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SURFACE WAVES ON THE DAWN MAGNETOPAUSE: CONNECTION WITH GROUND PC 5 PULSATIONS

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ABSTRACT

Observations of the Geotail spacecraft show that ion flow oscillations in the Pc 5 frequency range are fairly common at the equatorial region in the dawn magnetosphere ($-5 \leq X_{GSM} \leq 5$). The amplitudes of these oscillations sometimes exceed 250 km/s. We examined in detail several events associated with temporal magnetopause crossings during the course of oscillations. It is found that plasma flow oscillations near the magnetopause correspond closely with magnetic field pulsations at latitudes of 70 - 75 degrees on the ground, although the form of the flow oscillation is spiky rather than sinusoidal. The boundary normal inclines sunward (tailward), when the spacecraft enters the magnetosheath (magnetosphere). Most of magnetopause crossings analyzed are cases with high magnetic shears (Bz in the magnetopause was negative in most cases). Outward and sunward flows, whose magnitudes are greater than those in the magnetosheath, were observed in the magnetosphere after inbound crossings, while inward and tailward flows were detected before outbound crossings. These characteristics are not necessarily consistent with the excitation of surface waves by the Kelvin-Helmholtz instability. A high-speed flow with the sunward and outward component was also observed in the magnetosphere after the inbound crossing with high magnetic shear in an isolated and temporal magnetopause crossing event driven by a pressure pulse.

INTRODUCTION

Pc 5 waves are believed to be generated as the normal mode of the field line resonance (FLR) whose energy source is surface waves excited by the Kelvin-Helmholtz (K-H) instability at the magnetopause or in the low-latitude boundary layer (LLBL) (Chen and Hasegawa, 1974; Southwood, 1974). Related works on the FLR have been developed by a number of researchers and account for many observed properties of magnetic pulsations and ionospheric flows detected by radar measurements (e.g., Fenrich and Samson, 1995). A few studies have been conducted on properties of plasma flow oscillations in the magnetosphere (Mitchell, *et al.*, 1990; Nakamura *et al.*, 1994), while the FLR has been clarified by magnetic field observations (e.g.,Kokubun *et al.*, 1976, 1977; Singer *et al.*, 1982). Early observations revealed the presence of tailward propagating surface waves on the magnetopause (Lepping and Burlaga, 1979; Song *et al.*, 1988). The wave characteristics and the relationship with the LLBL structure were described in the analysis of an event observed by the ISEE 1 and 2 spacecraft (Sckopke *et al.*, 1981). Sckopke *et al.* (1981) interpreted the observed pulses as antisunward moving blobs of LLBL plasma produced by the K-H instability at the inner edge of the LLBL. However, different interpretations of this event have been put forth (see Kivelson and Chen, 1995). As for the relationship of surface wave events to ground pulsations, more observations will be needed, although Kivelson and Chen (1995) reported that the frequency bands of ground magnetic variations were same as those at the spacecraft positions for the two surface wave events on the dawn and dusk sides.

We have surveyed Geotail data obtained from January to July in 1995, 1996 and 1997 when the spacecraft passed the dawnside of the magnetosphere and found that ion flow oscillations in the Pc 5 frequency range existed in more than half of orbits near the magnetopause. In this paper we will examine data obtained from the two orbits on quiet and moderately active days, April 29, 1996 and February 1, 1995, respectively (Figure 1). Analysis was also made to compare Geotail observations with ground magnetic variations in the region conjugate to the spacecraft. To monitor the ground magnetic activity we used data (1 minute resolution) from standard magnetic stations and the 210 magnetic meridian network (Yumoto *et al.*, 1996). High-resolution data from the CANOPUS array were used to analyze spectral structures of magnetic fluctuations at high latitudes for specific intervals.

OBSERVATIONS

We will first present observations of Pc 5 ion flow oscillations in the magnetosphere. Figure 2a describes an example of observations in the dawn sector ($-7.8 \le X_{GSM} \le 7.5$). In Figure 2a the magnetic field component, ion density and ion velocities are plotted in GSM coordinates together with the total pressure, P_T ($B_T^2/2\mu_0 + N_PkT$) and ion β ($B_T^2/2\mu_0$ / N_PkT). During the five hour interval from 0700 UT regular plasma flow oscillations of amplitudes of greater than 50 km/s were observed. We note a transient magnetosheath entry of two minute duration around 1330 and multiple encounters of the magnetopause during the interval of 1430 - 1530. The characteristics of magnetopause crossing events will be discussed later.

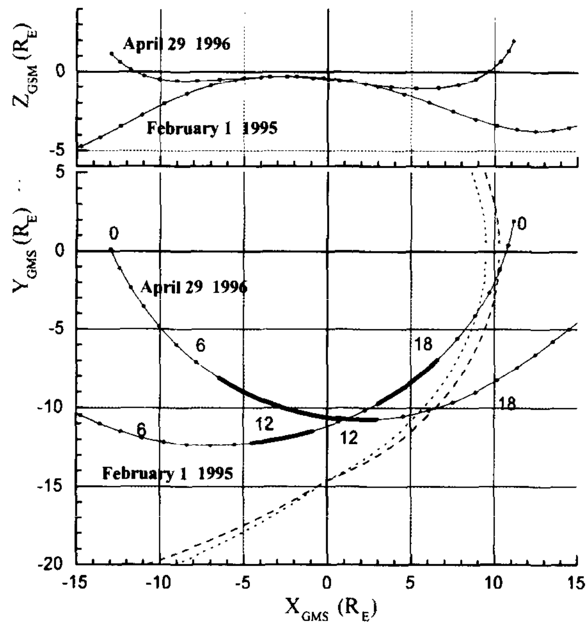


Fig. 1. Geotail trajectories on February 1, 1995 and April 29, 1996 together with the locations of the model magnetopause for the solar wind dynamic pressure of 2.1 nPa. The dashed and dotted curves correspond to magnetopause locations for the Bz components of the interplanetary magnetic field (IMF) of 0 nT and -5 nT (Petrinec and Russell, 1996). Ion flow oscillations were observed at locations indicated by bold lines.

The complex FFT method is used to examine the spectrum and polarization of plasma flows and magnetic variations. In this analysis we used the average field-aligned coordinates, since the direction of the ambient magnetic field changes along the orbit. The average magnetic field is defined in terms of sliding averages of observed magnetic field variations for 1500 seconds. In the average field-aligned coordinates, e_{zz} is parallel to the average field direction, e_{xx} is perpendicular to the magnetic field in the average magnetic meridian and $e_{yy} = e_{zz} \times e_{xx}$. The direction of e_{xx} is opposite the Earth, except for intervals of the tail-like field configuration. Figure 2b presents magnetic field and plasma flow data for the three-hour interval for these coordinates. In the upper six panels magnetic field and ion velocity are plotted such as Bxx, Vxx, -- from the top panel. The characteristics of the wave signals significantly changed around 0940. Plasma flows and magnetic field variations perpendicular to the local magnetic meridian were dominant in the period before 0940, while variations in the magnetic meridian predominated after 0940. Spectral analysis indicates that the wave frequency was almost constant, 3.2 - 3.8 mHz, in the period of 0700 - 1100, although the spacecraft moved along the L-shell of ~10.5 by 40° in longitude. This means that Pc 5 waves observed in the dawn sector have a low azimuthal wave number, as have been reported in previous studies. Southwood (1976) shows that the following diamagnetic relation holds for wave perturbations with a high azimuthal wave number.

$$\delta b_l + \mu_0 \delta p / B_T = 0$$

In other words, the ion pressure and magnetic pressure should be anti-correlated. This feature is not seen in the bottom panel of Figure 2b. We also confirmed that observed perturbations of the field magnitude do not correlate with calculated values from pressure perturbations, indicating that the wave numbers of the analyzed Pc 5 signals were not high.

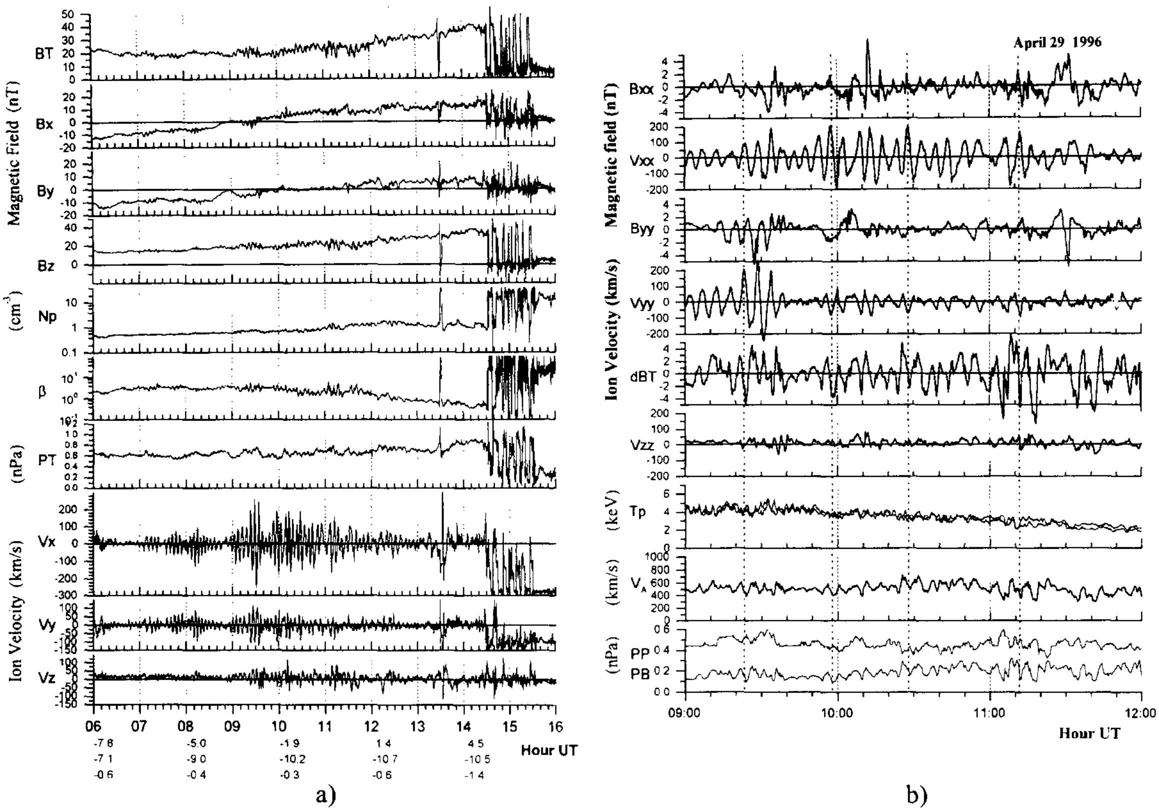


Fig. 2. a) Geotail measurements of magnetic field and ion moments for the 10-hour interval from 0600 UT on April 29, 1996 are plotted in GSM coordinates along with the ion β and total pressure (P_T). Impulsive variations around 1330 and during the interval of 1430 - 1530 are associated with magnetopause crossings of the spacecraft.
b) An interval of ion moment and magnetic field data in the average field-aligned coordinates. The ion temperature, the Alfvén velocity, ion pressure (PP) and magnetic pressure (PB) are plotted in the bottom three panels.

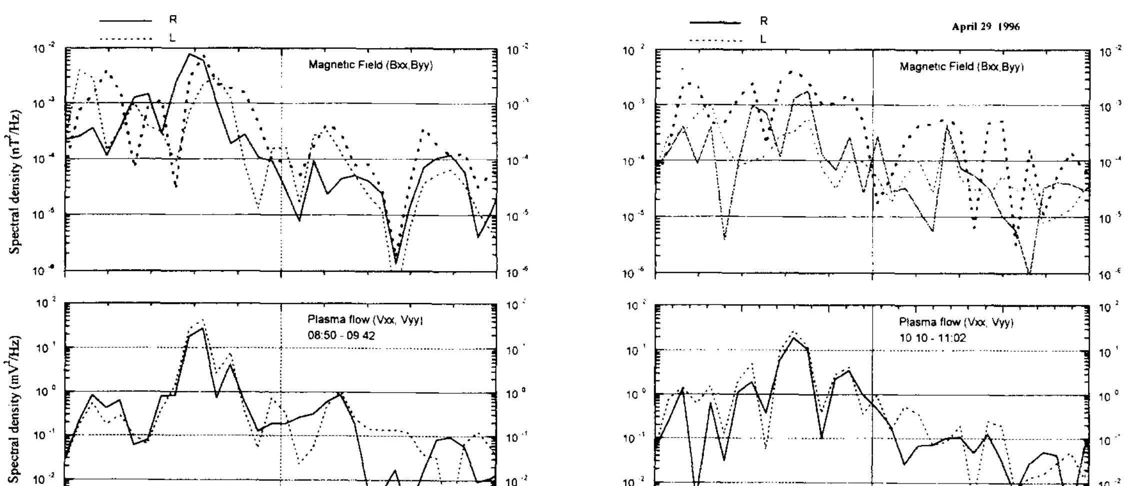


Fig. 3. Spectra for the two intervals, 0850 - 0942 and 1010 - 1102 for transverse components of the ion flow and magnetic field and the compressional component of magnetic filed. Bold dotted lines indicate spectra of the compressional component.

In Figure 3 is described the spectra of two intervals, 0850 - 0942 and1010 - 1102, for transverse components of the ion flow and magnetic field and the compressional component of the magnetic field. Common to the spectra for both intervals are the 3.2 mHz major spectral peak and the slightly left-handed polarization of transverse component of the ion velocity. Magnetic spectra contain more power relative to the major peak than flow spectra at frequencies below the peak frequency. We also note that sub peaks of the compressional component around 1.0 and 6.4 mHz in the former period and at 1.0, 2.3, and 4.4 mHz in the latter period correspond to those of the flow spectra. Spectral densities of the compressional component were larger than those of the transverse component around peak frequencies in the latter period, indicating that the spacecraft was located close to the equatorial node of magnetic oscillation. To confirm the standing wave property we calculated the Poynting flux of wave signals for perturbations in the average field-aligned coordinates, assuming that the electric field perturbation is given by $\boldsymbol{\delta E} = -\boldsymbol{V} \times \boldsymbol{B}_{av}$, where $\boldsymbol{V}$ = (Vxx, Vyy, Vzz) and $\boldsymbol{B}_{av}$ = (0, 0, B_{av}). Average values of the field-aligned flux for 500 seconds were found to be small except for the period of 1007 - 1017, indicating the standing nature of waves. On the other hand, fluxes perpendicular to the ambient magnetic field were larger than the field-aligned flux. The Poynting flux in the magnetic meridian was negative (positive but small in the period of 1050 - 1100). Accordingly, the energy was transfered inward by the compressional waves. This observation is consistent with the accepted scenario for the excitation of the FLR whose energy source originates near the magnetopause (Chen and Hasegawa, 1974; Southwood, 1974). In following sections the analysis will focus on the feature of plasma flow oscillations near the magnetopause in relation to ground magnetic field variations.

Events on February 1, 1995

From the scan of three year data set, we found events, in which temporal magnetosheath entries of several minute duration occurred during the intervals of a series of plasma flow oscillations. An example of this type of event occurred on February 1, 1995 (Figure 4a), where Geotail detected quasi-periodic oscillations of the plasma flow associated with temporal magnetopause crossings near the low-latitude dawnside magnetopause. On February 1 Geotail also observed Pc 5 plasma oscillations from1030 to1400 in the early morning sector, similar to the events occurring on April 29, 1996. Peak frequencies were 2.6 mHz, and 3.3 mHz during the intervals of 1030 - 1300 and 1300 - 1400, respectively. In Figure 4a are seen several sheath entries of a few minute duration during the period from 1600 to 1800. Large amplitude oscillations of more than 200 km/s in plasma flow were observed during the intervals of 1530 - 1600 and 1655 - 1740. In the latter period temporal entries of the spacecraft into the magnetosheath were clearly noted in the magnetic field data. Corresponding magnetic field variations on the ground were registered in northern Canada (Figure 4b). Note that Geotail and YKC were nearly at the 8h meridian at 1700 UT. BLC and FCC were around the 10h LT meridian. Ground magnetic pulsations correlating with plasma flow oscillations near the magnetopause were observed in a limited region. As seen in Figure 4b, variations with wave forms similar to those at Geotail were registered at YKC. Wave forms at FCC were less regular than those at YKC, although the same frequency components, 5.3 mHz during 1530 - 1600 and 4.4 mHz during 1655 - 1740, were dominant at both the stations. Another peak at 5.3 mHz in the former interval is seen at YKC, but is not found at FCC. Figure 5 illustrates spectra of electric field variations at Geotail for the two intervals. Because of data gaps in plasma data, we used the electric filed data (three second resolution) to calculate the spectrum. It is noted that there were spectral peaks at 2.3, 3.3, 4.3, 5.2, and 7.2 mHz for the period of 1655 - 1746. The dominant peak at 4.3 mHz and a subpeak at 5.2 mHz correspond to those at YKC. We also examined magnetic field data from the CANOPUS array to search for the signature of FLR. Spectral analysis indicates that spectral peaks with a high degree of polarization were observed at 4.4 mHz and 5.4 - 5.8 mHz at Contwoyto (CONT: 73.4, 299 in geomagnetic coordinates), which is located to the north by 4° from YKC. The frequency of the major peak was 3.2 mHz at Rankin Inlet (73.7, 331), which is separated from CONT to the east by 32° of longitude. This suggests that a direct conjunction of ground magnetic variations with ion flow oscillations near the magnetopause occurred in a limited region in longitude. By comparing highpass-filtered signals (the cutoff frequency of 2 mHz) at 14 CANOPUS stations, we confirmed the signature of the FLR, that is, the phase reversal in the X component between CONT and the lower-latitude stations at geomagnetic longitude of 291 - 316°.

Figure 6 shows plots of plasma flows and magnetic fields in LMN coordinates along with plasma parameters during the interval of 1630 - 1800. To determine the specific LMN coordinates the average model magnetopause (Roelof and Sibeck, 1993) was deformed self-similarly so as to coincide with satellite positions. We identified eight magnetosheath entries during this interval, referring to the energy-time diagram (not shown) of ions and electrons. The Bz component was negative for four entries (see also Figure 4a). In Figure 7 we compare the Bz component at Geotail with the IMP 8 measurement. IMP 8 was located near GSM = (-3, 20, 22) R_E, and Geotail was located at the local time sector of

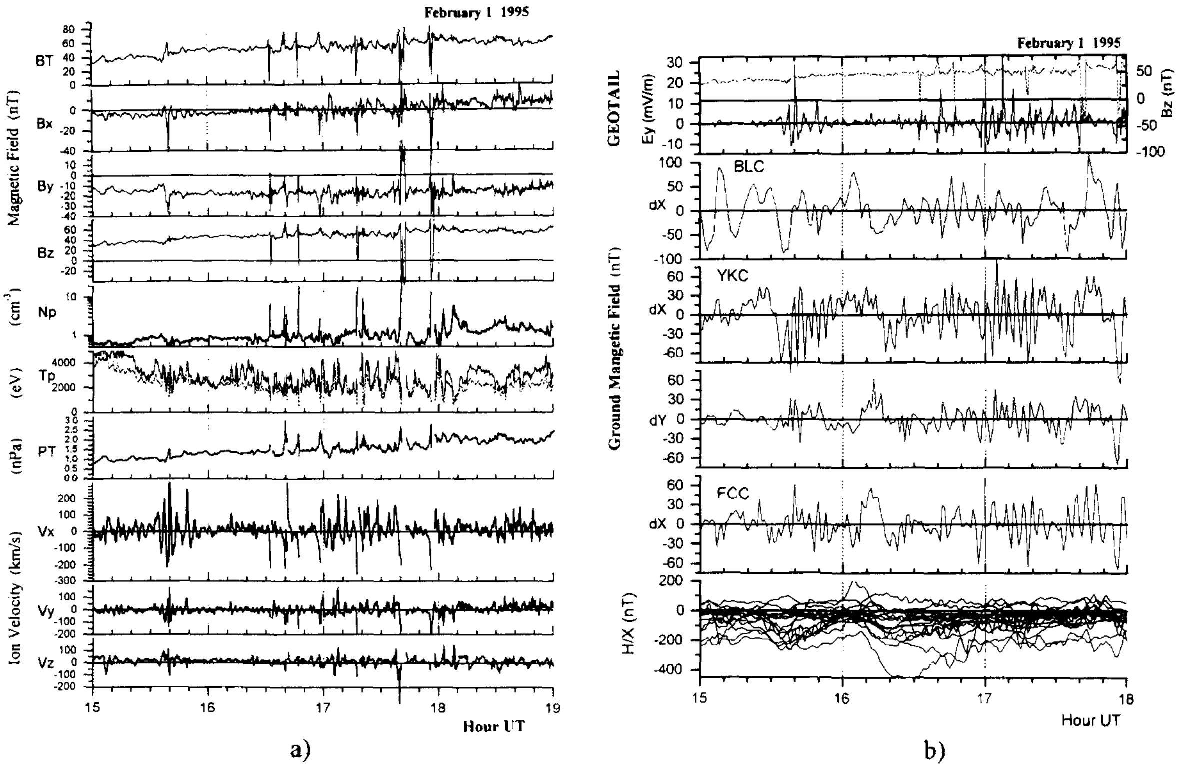


Fig. 4. a) An interval of ion moment and magnetic field data in GSM coordinates on February 1, 1995. The two curves in the temperature panel indicate the Y and Z components of the ion pressure tensor in spacecraft coordinates. Ty (thick line) is higher than Tz (thin line), suggesting that the temperature perpendicular to the magnetic field is larger than the parallel temperature.
b) . Comparison between the electric and magnetic field variations at Geotail and the magnetic variations on the ground. Overlapping plots of the H or X component at high-latitude stations are shown in the bottom panel as a measure of auroral electrojet activity. Ground magnetic field data at Baker Lake (74.3, 316), Yellowknife (69.0, 293) and Fort Churchill (68.7, 323) are highpass-filtered by subtracting a sliding average of 60 minutes.

~0800. Although the IMF varies with time scales of10 to-20 minutes, the Bz component in the magnetosheath measured with Geotail appears to follow the variation of the IMF Bz. It is noted that the Bz component of the magnetosheath periods around 1632, 1647, 1741, and 1757 was negative or positive but small, corresponding to the Bz variation of IMF. The two transient entries around 1640, which were identified by high-resolution magnetic field data (1/16 second), are associated with a northward turning of the IMF. The magnitude of magnetosheath field at these entries was comparable to that in the magnetosphere. This feature is same as that reported for surface wave events in the interval of northward IMF (Chen *et al.*, 1993; Kivelson and Chen, 1995; Kokubun *et al.*, 1994).

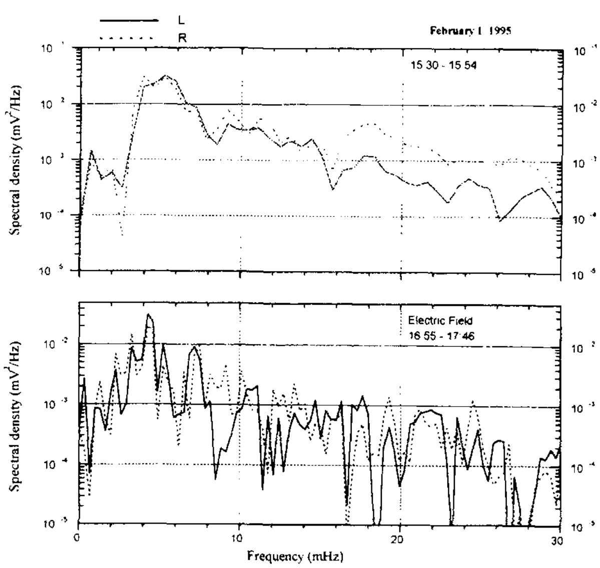


Fig. 5. Electric field spectra for the two intervals on February 1, 1995.

Returning to Figure 6, we note the common feature that the field magnitude increases toward the magnetopause and that the ion flow is inclined inward by 10 - 45°

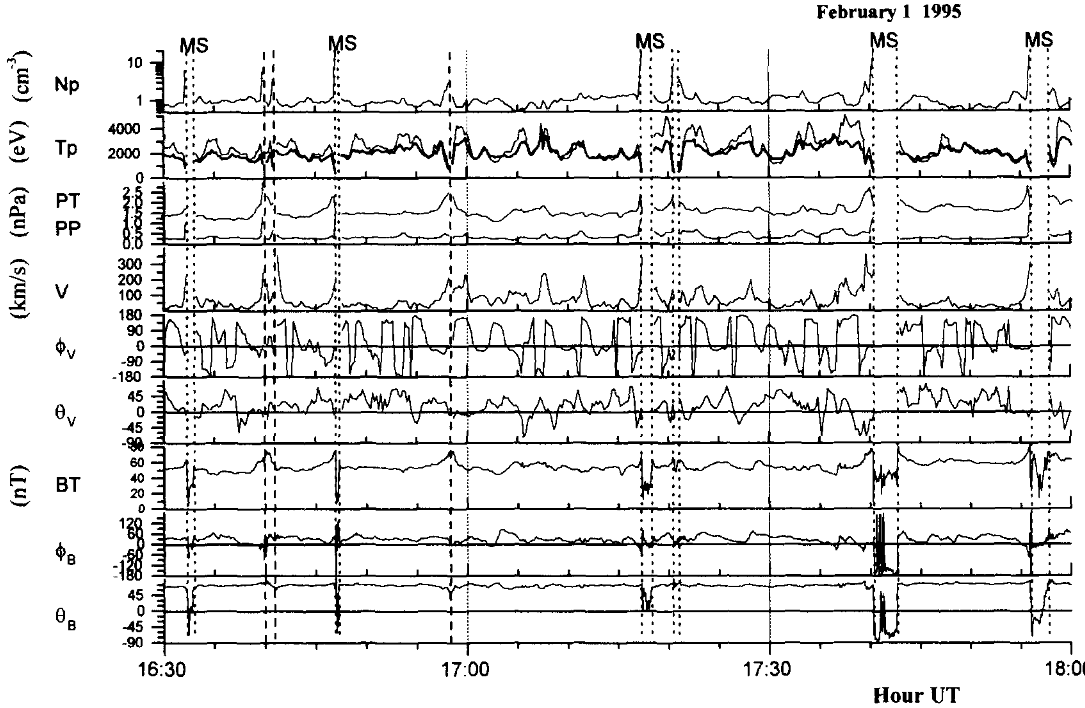


Fig. 6. Ion flow and magnetic variations in the model LMN coordinates. The three central panels show the ion bulk speed, the flow azimuth ϕ_v from the M axis (positive tailward), and the elevation θ_v. The lower three panels show the magnetic field as magnitude B_T, azimuth ϕ_B, and elevation θ_B. The bold line in the upper second panel indicates the z component of temperature in spacecraft coordinates. The dashed lines around 1640 shows two transient entries into the magnetosheath.

before the outbound crossing. After the inbound crossing the field magnitude decreases and the ion flow turns sunward and outward. Figure 6 is notable for the fact that peaks in magnetospheric bulk speed were observed when the sunward component was dominant. In the magnetosphere ion flows with the sunward component tend to have higher speed than those with the tailward component.

We have applied the minimum variance analysis to the high resolution magnetic field data for six pairs of inbound and outbound crossings, indicated by dotted lines in Figure 6. The normal vector was found to contain a systematic difference between the inbound and outbound crossings. The normal direction at the outbound (inbound) crossing inclines sunward (tailward) in the MN plane, except for the last inbound crossing at 1758. The deviation of the normal vector from the positive N axis is larger for the outbound crossing. A clear inbound/outbound dependence of the magnetopause orientation, as in our case, has been reported for multiple magnetopause crossing events occurring during intervals of both northward (Chen *et*

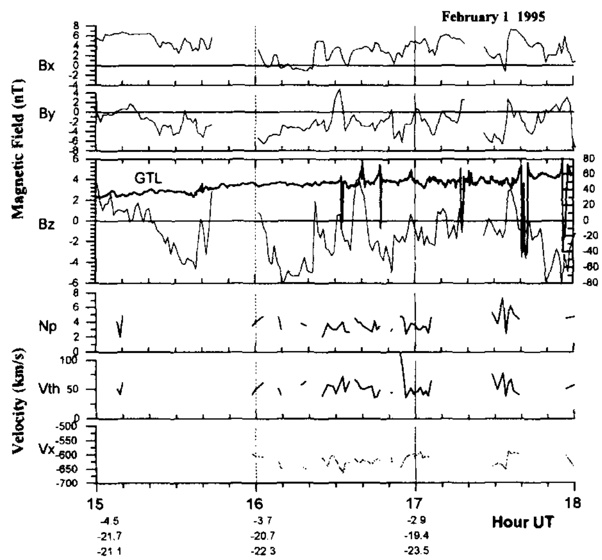
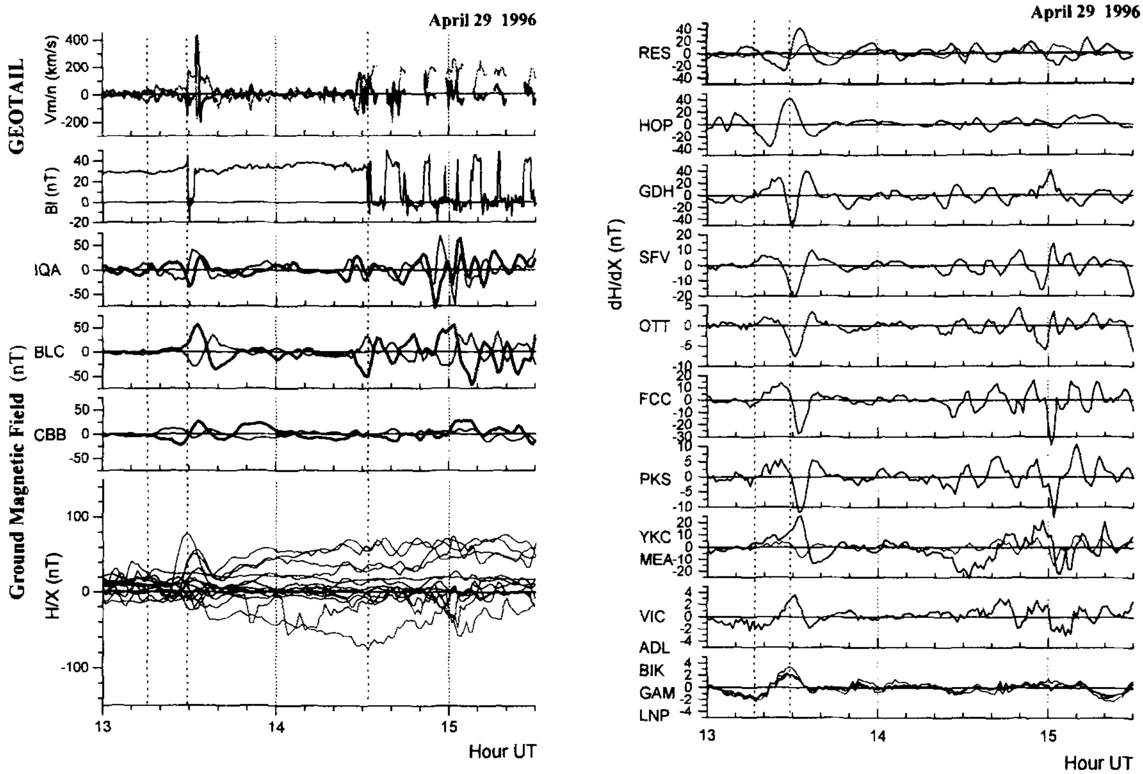


Fig. 7. IMP 8 magnetic field and plasma data from 1500 to 1800 on February 1, 1995. The Bz component of the magnetic field at Geotail is plotted in the third panel from the top.

al., 1993; Kokubun *et al.*, 1994) and southward IMF Bz (Kawano *et al.*, 1994). As shown in Figure 7, the condition of IMF for the present case is different from that in previous observations of tailward propagating surface waves (Kivelson and Chen, 1995: Kokubun *et al.*, 1994). Five out of six events examined previously were observed during intervals of northward IMF. In these events the magnitude of the magnetic field in the magnetosheath was larger than that in the low-latitude boundary layer (LLBL), while a high magnetic shear was observed at the magnetopause crossing in the cases examined here.

Events on April 29

A transient magnetosheath entry of ~ 2 minutes duration around 1330 and multiple magnetopause crossings were observed during the interval from 1430 to 1530, shown in Figure 2a. Comparisons between magnetic and ion flow variations at Geotail and ground magnetic field variations are illustrated in Figure 8. The ground magnetic field data are highpass-filtered by subtracting a sliding average of 60 minutes. For an hour from 1430 Geotail moved from (5.3, -10.4)R_E to (6.6, -9.9)R_E in the GSM XY plane. During this interval quasi-period magnetic fluctuations with a time



a) b)

Fig.8. a) Comparison between magnetic variations on the ground and ion flows at Geotail in LMN coordinates. Magnetic field variations at three stations, IQA (73.4, 14.7), BLC: and CBB (77.5,306.9) near the polar cap boundary are plotted in the middle three panels. Thick and thin lines in these panel indicate the X and Y components, respectively. The thick line in the top panel shows the N component of ion velocity.
b) Hipass-filtered records of magnetic variations on the ground. H component variations at four stations in the Pacific area are displayed in the bottom panel. Resolute Bay (RES) is in the central polar cap.

scale of ~12 minutes were observed at high-and mid-latitude ground stations from the morning to afternoon sectors, corresponding to multiple crossings of Geotail. No corresponding variation was detected at nighttime low latitudes (see the right bottom panel of Figure 8).On the other hand, the transient magnetosheath entry of 2.5 minutes duration starting at 1330 is associated with impulsive magnetic field changes on the ground. Although the magnitude was small (~4 nT) at low latitudes, a clear increase in the horizontal component was observed. An impulsive density increase was noted in WIND data, corresponding to ground magnetic increases.

Geotail was located at the 7h 20m LT meridian and FCC was almost at this meridian. In the right panel of Figure 8 we note that the times of minima in the horizontal component systematically shifted from GDH (1130 LT) to PKS (0500 LT), suggesting that a localized magnetopause dimple propagated tailward from the subsolar point. If an apparent speed of magnetopause deformation is estimated from the phase delay of ground magnetic variations, we obtain a speed of 0.3 - 0.5°per second. This corresponds to a speed of 300 - 500 km/s along the magnetopause, assuming that the distance of the magnetopause is 10 R_E from the Earth. Measured speeds in the magnetosheath were approximately half of this value and were in the range of 140 - 190 km/s. More detailed analysis by using high resolution magnetic data is required to resolve this difference. It is interesting to note here that wave forms of magnetic variations around 1330 are very similar to those of the traveling convection vortices (TCV). Typical propagation speeds of TCVs are 0.1° to 0.3°/s amounting to 3 to 10 km/s in the ionosphere or 130 to 400 km/s at the magnetopause (Lühr and Blawart, 1994).

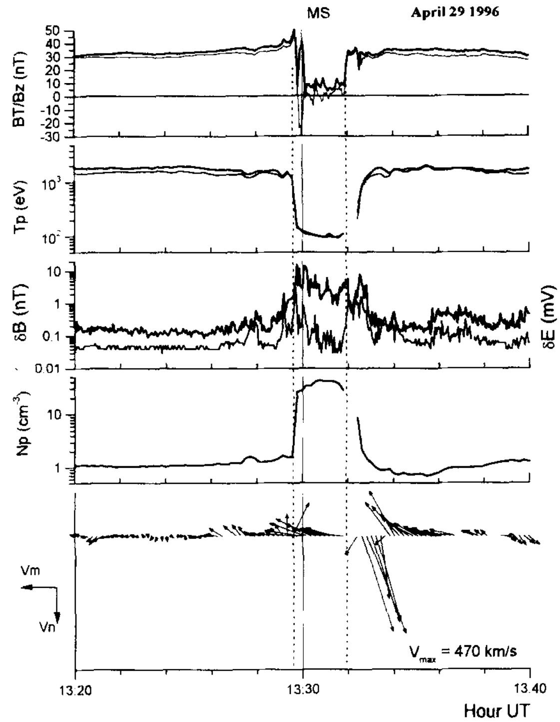


Fig. 9. Plots of flow vectors in the model MN plane, plasma parameters, magnetic field components and variances(δB: thick line, δE: thin line) in the magnetic and electric fields for the period of 1320 - 1340.

We note an interesting feature in Figure 8 (also in Figure 2), i.e., that high speed flows with the sunward component were observed in the magnetosphere after the inbound crossing at 1332. Figure 9 illustrates this feature more clearly. In Figure 9 magnetic and electric field variances in the spin period (3 seconds) are included as a measure for spacecraft locations relative to the magnetopause. Increases in magnetic field variances are usually observed in the magnetosheath and magnetospheric regions near the magnetopause. In the bottom panel which shows flow vectors in the model MN plane, we can see that ion flows are inward before the outbound crossing and that fast flows with large outward and sunward components are observed in the magnetosphere for a period of ~1 minute after the inbound crossing. High-speed flows were observed in regions of high variances in both magnetic and electric fields. The maximum speed of 470 km/s was observed approximately 40 seconds after the crossing. High speed flows were followed by inward flows in the reverse directions and at slower speeds. Directional changes of flow vectors suggest that a flow vortex with a rotation opposite to that expected from the K-H instability is formed in the LLBL after the passage of a transient magnetopause dimple. In cases on February 1 high-speed flows with the sunward component were also observed in the magnetosphere after inbound crossings. We have examined several events similar to the two cases examined in this paper. It was found that high-speed ion flows with the sunward and outward components occur in a few minutes following an inbound magnetopause crossing with a high magnetic shear.

SUMMARY

The survey of Geotail data for January - July, 1995, 1996 and 1997 shows that plasma flow oscillations in the Pc 5 frequency range are fairly common in the dawn sector ($-5 \leq X_{GSM} \leq 5$) from radial distances beyond 9 R_E to the magnetopause. Plasma flow oscillations with amplitudes of larger than 50 km/s were observed in 54 orbits. The amplitudes of these oscillations sometimes exceed 250 km/s. The characteristics of standing oscillations were confirmed by the phase difference of ~ 90° between transverse flows and magnetic field variations. These features were also apparent from the estimation of the Poynting flux as discussed above. Statistical results of Pc 5 ion flow oscillations will be discussed in a separated paper.

We have examined several flow oscillation events in the dawn sector, which are associated with temporal magnetopause crossings, similar to the case analyzed in this report. Most of magnetopause crossings analyzed were cases with high magnetic shears (Bz in the magnetopause was negative in most cases). It is shown for the first time that plasma flow oscillations near the magnetopause are closely coupled with magnetic field variations at latitudes of 70 - 75 degrees on the ground, although the form of flow oscillation is spiky rather than sinusoidal near the magnetopause. We confirmed from spectral analysis that the major spectral peak of ion flow and electric field oscillations agrees with that of magnetic variations on the ground, indicating a close coupling between surface waves on the magnetopause and ground magnetic field oscillations near the polar cap boundary. Outward and sunward flows, whose magnitude are larger than those in the magnetosheath, are observed in the magnetosphere after inbound crossings, while inward and tailward flows with magnitudes comparable to the magnetosheath flow are registered before outbound crossings. These characteristics are not necessarily consistent with the excitation of surface wave by the K-H instability. K-H instability models do not predict ion flows with the sunward component which are higher tailward flows (e.g. Miura, 1995). A high speed flow with the sunward and outward components associated with a pressure pulse is also observed at an isolated and temporal magnetosheath entry with a high magnetic shear.

Analyses of well-documented intervals of plasma and magnetic field data observed on November 6, 1977 by ISEE 1/2 (Sckopke *et al.*, 1981) have led to various interpretations of the nature of the variations near the magnetopause (Paschmann *et al.*, 1982: Sibeck *et al.*, 1990). This event was observed at the northern dawn magnetopause at ~0800 LT when the IMF lay parallel to the ecliptic plane. Models of the process for explaining this event include: temporally modulated bursts of strong diffusion across the magnetopause (Sckopke, *et al.*, 1981), flux transfer events (FFTs) on open field lines (Paschmann *et at.*, 1982), and pressure pulses (Sibeck et al., 1990). The observations were originally interpreted as evidence of the K-H instability at the inner edge of the LLBL. However, Kivelson and Chen (1995) favors the interpretation by Sibeck *et. al.* (1990) which implies that the unstable boundary is the magnetopause itself. In his review Sibeck (1994) has pointed out that some aspects of the transient event on this day were consistent with boundary waves, but others with FTEs. Russell, *et al.* (1997) have recently shown that the magnetopause oscillations dominantly occur on the morning side behind the quasi-parallel shock and foreshock for both northward and southward IMF. They interpret these increased motions as driven by the pressure variations associated with the foreshock or quasi-parallel shock. Localized magnetopause dimples such as shown in Figure 9 occur on the morning side and are rarely observed on the afternoon side. In this respect Geotail observations are consistent with the statistical result by Russell et al., (1997).

The properties of surface waves on the magnetopause during the interval of the northward IMF have been discussed by Chen *et al.* (1993), Kivelson and Chen (1995) and Kokubun *et al.* (1994). It is found that the surface waves have a very non-sinusoidal form with steepened trailing edges. Kivelson and Chen (1995) speculate that the non-sinusoidal wave form is produced by curvature forces exerted by the magnetosheath magnetic field on initially sinusoidal waves. We note from Geotail observations that sunward ion flows in the magnetosphere, induced by the surface waves and a localized propagating dimple on the magnetopause, are dominant in comparison with tailward flows when magnetosheath magnetic fields incline to the south or lie parallel to the ecliptic plane. These observations indicate that the surface waves and induced plasma motions near the magnetopause strongly depend on the directions of magnetosheath magnetic fields which are controlled by the IMF. However, we have not yet separate effects due to the foreshock from those due to variations in the solar wind itself, such as done by Russell, et al. (1997). In order to understand the cause of high speed flows, more detailed analysis will be needed for the solar wind condition.

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