+ and O^+/H^+ in the plasmasphere were ~0.2 and ~0.01 in local morning (0700–1100 LT), respectively [*Comfort et al.*, 1988; *Horwitz et al.*, 1990]. This means that plasmaspheric plasma consists of 83% H^+, 16.2% He^+, and 0.8% O^+, resulting in a mean ion mass of $\sim 1.6 m_p$. From Figure 10 we found that the model period of plasmaspheric cavity mode is 87 s for $p = 3$ and 67 s for $p = 4$ when $M \sim 1.6 m_p$.

3.2.2. 2-D Trapezoid-Shape Model

[31] We considered a model in which the length of the magnetic field line becomes long as L becomes large. The coordinates were taken the same as those of the above box-shape model. The field line length varied linearly from 2 R_E at the inner boundary ($x = 1.5\ R_E$) to 16.84 R_E at the outer boundary ($x = 6.8\ R_E$). These changes of the field line length are based on the dipole field, and the location of the ionospheres z_I is expressed as $z_I = \pm(2.8x - 2.2)\ R_E$. This will make the shape of the model plasmasphere to be a trapezoid. The strength of the magnetic field at the equator ($z = 0\ R_E$) was taken as that of the dipole field. The equatorial electron number density was chosen as that in Figure 9. In the real plasmasphere the Alfvén velocity is expected to become larger as an observer moves from the equator to the ionosphere along a field line. Thus we assumed that the model Alfvén velocity increases by $(1 + 9(z/z_I)^4)\ V_{A,\ eq}$, where $V_{A,eq}$ is the Alfvén velocity at the equator. We calculated the resonance period of cavity waves for this 2-D trapezoid-shape plasmaspheric model, using the numerical code developed by *Nakata et al.* [2000]. The ionospheric Pedersen and Hall conductivities were set to 100 Σ_{A0}, where Σ_{A0} is $1/\mu_0 V_{A,\ eq}$ at $x = 6.8\ R_E$, as adopted by *Nakata et al.* [2000] in their Figures 2 and 3. Results showed that the model period of plasmaspheric cavity mode is 74 s for $p = 3$ and 53 s for $p = 4$ when $M \sim 1.6 m_p$.

3.2.3. Comparison Between Model Period and Observed Period

[32] The box-shape plasmaspheric model is too simple in comparison with the actual plasmasphere. However, the box-shape model has been used by previous studies to calculate the resonance periods of cavity waves [*Yeoman and Orr*, 1989; *Lin et al.*, 1991; *Cheng et al.*, 1998, 2000]. *Lin et al.* [1991] and *Cheng et al.* [2000] showed that the derived resonance period is in the period range of Pi2 pulsations and is close to the observed periods. Our calculation with the box-shape plasmaspheric model also gave the periods (87 s for $p = 3$ and 67 s for $p = 4$) that are roughly consistent with the observed period of ~70 s. A more realistic model, that is, the trapezoid-shape model exhibited the periods of 74 s for $p = 3$ and 53 s for $p = 4$. The coincidence of the period supports the idea that the Pi2 pulsation on the morningside was caused by the plasmaspheric cavity mode resonance.

3.3. Longitudinal Structure of Plasmaspheric Cavity Mode Wave

[33] We found that low-latitude Pi2 pulsations at $L \leq 1.5$ ($|\text{GMLAT}| \leq 35°$) were observed globally and showed no phase differences among stations (Figure 3). *Kitamura et al.* [1988] also reported that Pi2 pulsations at the equator and at low-latitude had phase differences much less than 1/10 of a pulsation period between stations with a longitudinal separation of ~90°; that is, the azimuthal wave number (m) is close to 0. *Villante et al.* [1992] found that Pi2 pulsations observed at USA (52° GMLAT) and Italy (42.5° GMLAT) had $m \sim 1$. *Stuart and Barsczus* [1980] showed that there were no systematic differences in onset time of Pi2 pulsations at UK (58.5° GMLAT) and Tahiti (15.3° GMLAT).

[34] In this study we had no ground and satellite observations at $L > 3$ on the nightside and the afternoonside so that we could not conduct a direct examination of the plasmaspheric cavity mode on these local times. However, our study and some previous studies revealed that the ground Pi2 pulsations have $m \sim 0$; thus we conclude that the plasmaspheric cavity mode is rather uniform in longitude.

3.4. Solar Wind Condition

[35] The dayside magnetosphere is generally an active region for Pc3-4 pulsations, whose period range is 10–150 s and covers the Pi2 period (40–150 s). Azimuthal Pc3-4 pulsations observed by satellites have a high occurrence probability in daytime with a strong peak at midmorning [*Arthur and McPherron*, 1977; *Anderson et al.*, 1990; *Nosé et al.*, 1998]. These Pc3-4 pulsations will mask Pi2 activities and make it difficult to find dayside Pi2 pulsations in the plasmasphere. From a statistical study, *Takahashi et al.* [1995] actually found that dayside oscillations in Pi2 frequency band have low coherence with the nightside ground Pi2 pulsations. Nevertheless, in the 20 September 1995 event the ETS-VI spacecraft detected clear oscillations in the morning side that are highly correlated with ground Pi2 pulsations (Figure 5).

[36] It is worthwhile to examine solar wind data here, because activities of the dayside Pc3-4 pulsations are controlled by solar wind. Review papers by *Yumoto* [1986], *Odera* [1986], and *Verö* [1986] documented a large number of studies reporting that wave power of the Pc3-4 pulsations depends on the solar wind speed V_X and the IMF cone angle θ_{XB}, where θ_{XB} is defined by $\theta_{XB} = \cos^{-1}\left(|B_X|/(B_X^2 + B_Y^2 + B_Z^2)^{\frac{1}{2}}\right)$. The slower the solar wind speed becomes and the larger the IMF cone angle becomes, the smaller the Pc3-4 activities become. We suggest that the unfavorable condition of the solar wind for excitation of Pc3-4 gave rise to the unambiguous appearance of the dayside Pi2 pulsation in this event. Figure 11 shows data from the Geotail satellite for the period 0500–0600 UT on 20 September 1995, during which Geotail observed the solar wind at (X_{GSM}, Y_{GSM}) ~ (−2.5, −28) R_E. We displayed 1-min averages in GSM coordinates. The top panel is the solar wind speed $|V_X|$ obtained with the low energy particle (LEP) instrument [*Mukai et al.*, 1994]. The next three panels are the IMF data from the magnetic field (MGF) experiment [*Kokubun et al.*, 1994]. The bottom panel shows θ_{XB}. The solar wind speed was about 360 km/s, which is slower than the average solar wind speed of 400–450 km/s. The IMF was directed mostly along the Z axis during 0510–0540 UT, that is, before the substorm occurred. This IMF direction was reflected in θ_{XB}, which was larger than 70°. These solar wind conditions (i.e., small $|V_X|$ and large θ_{XB}) are unlikely to excite Pc3-4 pulsations and support the above idea. We think that dayside Pi2 pulsations in the plasmasphere are observable by satellites if Pc3-4 activities are suppressed by the solar wind

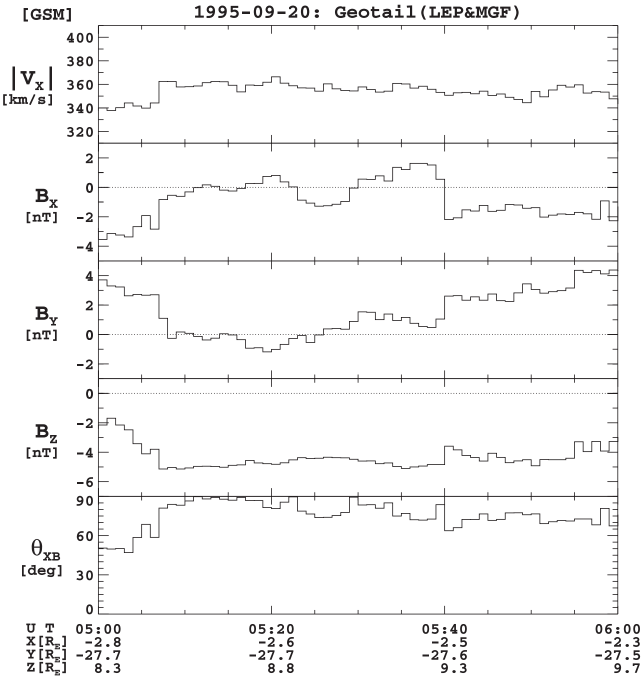

Figure 11. Solar wind data from the LEP and MGF instruments on board the Geotail satellite for the period 0500–0600 UT on 20 September 1995. From top to bottom: the solar wind speed $|V_X|$; the X, Y, and Z components of the IMF; and the IMF cone angle θ_{XB}.

with a slow speed and a large cone angle, as can be found in this event.

3.5. Remaining Questions

3.5.1. Change of Wave Characteristics Across the Plasmapause

[37] We found that Pi2 pulsations on the morningside showed no phase shift across the plasmapause location (L = 6.8) in the X component but showed ~180° shift in the Y component (Figure 8). However, *Fukunishi* [1975] obtained a contrary result for nighttime Pi2 pulsations; that is, the H component showed large phase shift (~180°) among stations at L = 3.2 – 4.4, whereas the D component was almost in phase at all latitudes. This phase reversal in the H component roughly corresponds to the plasmapause location. Using magnetometer arrays deployed from L = 2.5 to L = 6.0 – 6.7, *Lester and Orr* [1981] and *Yeoman and Orr* [1989] also reported that nighttime Pi2 pulsations had the H component phase reversal near the plasmapause position with no phase changes in the D component. We have no clear answer for this contradiction, but it might originate in different local time surveyed.

[38] We have assumed that the plasmapause is a perfect reflector for fast mode waves (i.e., rigid boundary). If the plasmapause behaves as a perfect reflector, fast mode waves should be confined in the plasmasphere and no waves appear outside the plasmapause. However, we found in Figure 8 that Pi2 pulsations were observed at HOR and BJN, which are located outside the plasmasphere. The amplitude of these Pi2 pulsations was about twice as large as that inside the plasmasphere. This observation suggests that the plasmapause is not a perfect reflector but a partial reflector (i.e., nonrigid boundary) for fast mode waves and that some portion of wave energy was leaking out. In this case, the plasmasphere virtual resonance (PVR), which is essentially the same as the plasmaspheric cavity mode resonance, is thought to be established [*Fujita and Glassmeier*, 1995; *Lee and Lysak*, 1999; *Fujita et al.*, 2000, 2002]. In the PVR, the minimum amplitude of the X component is expected around the plasmapause. If the magnetopause is open boundary for fast mode waves, an antinode of the X component will appear there; accordingly, amplitude of the X component will have a positive gradient. This might explain the larger amplitude of Pi2 outside the plasmasphere.

[39] A numerical simulation study of the PVR is needed to investigate characteristics of waves transmitting from the plasmapause to the plasma trough. That study will give us a clue to resolve the contradiction about the phase shift and will reveal the radial profile of Pi2 amplitude in the plasmasphere and the plasma trough.

3.5.2. Phase Delay Between Low and Middle Latitude

[40] Figure 12a shows the X component of the geomagnetic field data at low latitude (HER, L = 1.45) and middle latitude (NUR, L = 3.5) on the morningside. As stated in section 2.4, waveforms and periods of Pi2 pulsations are similar at both stations, though there was a small phase delay; that is, Pi2 at NUR (L = 3.5) lagged behind that at HER (L = 1.45) by ~10 s. The phase delay between low and middle latitude can be seen not only on the morningside but also on the afternoonside. Figure 12b plots data from a low-latitude station (MSR, L = 1.51) and a midlatitude station (MGD, L = 2.6) on the afternoonside (~1500 MLT), where we recognized the similar ~10-s phase lag at MGD. We expect that the phase lag occurred in the region of $L \sim 1.5–2.5$.

[41] This phase delay may be explained by the PVR because wave energy is gradually leaking out of the plasmapause in the PVR, causing energy flows from the inner

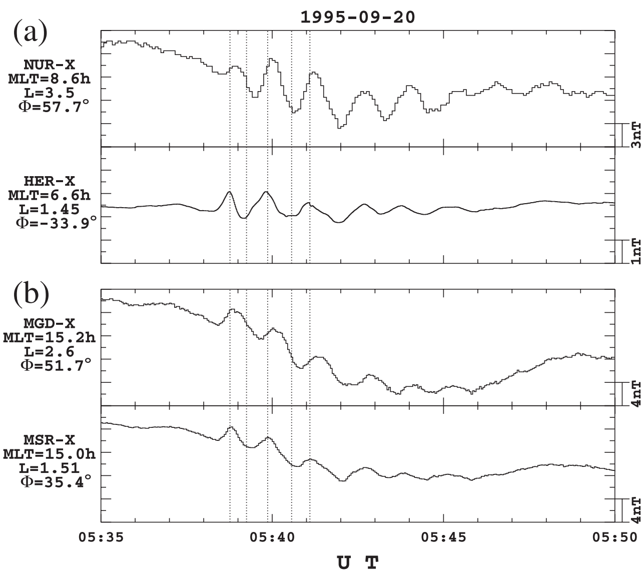

Figure 12. (a) The X component of the geomagnetic field data at low latitude (HER, L = 1.45) and middle latitude (NUR, L = 3.5) on the morningside. (b) Same as in Figure 12a except for stations (MSR, L = 1.5 and MGD, L = 2.6) on the afternoonside.

plasmasphere (low L) to the outer plasmasphere (high L). There may also be a possibility that there was a number density anomaly around $L = 1.5 - 2.5$. The number density anomaly will cause the Alfvén wave velocity to change and may give rise to the phase delay of Pi2 pulsations. Unfortunately, we have no direct measurements of number density at $L < 2.5$ (see Figure 9) in this event, so we cannot examine this possibility. An explanation of this phase delay around $L = 1.5 - 2.5$ remains for future studies.

3.5.3. Transverse Oscillation Observed by ETS-VI Satellite

[42] The ETS-VI satellite detected continuous oscillations in the radial and azimuthal components after 0542 UT (Figure 5a). *Takahashi et al.* [1996], *Saka et al.* [1996a], and *Nosé et al.* [1998] have reported that azimuthally polarized oscillations often appeared in postmidnight at $L = 4-7$ after substorm onset. This oscillation was thought to be different from Pi2 pulsations and was given names such as "TTW (transient toroidal wave)," "QPO (quasi-periodic oscillation)," and "azimuthal Pc4 pulsation on the night side" by each study. We will call this oscillation TTW hereafter. TTWs can be found even on the dayside [*Takahashi et al.*, 1996]; thus it may be possible to think that the oscillation observed by ETS-VI is a TTW. According to *Takahashi et al.* [1988, 1996] and *Nosé et al.* [1998], TTWs are the fundamental mode of standing Alfvén waves on individual magnetic field lines. Then to check if the continuous waves observed by the ETS-VI satellite are TTWs, we calculated eigenperiods of standing Alfvén waves at $L = 6.3$, where ETS-VI was located during the event. In the calculation we used the toroidal mode wave equation of *Cummings et al.* [1969]. From Figure 9 we took $n_{eq} = 9.8$ cm^{-3} for $p = 3$ and $n_{eq} = 3.6$ cm^{-3} for $p = 4$; the magnetic field was assumed to be dipole and M was taken to be $\sim 1.6 m_p$. The result of the calculation showed that the fundamental period is 193 s for $p = 3$ and 121 s for $p = 4$. The second harmonic oscillation has the period of 81 s for $p = 3$ and 53 s for $p = 4$. The observed period of ~80 s is much shorter than the calculated fundamental period and is rather close to the period of the second harmonic oscillation. Moreover, a slight difference of oscillation periods between the radial component (~70 s) and the azimuthal component (~80 s) suggests that the oscillations are decoupled into each component, which is unfavorable for excitation of TTWs, that is, field line resonance with fast mode waves [*Nosé et al.*, 1998].

[43] We conclude that the oscillation observed by the ETS-VI satellite is unlikely to be TTWs. This oscillation might be excited by the azimuthal plasma pressure arising from drift of the electron cloud [*Saka et al.*, 1996b] or by the drift-bounce resonant interaction with energetic ions [*Southwood et al.*, 1969]. *Takahashi et al.* [1990] reported a second-harmonic standing Alfvén wave near local noon that was excited by the drift-bounce resonance. In terms of harmonics the continuous wave observed by ETS-VI might be caused by the drift-bounce resonance. Further studies are necessary to examine whether this kind of oscillation is a common phenomenon on the morningside and how the oscillations are excited.

3.5.4. Azimuthal Wave Number of Pi2 Pulsation

[44] We have found no phase delay between low-latitude Pi2 pulsations observed at 0700 MLT, ~0200 MLT, and ~1500 MLT, indicating $m = 0$ and a longitudinally uniform structure of plasmaspheric cavity mode waves. This result is supported by the previous studies [*Stuart and Barsczus*, 1980; *Kitamura et al.*, 1988; *Villante et al.*, 1992]. However, we recognize that there are some recent studies reporting a propagating nature of Pi2 pulsations. According to *Li et al.* [1998], Pi2 pulsations at $L \sim 1.5$ had typically $|m| \leq 3$ and a dominant westward propagation. *Liou et al.* [2000] showed that Pi2 observed at Kakioka propagates eastward in the premidnight sector and westward in the postmidnight sector with a velocity of $\sim 2.3° \ s^{-1}$. *Yumoto et al.* [2001] referred to results of a doctoral thesis by *Uozumi* [2000], who found an eastward propagation of Pi2 energy at $L \sim 1.2$.

[45] Further investigation is needed to answer the question of why Pi2 pulsations are observed simultaneously at different local times in some cases and are observed as propagating waves in other cases.

4. Summary

[46] In the present study a Pi2 pulsation that occurred at 0538 UT on 20 September 1995 has been investigated with data from ground stations and the ETS-VI and EXOS-D satellites. Since a number of ground stations at $L = 1.45 - 12.6$ and both satellites were located at 0700–1000 MLT, we could examine characteristics of a morningside Pi2 in detail. In addition, ground station data at 0200 MLT and 1500 MLT gave us an opportunity to examine the longitudinal structure of the Pi2 pulsation.

[47] We found that all ground stations located on the morningside at $L = 1.45 - 6.1$ observed Pi2 pulsations with almost the same period ($T \sim 70$ s) and waveforms. The ETS-VI satellite at $L = 6.3$ and GMLAT = 7° − 8° observed a Pi2 pulsation that had nearly the same period and waveform as the ground Pi2 pulsations. The Pi2 pulsation detected by ETS-VI was dominated by the parallel and radial components, indicating a fast mode wave. Phase lag between these component was ~180°. Oscillations in the compressional (radial) components had the out-of-phase (in-phase) relation with those in the X component on the ground. From the EXOS-D observation, the plasmapause location was estimated to be at $L = 6.8$, across which ground Pi2 pulsations changed their characteristics. These observational results lead us to conclude that the plasmaspheric cavity mode resonance can be established even on the morningside and is a plausible mechanism of the morning side Pi2 pulsation. Model calculation of the eigenperiod of the plasmaspheric cavity mode supports this idea.

[48] It was also found that low-latitude Pi2 pulsations were observed globally and showed no phase differences among stations around 0700 MLT, 0200 MLT, and 1500 MLT. We believe that this result reflects a longitudinally uniform structure of the plasmaspheric cavity mode resonance.

[49] **Acknowledgments.** The geomagnetic field data from AE stations were provided by institutes operating each station through INTERMAGNET and T. Kamei. The ASY index was provided by T. Iyemori at WDC for Geomagnetism, Kyoto. The geomagnetic field data from Kakioka were supplied by Kakioka Magnetic Observatory. We thank A. Viljanen for providing the geomagnetic field data from the IMAGE magnetometer network. We thank all institutes maintaining the IMAGE magnetometer

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T. Goka and H. Matsumoto, Office of Research and Development, National Space Development Agency of Japan, 2-1-1 Sengen, Tsukuba, Ibaragi, 305-0047, Japan. (goka.tateo@nasda.go.jp; matsumoto.haruhisa@nasda.go.jp)

D. K. Milling, Department of Physics, University of York, Heslington, York Y010 5DD, United Kingdom. (dave@samsun.york.ac.uk)

Y. Miyoshi and A. Morioka, Graduate School of Science, Tohoku University, Aramaki, Aoba-ku, Sendai 980-8578, Japan. (miyoshi@pparc.geophys.tohoku.ac.jp; morioka@pparc.geophys.tohoku.ac.jp)

H. Nakata, Graduate School of Science and Technology, Chiba University, Yayoi-cho, Inage-ku, Chiba 263-8522, Japan. (nakata@cute.te.chiba-u.ac.jp)

M. Nosé, Data Analysis Center for Geomagnetism and Space Magnetism, Graduate School of Science, Kyoto University, Oiwake-cho, Kitashirakawa, Sakyo-ku, Kyoto 606-8502, Japan. (nose@kugi.kyoto-u.ac.jp)

P. R. Sutcliffe, Hermanus Magnetic Observatory, P. O. Box 32, Hermanus 7200, South Africa. (psutcliffe@hmo.ac.za)

K. Takahashi, Applied Physics Laboratory, Johns Hopkins University, 11100 Johns Hopkins Road, Laurel, Maryland 20723-6099, USA. (Kazue.Takahashi@jhuapl.edu)

T. Uozumi and K. Yumoto, Department of Earth and Planetary Sciences, Kyushu University, 6-10-1 Hakozaki, Higashi-ku, Fukuoka 812-8581, Japan. (uozumi@geo.kyushu-u.ac.jp; yumoto@geo.kyushu-u.ac.jp)