Proc. NIPR Symp. Upper Atmos. Phys., **6**, 103–116, 1993

ULF WAVES AND MAGNETIC FIELD CHARACTERISTICS IN THE POLAR CUSP OBSERVED AT GODHAVN

Tohru SAKURAI[1], Yutaka TONEGAWA[1], Ken-ichi KATO[1], Kazuo MAKITA[2], Masaki EJIRI[3], Hisao YAMAGISHI[3] and Natsuo SATO[3]

[1] *Tokai University, 1117, Kitakaname, Hiratsuka 259-12*
[2] *Takushoku University, 815-1, Tatemachi, Hachioji-shi, Tokyo 193*
[3] *National Institute of Polar Research, 9-10, Kaga 1-chome, Itabashi-ku, Tokyo 173*

Abstract: For the intrusion of the solar wind energy into the magnetosphere the polar cusp has been believed to be the most important region in the magnetosphere. By using magnetometer data obtained in November 1989 at Godhavn (Inv. Lat. = 76°) in Greenland located in the polar cusp the dayside enhancement of ULF wave activity is studied in relation to both variations of the ground magnetic field and the interplanetary magnetic field. The important results are as follows; 1) Godhavn is found to be one of the appropriate stations for studying magnetic field variations and ULF waves in the polar cusp, *i.e.*, the normal-run magnetograms show negative H component excursion during the daytime, sometimes sporadically and in the other times gradually. The ULF waves enhance their activity closely associated with these negative field variations. These field variations might be considered to occur when the station passes under the westward current flowing in the cusp ionosphere. 2) By comparing the ground magnetic activities with the interplanetary magnetic field the ground magnetic activities occur in association with high frequency fluctuations of the IMF. 3) A comparison of spectral power of the ULF waves at Godhavn (cusp latitude) with those at Syowa (auroral latitude) shows more enhanced magnetic power and more resonance-like oscillation of ULF waves at the auroral latitude. Thus, the cusp might be a source region of magnetic energy penetrating into the magnetosphere, and resonant oscillations of ULF waves are clearly observed at the auroral latitude.

1. Introduction

Studies of cusp-related magnetic ULF waves have been started on the basis of the ground observation data since 1970's. During two decades since 1970's the research has been extended to cover all of the frequency range of ULF waves from Pc 1 to Pc 5. The spectral studies have revealed the presence of these ULF waves in the polar cusp. They have been examined mainly for three ranges. The first is the Pc 1 range of higher frequency near 0.5 Hz. This category of the pulsations has been first reported by ROKITYANSKAYA (1969). HEACOCK *et al.* (1970) and HEACOCK (1974) extended their research in this category. HEACOCK and HUNSUCKER (1977) found the impulsive Pi-type pulsations associated with the polar cusp in this category. The second is the middle frequency range from 20 to 50 mHz, which is nominally called Pc 3. This frequency band has been found to be composed of packets in the cusp region, which have been extensively studied in connection with solar wind conditions by many researchers (BOL'SHAKOVA and TROITSKAYA, 1984; WOLFE *et al.*, 1987; ENGEBRETSON *et al.*, 1986, 1987, 1989; YUMOTO, 1986; YUMOTO *et al.*, 1987; MORRIS and COLE, 1987). The third category is the lower frequency band containing the frequency of 1–5 mHz, which has been nominally called Pc 5. The wave forms are, however, different from those observed as typical Pc 5 pulsations in the lower latitudes. Irregular pulses appeared in the polar cusp. These pulsations have been shown by OLSON (1989) in Fig. 2 of his paper, and do not look like a continuous wave train. OLSON has examined these irregular pulses observed at two separate stations of the polar cusp, Cape Parry (Geomag. lat. = 73.82°N, Geomag. long. = 270.49°E) and Sachs Harbor (Geomag. lat. = 75.20°N, Geomag. long. = 266.01°E), and he found that they moved poleward with speed of 1–5 km/s. This speed was slower than that of the auroral luminosity which SANDHOLT *et al.* (1985) attributed to Flux Transfer Events (FTE's). The scale size of the current filament corresponding to these irregular pulses was inferred to be order of 500 km. Spectral structures of the polar cusp pulsations were examined by KATO *et al.* (1985) with the data at Cambridge Bay (Geomag. lat. = 76.77°N, Geomag. long. = 299.13°E) and compared them with those at the auroral latitude station, Fort Smith (Geomag. lat. = 65.01°N, Geomag. long. = 301.02°E). Spectral structures were recognized similarly at both stations. However, the spectral peak showed higher Q value in the auroral zone than in the polar cusp. These results seem to indicate the resonance of the magnetic field line for these ULF waves exhibiting well in the auroral latitude rather than in the polar cusp.

These examinations of ULF waves in the polar cusp described above dealt only with the data obtained by induction magnetometers. In this report we analyze the high resolution data of a fluxgate magnetometer together with an induction magnetometer, in order to examine the property of polar cusp ULF waves with reference to the magnetic field variations, which seem to be important to understand the relationship between the ULF wave activity and the convection motion in the ionosphere. We shall first look for the relation of ULF wave activation to the cusp-related ionospheric convection motion. By analyzing the magnetograms observed at Godhavn (Geomag. lat. = 79.25°N, Geomag. long. = 34.62°E) we found a distinct relation for the ULF wave activation to the magnetic field variations.

2. Magnetic Field Variations in the Polar Cusp

Figure 1 shows a typical magnetic field variation observed at a polar cusp ground station, Godhavn on November 4, 1989, which is plotted with the solid curve. Magnetic local time (MLT) at Godhavn is two hours ahead of the universal time (UT). Characteristic magnetic field variations to be discussed in the present study are those observed when the station moved under the dayside cusp. The quiet time magnetic field variation on November 25, 1989 is presented for comparison with the broken curve. The most distinct field variations of Nov. 4, 1989 are negative excursions of the H component magnetic field, which accompany enhanced activation of ULF waves at Godhavn. Figure 1 shows that a gradual decrease started around 07 UT (05 MLT) and the decrease continued about 11 hours until 18 UT (16 MLT). In this long period the field exhibited intermittent recoveries of a few times with a gradual and a rapid field

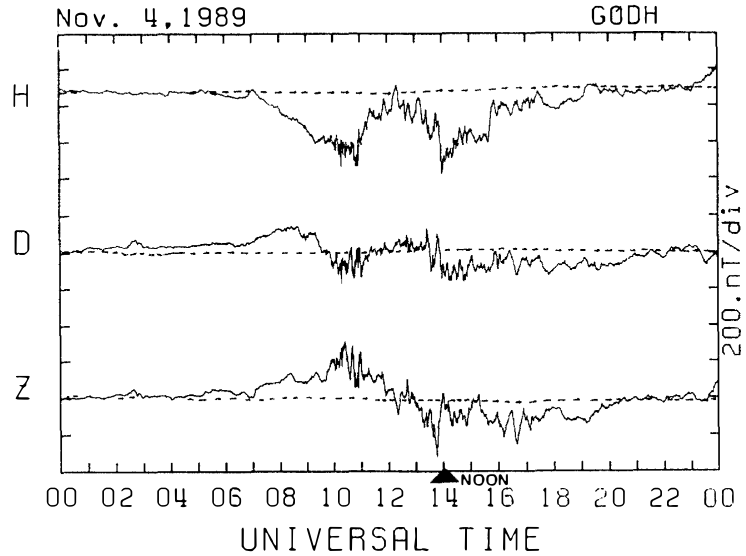

Fig. 1. A typical example of magnetic field variations observed at Godhavn on November 4, 1989 plotted with solid curves. The broken curves are the quiet time magnetic field variations observed on November 25, 1989. Representative negative field variations of H component magnetic field are observed during the daytime. ULF waves bursts are observed closely associated with the negative excursions of the H component magnetic field.

variations. The decreased field recovered gradually around 12 UT (10 MLT) and sustained the quiet-time level until noon; the field decreased sharply again and recovered with a rapid change around 16 UT (14 MLT). After then the magnetic field gradually increased to the midnight value. These H component field variations accompanied the field variations of the D and Z components. The gradual increase of the D component started simultaneously with that of the H component and turned to the negative around 09 UT (07 MLT) with superimposed high frequency variations around 11 UT (09 MLT). A step-like field change occurred around the noon (14 UT) and then the field sustained the positive value until 19 UT (17 MLT). The Z component field started to increase gradually around 07 UT (05 MLT) and attained its peak value around 10 UT (08 MLT). Then the field decreased with step-like field changes until 19 UT (17 MLT). These are the typical magnetic field variations observed only during the daytime at Godhavn. The negative change of the H component (associated usually with positive change of the D and Z components) accompanied the enhancement of high frequency variations, *i.e.*, the ULF waves. Thus, the ULF waves activated intermittently in close association with the characteristic magnetic field variations during the daytime. The enhanced activity of the ULF waves can be also seen in the induction magnetometer data shown in Fig. 2. The lowest three curves show the activity of the VLF waves in the frequency band of 1.6 kHz and 630 Hz, and the CNA activity. Slight decreases of the CNA intensity occurred in association with the activations of the ULF waves. Thus, the CNA observation suggests that the activation of the ULF waves has a close relation with a CNA intensity decrase that will be caused by a particle precipitation in the polar cusp.

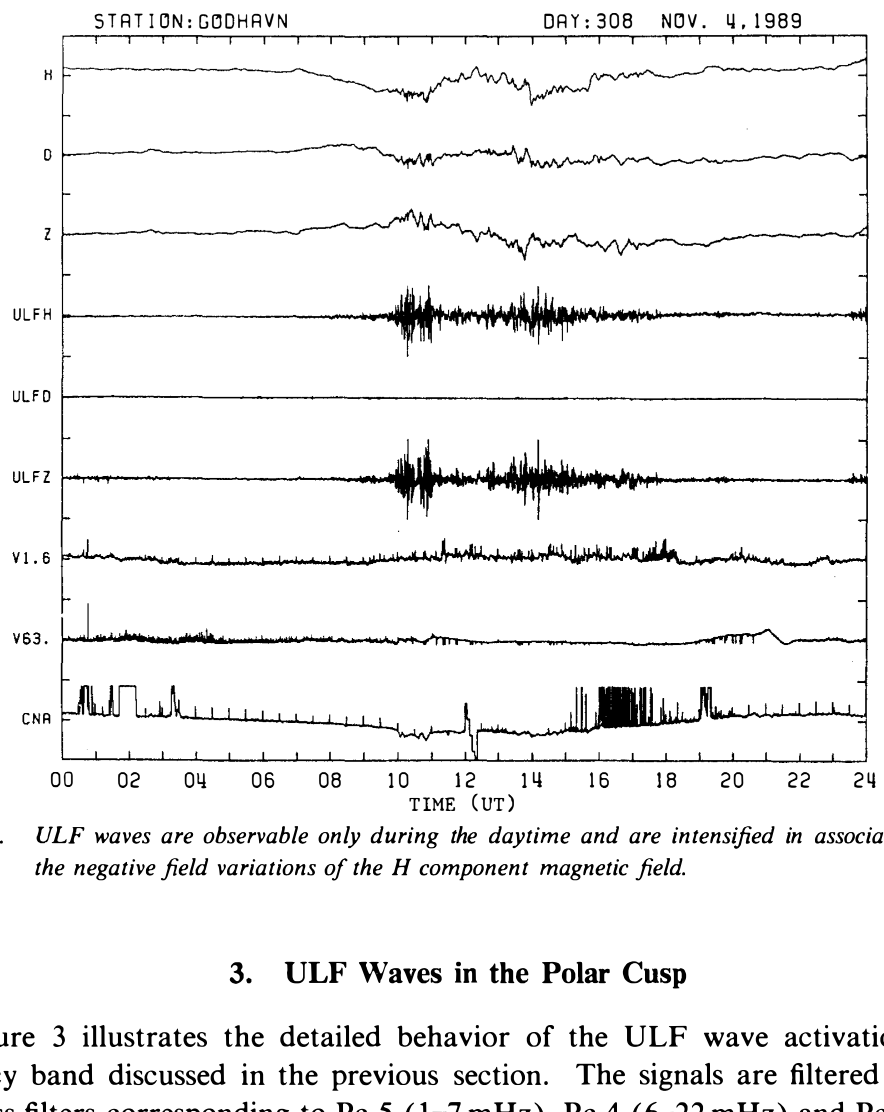

Fig. 2. ULF waves are observable only during the daytime and are intensified in association with the negative field variations of the H component magnetic field.

3. ULF Waves in the Polar Cusp

Figure 3 illustrates the detailed behavior of the ULF wave activation in each frequency band discussed in the previous section. The signals are filtered with three band-pass filters corresponding to Pc 5 (1–7 mHz), Pc 4 (6–22 mHz) and Pc 3 (22–100 mHz), respectively, and they are displayed from the top to the bottom panels. The ULF wave activation occurred in all of the frequency bands simultaneously in the two time intervals of 1000–1100 UT and 1330–1500 UT.

The power spectra for these ULF waves are calculated for the interval of twenty minutes from 1000 to 1020 UT (0800–0820 MLT) and from 1400 to 1420 UT (1200–1220 MLT), as are illustrated in Fig. 4. The upper two panels show the power spectra at Godhavn. The spectra indicate rather a smooth slope against the frequency with some bumps around 5–7 mHz for the former interval, and around 2–3 mHz for the latter interval, respectively. The spectra also show additional bumps in the higher frequency range of 20 mHz and 40–60 mHz, for both intervals. The spectral characteristics in the polar cusp at Godhavn are compared with those in the auroral zone at Syowa (bottom two panels in Fig. 4). The result shows that the spectral feature in the auroral zone is different from that in the polar cusp. The power dominates in the frequency band of Pc 5 at Syowa. The spectra at Syowa do not appear as bumps but as peaks outstanding in the general trend of the spectral slope, *i.e.*, the Q-value seems to be higher at Syowa

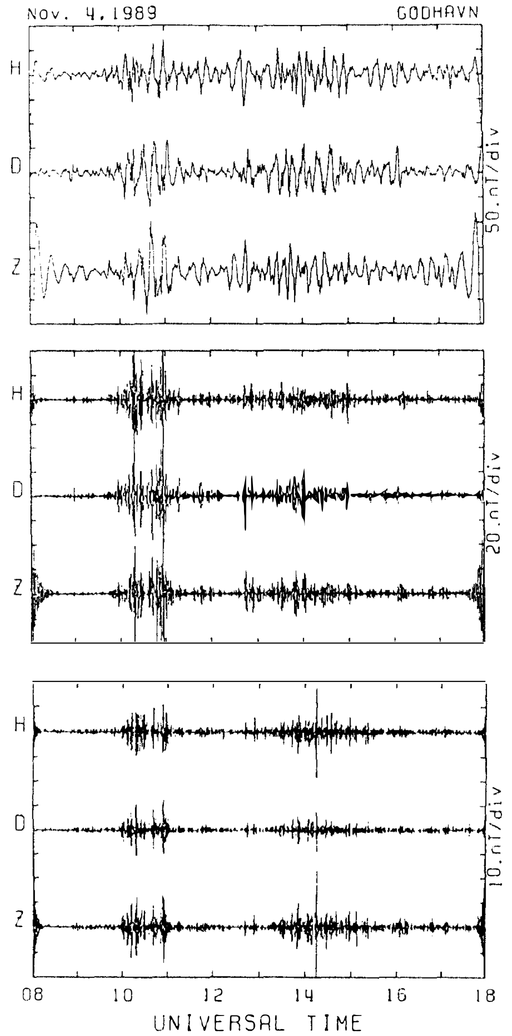

Fig. 3. The bandpass filtered ULF wave activities for the interval from 08 to 18 UT (06 to 16 MLT). The activities from the lower to higher frequency ranges are illustrated from the top to the bottom panels, i.e., top: Pc 5 (1–7 mHz), middle: Pc 4 (6–22 mHz) and bottom: Pc 3 (22–100 mHz), respectively.

rather than at Godhavn. The ellipticity shown in the third panel shows also more linear characteristic at Syowa. From these spectral characteristics it is recognized that the spectra at Syowa appear more resonance characteristics for Pc 5 frequency band rather than at Godhavn. The Pc 3 band shows that the spectral power is larger at Godhavn than at Syowa. These observed facts indicate that Godhavn is located near the source region for ULF wave energy into the magnetosphere.

4. A Typical Pc 5 Event in the Polar Cusp

The upper panel of Fig. 5 shows typical Pc 5 pulsations observed at Godhavn during the daytime from 1400 UT (1200 MLT) to 1700 UT (1500 MLT) of Nov. 6, 1989. The pulsations appear with two or three pulses. The amplitude of the pulses is 50 –100 nT, showing almost the same magnitude in the three components of the magnetic

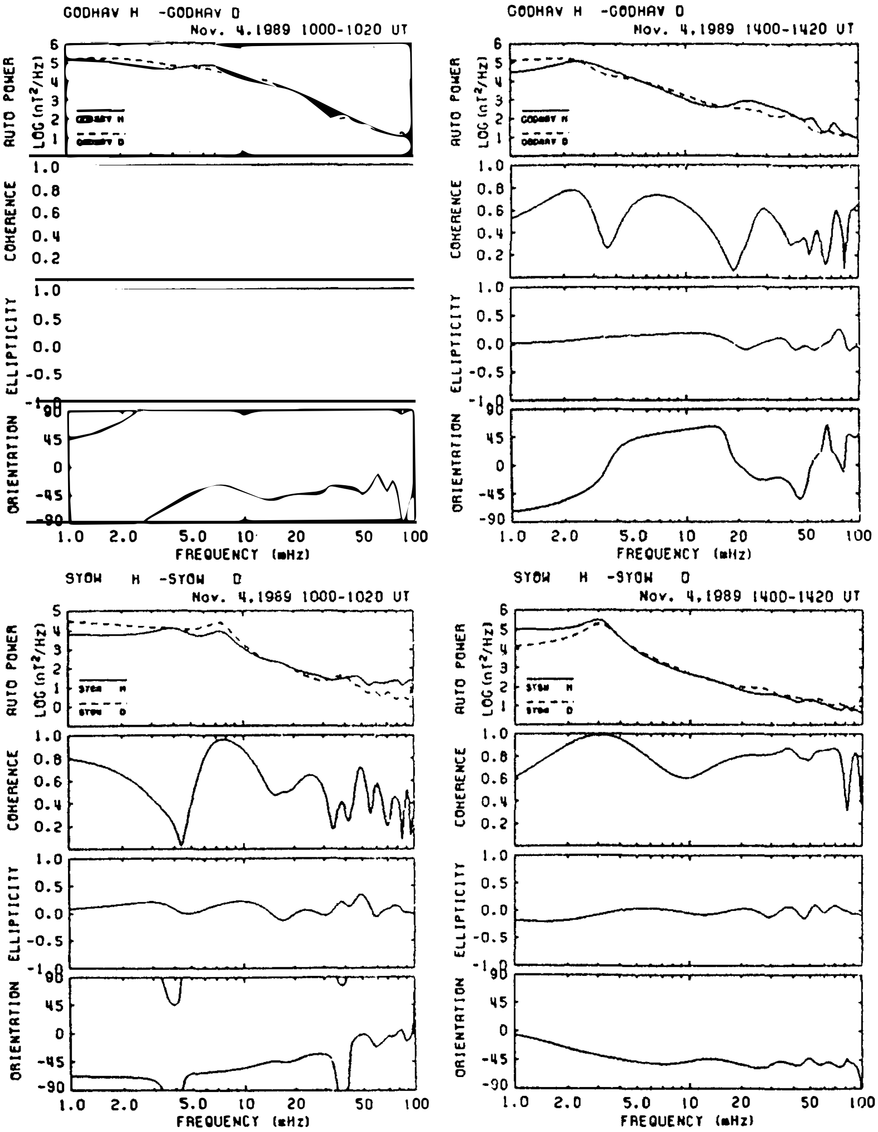

Fig. 4. ULF wave power spectra obtained at Godhavn (upper two panels) and at Syowa Station (lower two panels). Each of 4 panels shows auto spectrum of the H and D components of the magnetic field variations (top diagram), coherency (second diagram), ellipticity (third diagram), and orientation (bottom diagram). The spectra are calculated for the interval of 20 minutes from 1000 to 1020 UT (left panels) and from 1400 to 1420 UT (right panels), respectively. Spectral power corresponding to Pc 5 frequency is dominant at both stations and is enhanced at Syowa Station rather than at Godhavn. Pc 3 and 4 spectra are much more activated at Godhavn than at Syowa Station.

field. On the other hand, the Pc 5 pulsations were observed also at Syowa and at its conjugate station, Husafell, at the same time as shown in the lower panel of Fig. 5. These Pc 5 events observed at Syowa and Husafell are exhibited as typical Pc 5 pulsations observed in the auroral latitudes. The amplitude is dominant in the *H* component with a maximum amplitude of about 150 nT. The power spectra of Fig. 6 show a dominant spectral peak at the frequency of 2–3 mHz in the frequency range of Pc 5. The spectral power and Q-value are larger at Syowa and Husafell than at

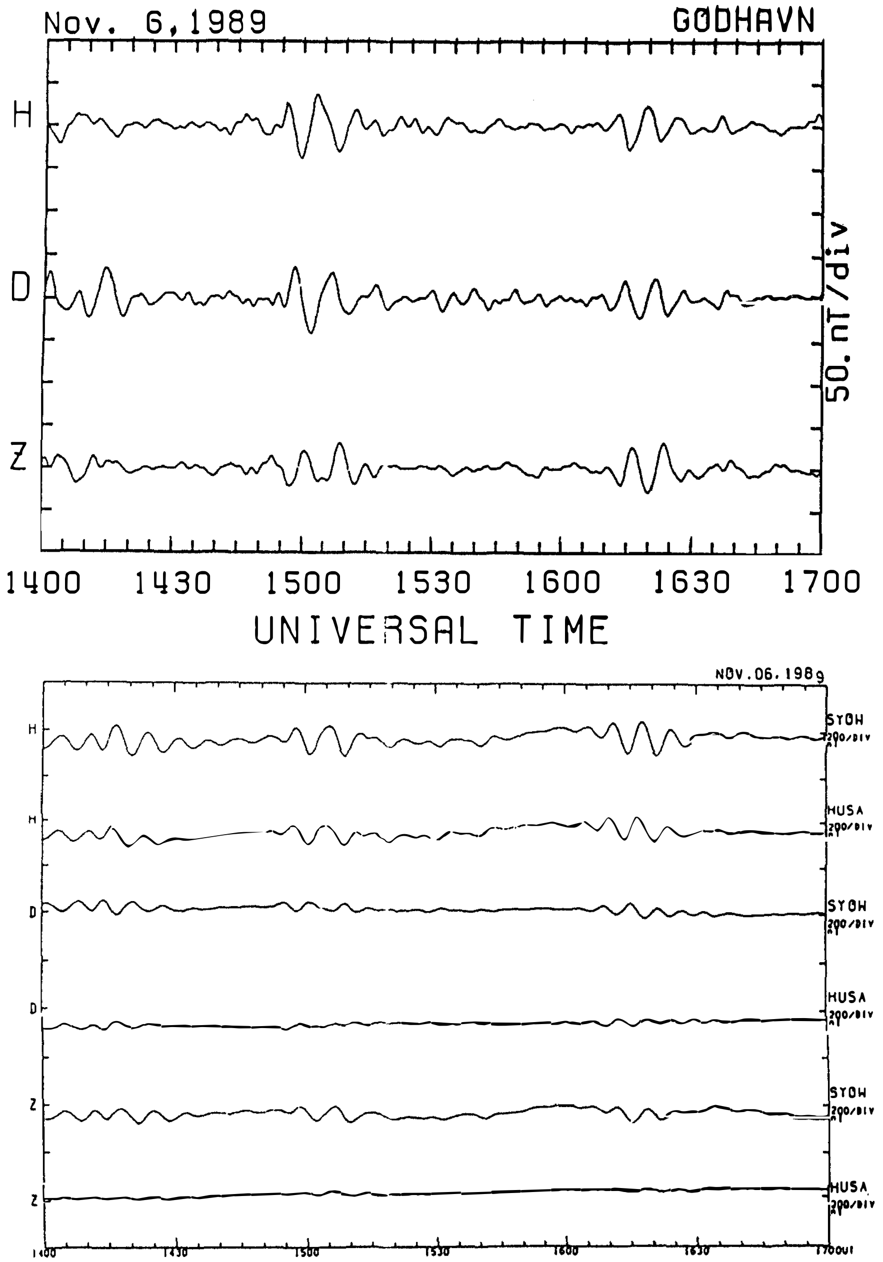

Fig. 5. Typical examples of Pc 5 pulsations observed at both stations, Godhavn (top panel) and Syowa Station (bottom panel). Note the similar activity at both stations and the differrent wave form at each station. The wave form appears to be pulse-like at Godhavn, and the continuous wave train at Syowa Station. Almost the same amplitude activities are observed in the three components of the magnetic field at Godhavn, whereas the activity is dominant only in the H component at Syowa Station.

Godhavn. The ellipticity of this spectral peak is 0.5–0.8 at Godhavn and 0.0–0.2 at Syowa, indicating that the linear polarization occurs at Syowa and Husafell rather than at Dodhavn. The field line resonance for the Pc 5 band tends to appear in the auroral latitudes.

From these examinations the Pc 5 pulsations observed at Godhavn seem to have a

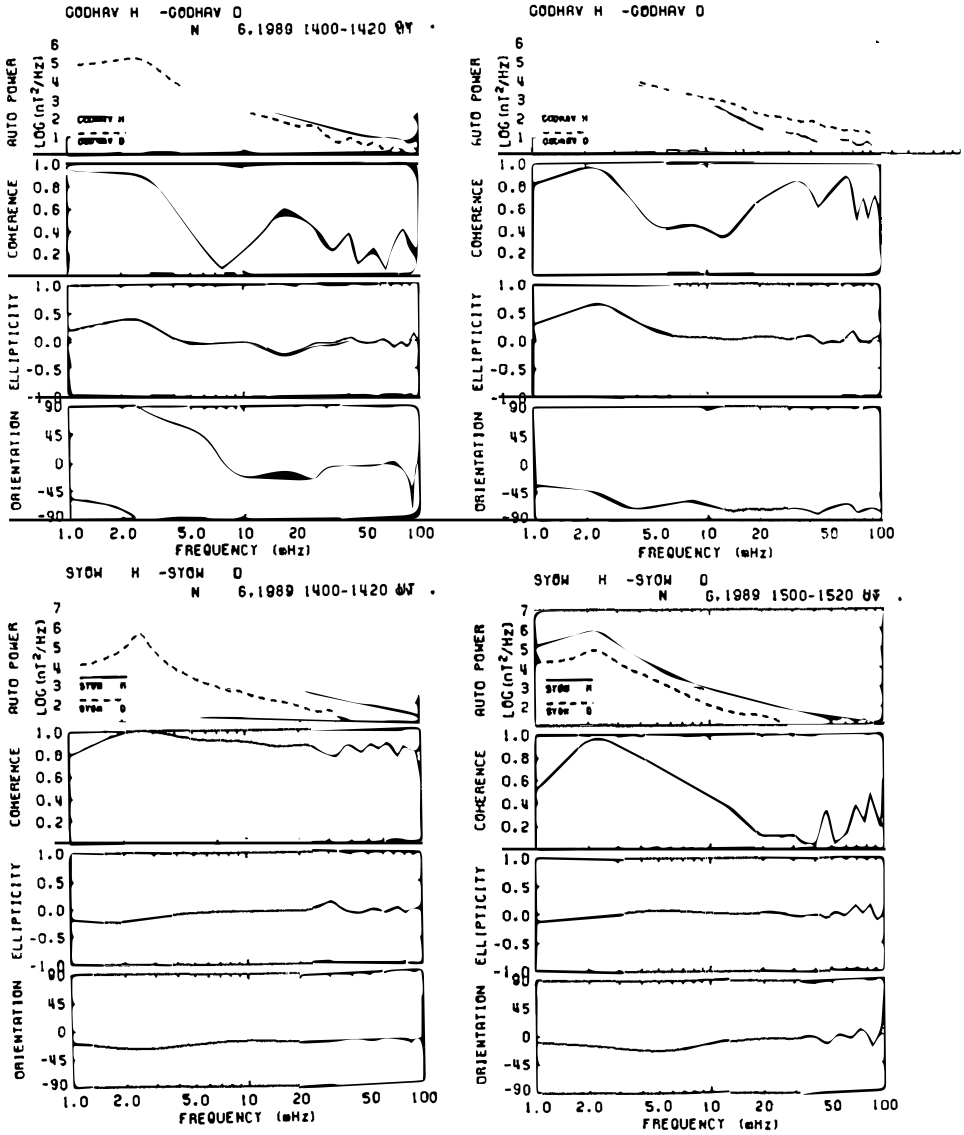

Fig. 6. Format is the same as in Fig. 4 except for the Pc 5 event of Nov. 6, 1989. The spectral power is calculated for the interval from 1400 to 1420 UT (left column) and from 1500 to 1520 UT (right column). The spectral peak corresponding to Pc 5 frequency is clearly recognized in the spectra at Syowa. The ellipticity is rather smaller at Syowa.

signature of source wave, while the pulsations observed in the auroral latitudes show continuous wave train with more enhanced power.

5. Discussion and Conclusions

In the present paper we studied when and how the ULF waves enhanced their activity at the latitude of polar cusp with the data observed at Godhavn located in the cusp latitude. Their occurrence relation to the interplanetary magnetic field variations will be discussed later in this section.

One of the most important results is that the ULF waves activated in close

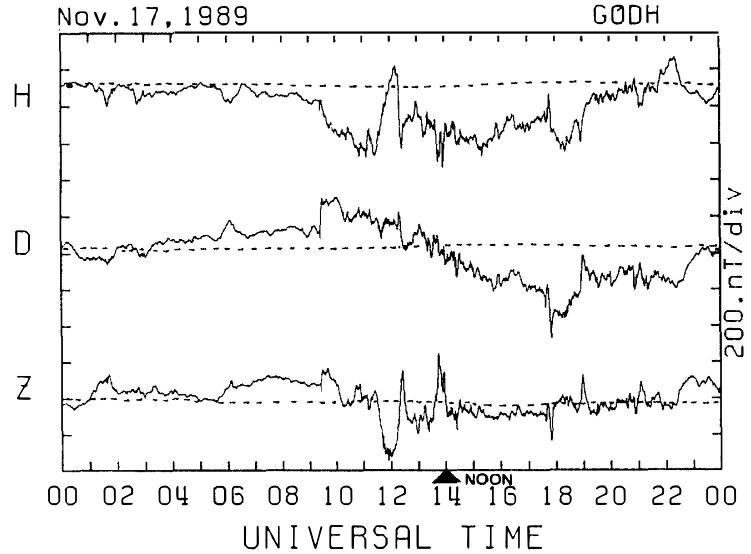

Fig. 7. Another example of the magnetic field variations on November 17, 1989, the most active day ($\Sigma Kp = 31-$) in November 1989. The broken curves are the magnetic field variation of the day most quiet of November 25, 1989 ($\Sigma Kp = 3+$). The similar tendency of the magnetic field variations described in detail for November 4, 1989 in the text is also clearly recognized.

association with the characteristic negative change in the H component magnetic field during the dayside; the simultaneous variations in the D and the Z components are $\Delta D > 0$, $\Delta Z > 0$ in the forenoon, while $\Delta D < 0$, $\Delta Z < 0$ in the afternoon. The magnetogram of Nov. 4, 1989 shown in Fig. 1 is a typical example of these field variations. These characteristic field variations can be confirmed with another example on Nov. 17, 1989, the most active day in November 1989 at Godhavn, shown in Fig. 7. The quiet time level is displayed as a reference by broken curves, which indicate very minor field variation during the day. The negative excursions of the H component magnetic field are clearly recognized in the interval from 09 UT (07 MLT) to 19 UT (17 MLT) in the daytime.

The decrease in the H component during the day is attributable to the intensification of the overhead westward current associated with the convection motion in the ionosphere, when the observing station moves under the throat region, where the convection flow reversals are usually observed (HEELIS, 1979). HEELIS pointed out that the convection flows were frequently observed in the east-west direction near noon. By examining the magnetograms during November and December 1989, the dayside decrease of the H component was recognized as a general event during the magnetically active period.

Another characteristic magnetic field variation is a sudden step-like field change near noon. In a typical example of Nov. 4, 1989 this step-like field change occurred in the three components of the magnetic field near noon. OLSON (1986) has first pointed out such a step-like change, which was observed near noon and only in the D component magnetic field. Such a step-like change was observed also in Fig. 7 around 1230 UT (1030 MLT) and was identified in the three components of the magnetic field. The difference between the OLSON's result and ours seems to be explainable by taking into account of the relative position of the observing station to the convection flow reversal.

The Z component field variation gives also important information on the relative location of the observing station, Godhavn, with respect to the ionospheric current. The positive Z in the forenoon indicates that Godhavn locates at the higher latitude side with respect to the westward current. The reversal of the sign of the Z variation in the afternoon indicates that Godhavn is located on the lower latitude side in the afternoon. Thus the relative location of Godhavn with respect to the westward current changes in the forenoon and in the afternoon.

These characteristic changes of the magnetic field variation are found to occur only during the daytime at Godhavn. This will prove that Godhavn enters the polar cusp during the dayside. Our conclusions are supported with a recent investigation reported by MAKITA *et al.* (1990), in which the cusp-type aurora and its associated particle precipitation were observed during the daytime at Godhavn. Another report which supports our conclusion has been presented by CARBARY and MENG (1986), in which the correlation of the cusp lattitude for the DMSP electron data with the interplanetary magnetic field (IMF) B_z and the AE (12) indices has been statistically examined. According to their analyses of the particle data the magnetic latitude 79° (76° INV) of Godhavn seems to be at the poleward boundary where the cusp-type particle precipitation is observable during the dayside. HEELIS (1979) also pointed out the rotational reversal of the convection flow occurred near noon, where the most dominant component of the flow is in the east-west direction. Therefore, the negative variations of the H component magnetic field are believed to show that Godhavn entered into the cusp (throat) region during the dayside.

These magnetic field variations observed at Godhavn are found to occur in connection with the interplanetary magnetic field (IMF) fluctuations. The ULF waves are also observed closely associated with the negative field changes in the H component magnetic field and with the high frequency fluctuations of the IMF. It is unfortunate that there was no record of the IMF data on Nov. 4, 1989. We examined the IMF data during November 1989 obtained by the IMP J satellite. There is a high correlation between the characteristic magnetic field variations and associated intensification of the ULF wave activity observed at Godhavn during the enhanced fluctuations of the IMF. Good examples showing the relation are illustrated in Figs. 8 and 9. Figure 8 shows high frequency fluctuations occurred during the period from 10 UT to 15 UT of Nov. 7, 1989, which is closely accompanied by the negative field variations of the H component magnetic field and its associated ULF wave activation at the ground station, Godhavn. In Fig. 9 there is no any distinct magnetic field variation and associated ULF activities during the prolonged negative B_z of the IMF without any high frequency fluctuations. This observed fact indicates an important IMF effect on the magnetic field at Godhavn. In this case Godhavn did not yet enter into the cusp region. Therefore, any enhancement of the nagative H component field variation with its associated ULF wave was not observed at Godhavn. Figures 8 and 9 suggest that some high frequency variations of the IMF yield such negative field variations of the H component magnetic field at the cusp latitude. Therefore, it is conceivable that the ULF wave energy might be conveyed into the cusp region through some reconnection mechanisms with the high frequency

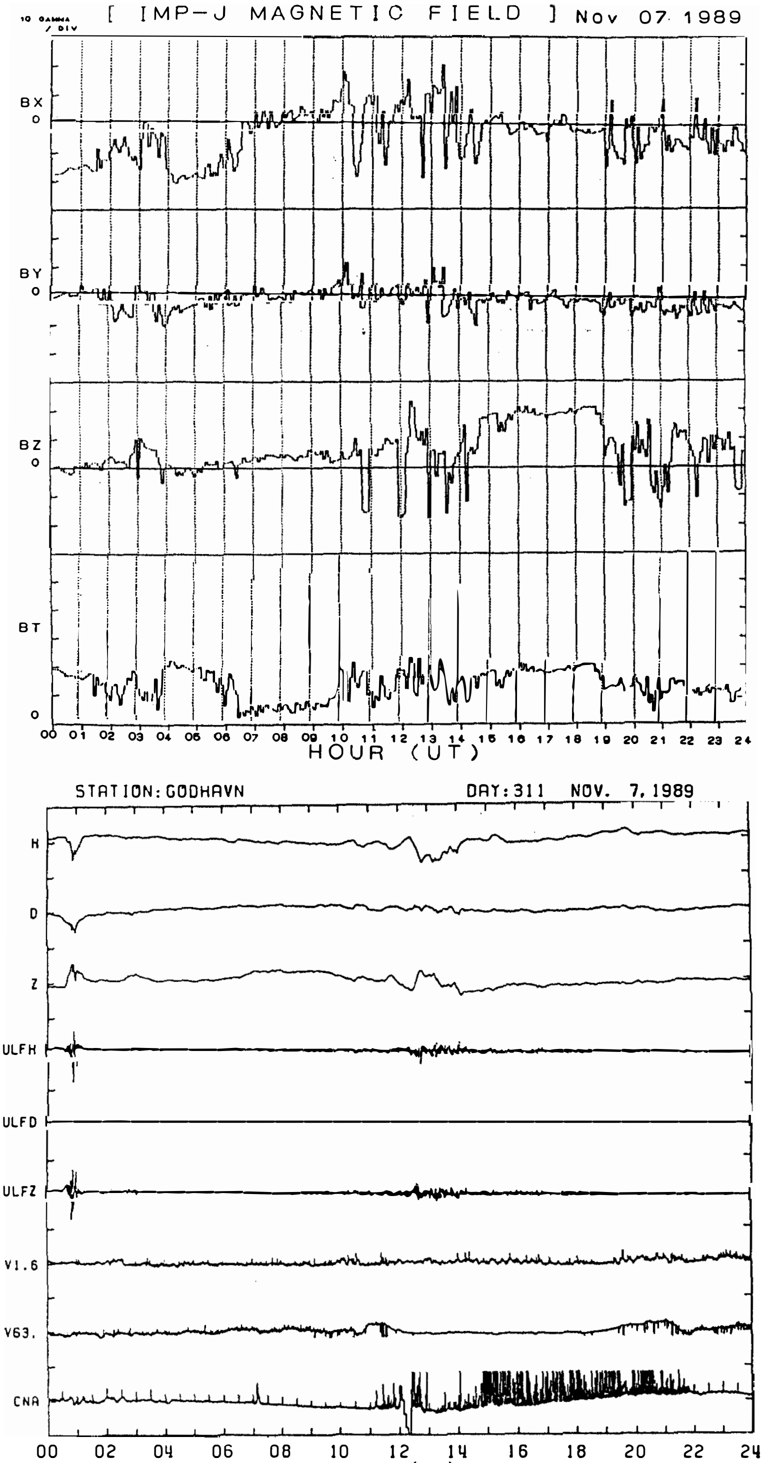

Fig. 8. A close correlation of the occurrence between high frequency fluctuations of the IMF (upper panel) and DC field variations and associated intensification of ULF waves (lower panel), which occurred during the period from 10 UT to 15 UT of November 7, 1989. In the upper panel one minute averaged IMP-J IMF data of B_x, B_y, B_z, and B_{total} are plotted from the top to the bottom curve, respectively. The magnetic field variations (H, D, Z), ULF waves ($\dot{H}$, $\dot{D}$, $\dot{Z}$), VLF 1.6 kHz, 630 Hz and CNA obtained at Godhavn on November 7, 1989 are displayed from the top to the bottom curve in the lower panel.

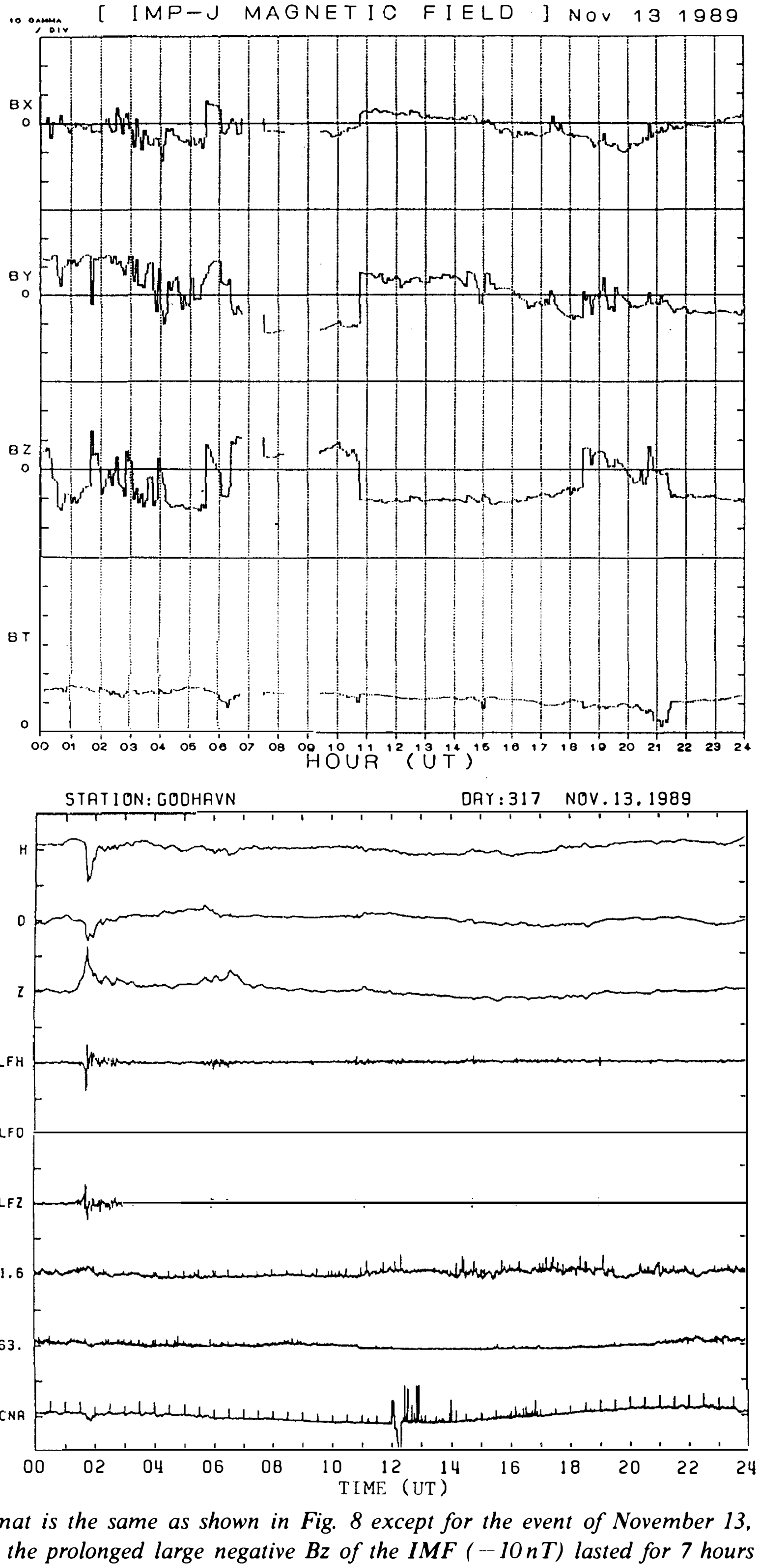

Fig. 9. Format is the same as shown in Fig. 8 except for the event of November 13, 1989. Note that the prolonged large negative Bz of the IMF ($-10\,nT$) lasted for 7 hours from 11 UT to 18 UT gave no effect on the magnetic activity at the cusp latitude ground station, Godhavn. The Kp index during this period was 3+, 5+, and 5+, respectively.

fluctuations of the IMF.

The power spectra in Fig. 4 showed rather bump-like features at Godhavn, in contrast to those observed at the auroral latitude stations, Syowa and Husafell, where the spectra showed dominant peaks in Pc 5 frequency bands. This indicates that resonant waves of the Pc 5 band frequently appeared in the auroral latitude rather than in the cusp latitude. The similar conclusions have been previously obtained by KATO *et al.* (1985).

The important results obtained in this study are summarized as follows;

1) Godhavn is found to be an appropriate stations for studying magnetic field variations and ULF waves of the polar cusp. The characteristic magnetic field variations observed at Godhavn are negative excursions of the H component magnetic field during the daytime, which are believed to be those observed at the poleward boundary of the polar cusp. The H component field variation accompanied the field variations in the other components, *i.e.*, $\Delta D>0$, $\Delta Z>0$ in the forenoon and $\Delta D<0$, $\Delta Z<0$ in the afternoon, respectively. These field variations are considered to be caused by an intense westward current flowing in the cusp ionosphere over the observing station.

2) ULF wave activities at Godhavn are observed during the daytime and are closely related to the magnetic field variations mentioned above. Therefore, the ULF waves are observed only when the station is located beneath the cusp region.

3) By comparing these magnetic activities including ULF waves with the interplanetary magnetic field fluctuations the magnetic field activities observed at Godhavn occur in association with the high frequency fluctuations of the IMF.

4) By comparing the spectral power of the ULF waves at Godhavn with those at Syowa in the auroral latitudes, it is found that the spectra showed more enhanced magnetic power at the auroral latitude, indicating more resonance-like oscillations in the auroral latitudes rather than in the cusp latitudes. Thus, the cusp may be the source region of the energy for magnetic variations in the earth's environmental space.

Acknowledgments

The authors wish to express their sincere thanks to all the members of the wintering party of the 30th Japanese Antarctic Research Expedition for their support of observations at Syowa Station. The magnetometer data obtained at Husafell are due to the conjugate observation campaign party. Thanks are due to T. WATANABE (The Solar Terrestrial Environment Laboratory, Nagoya University) for his great help in referring to the IMP-J magnetometer data, which were provided through the World Data Center A for Rockets and Satellites in NASA. The computer work was carried out with HITAC M-180 computer facilities of the Information Processing Center of the National Institute of Polar Research. One of the authors (T.S) wishes to express his heartfelt thanks to T. TAKAHASHI, and T. ADACHI for their great help in carrying out the data analyses by using the SX-1 computer of the Tokai University.

References

BOL'SHAKOVA, O. V. and TROITSKAYA, V. A. (1984): The relation of the high-latitude maximum of Pc 3 intensity to the dayside cusp. Geomagn. Aeron., **24**, 633–635.

CARBARY, J. F. and MENG, C.-I. (1986): Correlation of cusp latitude with B_z and AE (12) using nearly one year's data. J. Geophys. Res., **91**, 10047–10054.

ENGEBRETSON, M. J., ZANETTI, L. J., ARNOLDY, T. A. and CAHILL, L. J., JR. (1986): Pc 3 pulsations observed near south polar cusp. J. Geophys. Res., **91**, 8909–8918.

ENGEBRETSON, M. J., ZANETTI, L. J., POTEMRA, T. A., BAUMJOHANN, W., LUHR, H. and ACUNA, M. H. (1987): Simultaneous observation of Pc 3–4 pulsations in the solar wind and in the earth's magnetosphere. J. Geophys. Res., **92**, 10053–10062.

ENGEBRETSON, M. J., ANDERSON, B. T., CAHILL, L. J., JR., ARNOLDY, R. L., NEWELL, P. T., MENG, C.-I., LANZEROTTI, L. J. and POTEMRA, T. A. (1989): A multipoint case study of high-latitude daytime ULF pulsations. J. Geophys. Res., **94**, 17143–17160.

HFACOCK, R. R. (1974): Midday Pc 1–2 pulsations observed at a subcleft location. J. Geophys. Res., **79**, 4239–4245.

HEACOCK, R. R. and HUNSUCKER, R. D. (1977): Pi 1–2 magnetic field pulsations on dayside cleft field lines. Nature, **269**, 313–314.

HEACOCK, R. R., HESSLER, V. J. and OLESEN, J. K. (1970): The 2–0.1 Hz polar cap micropulsation activity. J. Atmos. Terr. Phys., **32**, 129–138.

HEELIS, R. A. (1979): Ionospheric convection at high latitudes. Proceedings of Magnetospheric Boundary Layers Conference, Alpbach, 11–15, June 1979, 175–181.

KATO, Y., TONEGAWA, Y. and TOMOMURA, K. (1985): Dynamic spectral study of Pc 3–5 magnetic pulsations observed in the north polar cusp region. Mem. Natl Inst. Polar Res., Spec. Issue, **38**, 58–63.

MAKITA, K., YAMAGISHI, H., EJIRI, M., HIRASAWA, T. and LASSEN, K. (1990): High latitude aurora observed at Godhavn. Proc. NIPR Symp. Upper Atmos. Phys., **3**, 1–11.

MORRIS, R. J. and COLE, K. D. (1987): Pc 3 magnetic pulsations at Davis, Antactica. Planet. Space Sci., **35**, 1437–1447.

OLSON, J. V. (1986): ULF signatures of the polar cusp. J. Geophys. Res., **91**, 10055–10062.

OLSON, J. V. (1989): Poleward propagation of pulsations near the cusp. Planet. Space Sci., **37**, 775–781.

ROKITYANSKAYA, D. A. (1969): Micropulsations with periods of 4–12 seconds. Geomagn. Aeron., **9**, 918–920.

SANDHOLT, P. E., EGELAND, A., HOLTLET, J. A., LYBEKK, B., SVENES, K., ASHEIM, S. and DEEHR, C. S. (1985): Large- and small-scale dynamics of the polar cusp. J. Geophys. Res., **90**, 4407–4414.

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

YUMOTO, K., WOLFE, A., TERASAWA, T., KAMEN, E. L. and LANZEROTTI, L. J. (1987): Dependence of Pc 3 magnetic energy spectra at south pole on upstream solar wind parameters. J. Geophys. Res., **92**, 12437–12442.

WOLFE, A., KAMEN, E., LANZEROTTI, L. J., MACLENNAN, C. G., BAMBER, J. F. and VENKATESAN, D. (1987): ULF geomagnetic power at cusp latitudes in response to upstream solar wind conditions. J. Geophys. Res., **92**, 168–174.

(Received September 11, 1992; Revised manuscript received September 21, 1992)