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ULF Pc5-6 magnetic activity in the polar cap as observed along a geomagnetic meridian in Antarctica

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[1] Latitudinal and diurnal distributions of spectral power and spatial coherency parameters of the geomagnetic variations in the Pc5-6 (1–6 mHz) frequency range are analyzed using data of magnetometer stations in Antarctica. The available stations give the possibility to form a latitude chain along the geomagnetic meridian 40°E stretching from magnetic latitude 69°S to 86°S. Long-period ULF activity at polar cap latitudes is characterized by lower amplitudes and wider spectra with lower central frequencies as compared with typical auroral Pc5 pulsations. The meridional distribution of average Pc5-6 spectral power is nonmonotonic and has a minimum near 80°. In general, the low-frequency broadband ULF activities in the polar cap and at auroral latitudes seem to be decoupled. This long-period ULF activity in the polar cap could be an image of wave activity in the tail lobes or the manifestation of turbulent component of the ionospheric convection at very high latitudes, but this requires further investigation. *INDEX TERMS:* 2744 Magnetospheric Physics: Magnetotail; 2752 Magnetospheric Physics: MHD waves and instabilities; 2776 Magnetospheric Physics: Polar cap phenomena; *KEYWORDS:* Geomagnetic pulsations, polar cap, MHD, magnetotail

1. Introduction

[2] The increase of interest in geomagnetic disturbances at very high latitudes has been stimulated by observations on spacecraft that cover the dayside magnetopause and from satellites in the magnetotail. The latter have revealed a realm of dynamical phenomena of different spatiotemporal scales in the geomagnetic tail. These include impulsive acceleration processes in the plasmasheet, multiple sporadic ion beams, bursty earthward flows, and flapping of the neutral sheet [*Angelopoulos et al.*, 1992]. Flapping motions of the magnetotail with an amplitude of several Re were studied by *Toichi and Miyazaki* [1976] by analyzing the observations made by Explorer-33, -34, -35 in the near and distant tail regions. Flapping modes with periods of ~200 and 500 s tend to be observed in early phases of the magnetospheric substorm. In some cases a good correspondence with the long period Pc5 micropulsations in the polar cap region was observed. In the tail lobes, the AKEBONO satellite observed wave-like fluctuations of magnetic and electric fields with apparent frequencies between 2 and 8 mHz [*Fukunishi et al.*, 1993], though spacecraft observations commonly indicate that magnetic variations in the tail lobes are less intensive than those in the plasma sheet [*Chen and Kivelson*, 1991]. Quasi-periodic sequence of irregular pulses with typical periods within the Pc5 frequency band (1.7–6.7 mHz) have been reported from IMP-8 at the dawn flank of the plasma sheet and by ISEE-1 near the plasma sheet boundary layer near midnight [*Sarafopoulos*, 1994]. The authors concluded that these pulsations had a global character occurring simultaneously throughout much of the nightside magnetosphere. *Bauer et al.* [1995] suggested that low-frequency (0.15–1 mHz) magnetic fluctuations with amplitudes about few nT observed by AMPTE/IRM in the plasma sheet reflect substorm dynamics and flapping motion of the tail.

[3] Information about nonsteady plasma processes can be transmitted by MHD waves to the ground along magnetic field lines. *Allan and Wright* [2000] analyzed numerically excitation and propagation of the coupled MHD modes in the magnetotail waveguide and showed that an Alfven wave could reach the near-Earth magnetosphere. Thus the dynamics of the magnetotail can be revealed in ground signals inside the polar cap and at the poleward boundary of the nightside auroral oval. However, the actuality of such information transfer has not been firmly established yet, despite theoretical predictions on the feasibility of the coupling between plasma sheet and poleward auroral boundary [*Liu et al.*, 1995; *Allan and Wright*, 1998, 2000].

[4] Ultra-low frequency (ULF) wave studies of high-latitude observations on the dayside have been concentrated to date on investigation of possible specific signatures that are related to the magnetosphere boundary (cusp, LLBL, mantle) processes [*Bolshakova et al.*, 1988; *Engebretson et al.*, 1995; *McHarg et al.*, 1995; *Lanzerotti et al.*, 1999]. Only a few studies have reported nightside ULF wave events at very high latitudes. *Weatherwax et al.* [1997] reported cosmic radio noise absorption (riometer) events

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Table 1. Meridional Antarctic Profile of Stations Along the Longitude 40°E

Station	Code	Geographic Latitude	Geographic Longitude	Geomagnetic Latitude	Geomagnetic Longitude	Midnight in UT
AGO P4	P4	−82.01	96.76	−80.04	41.83	0159
AGO P5	P5	−77.24	123.52	−86.76	29.65	0252
BAS A81	A81	−81.50	3.00	−68.68	36.21	0218
Vostok	VOS	−78.46	106.82	−83.52	54.78	0102

over 5 hours of LT at magnetic latitude higher than 80° in the recovery phase of a substorm (during high solar wind velocity conditions). ULF modulation (1–4 mHz) of the absorption, and hence of the causative fluxes of precipitating energetic electrons, was often observed together with concurrent Pc5 magnetic variations. *Wolfe et al.* [1996] reported pulsations in the Pc5 range (~2 mHz) with comparable amplitudes (~ 10–15 nT) at stations azimuthally separated by 75° in MLT along the geomagnetic latitude 80°. These types of Pc5-like events were observed at all local times. Simultaneous measurements by the low altitude SAMPEX satellite indicated that the ground-based stations were located on open field lines during the events. *Papitashvili et al.* [1996] reported several low frequency (~1–2 mHz) and low magnitude (~3–5 nT) magnetic pulsations at Vostok station (−83.6° CGM) which appeared to be associated with northward IMF and were observed during entire days but in the winter polar cap only.

[5] The only statistical study of low frequency (Pc5 band) pulsations at Antarctic stations along the 80° south geomagnetic latitude was performed by *Ballatore et al.* [1998]. They showed the occurrence of dominant peaks in the diurnal distribution of ULF intensity on the dayside, evidently related to the dayside cusp, and on the nightside, attributed to the extension of substorms to this latitude.

[6] With the deployment of arrays of stations across the Antarctic plateau, incorporating auroral, riometer and magnetic instruments, a new perspective on high latitude auroral dynamics is emerging. In this paper, the basic statistical features of ULF-band noise/waves are studied at the poleward auroral boundary and in the polar cap. The focus is on the night hours.

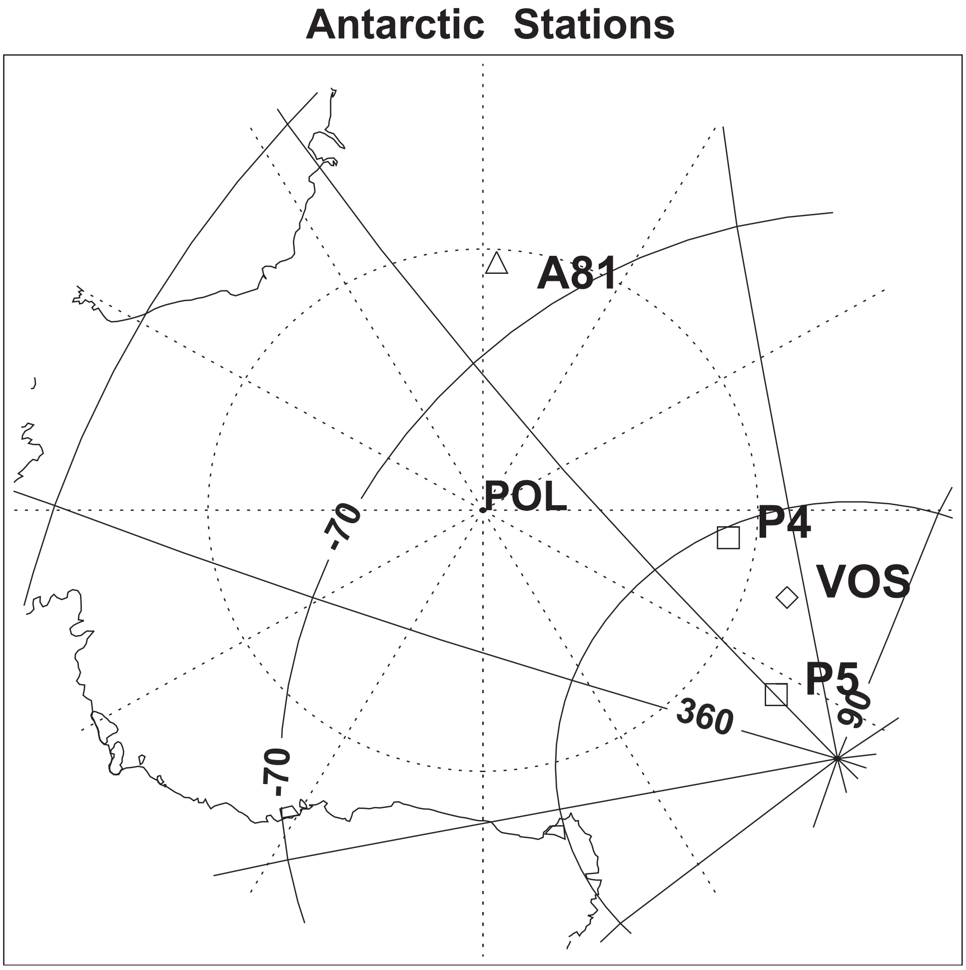

Figure 1. The map illustrating the position of the Antarctic stations. Both geographic (dashed lines) and geomagnetic (solid lines) coordinates are indicated.

2. Experimental Facilities

[7] Geomagnetic coordinates determined using only the main geomagnetic field do not describe well the actual geometry of geomagnetic field lines at very high latitudes. Nevertheless, these coordinates are used to organize the data from an Antarctic array of stations. The British Antarctic Station A81, the US Automatic Geophysical Observatories P4, and P5, and the US-Russia magnetic station Vostok (VOS) form a trans-Antarctic meridional profile along geomagnetic longitude ~40°E (magnetic local midnight ~0200 UT). The geographic and geomagnetic coordinates of the stations and a map illustrating their locations are shown in Table 1 and in Figure 1, respectively. The longitudinal structure of long-period magnetic activity in the polar cap region is considered in a work in progress. Each of the observatories is equipped with flux-gate magnetometers with flat frequency response and provide measurements of local geomagnetic H, D, and Z components.

3. Data Processing and Analysis Technique

[8] Visual inspection of the several data sets shows that quasi-periodic magnetic field disturbances at the polar cap latitudes often have somewhat lower frequencies than the Pc5 band (1.7–6.7 mHz). Therefore, in the analysis herein, the nominal Pc5-6/Pi3 frequency range (1–6 mHz or 17.0–2.5 min periods) is used. Data from the different stations have different sampling rates: 10 s at VOS and 1 s at A81, P4, and P5. Records from all stations have been decimated to the common 20 s sampling period.

[9] Spectral power has been estimated with the Blackman-Tukey method with a Kaiser-Bessel tapering window. The other estimated spectral parameters are as follows: (1) the average spectral slope α calculated as a best linear fit to the spectral power in logarithmic scale and (2) the dispersion σ_α of this approximation. A small dispersion, $\sigma_\alpha \to 0$, corresponds to the colored noise. Large values of σ_α indicate the occurrence of enhanced spectral power at some frequencies and enables the identification of quasi-monochromatic signals. Hereafter, the parameter σ_α is called the "S/N-index" (signal-noise index; it should not be confused with the common S/N ratio). (3) Another spectral parameter is the spectral coherence $\gamma(f)$ between observatory pairs, which is used to estimate a typical spatial scale of the observed disturbances.

3.1. Individual Events: Spatial Structure Along Meridian

[10] According to the spectral analysis, the observed high latitude oscillations can be categorized into two groups: (1) band-limited noise with a noticeable central frequency and (2) broadband noise with a power law ($\propto f^{-\alpha}$) spectrum (colored noise).

3.1.1. Band-limited noise

[11] An example from 17 February 1998 (DOY = 048) 2140–2400 UT of quasi-periodic oscillations, or band-limited noise, in the premidnight hours is considered. Plots of the location of the auroral oval from the low altitude DMSP satellites, generated using the closest satellite tracks, show that for this interval the poleward auroral boundary at nighttime hours is around 69°S geomagnetic latitude. Therefore station A81 is located near the poleward boundary of the auroral oval, whereas the higher latitude stations P5, VOS, P4 are in the polar cap.

[12] The band filtered (0.5–5 mHz) magnetograms of the two horizontal components from the four stations are shown in Figure 2 in the left set of panels; the amplitude spectra are given in the right set of panels. A visual inspection of the filtered magnetograms shows a close similarity between the variations at the high-latitude ($\Phi >$ 80°) stations (P5, VOS, P4), and these are distinct from those recorded at the A81 (Φ = 69°) station. In the H component power spectra, there is a spectral maximum at $f \simeq 1.5$ mHz at the high latitude segment of the profile (P5, VOS, P4), whereas in the D component a common maximum is at $f \simeq 1.0$ mHz.

[13] The spectral power is much higher at A81 than at the other stations, and the spectral features are different. The "polarization" at A81 also differs from the polarization at the higher latitude stations: at A81 the D component power is ~2 times the power in the H component, while the powers in the components are nearly equal at each of the high latitude stations.

[14] The meridional distribution of the amplitude in the signal fluctuations is nonmonotonic (Figure 2): peak-to-peak variation is maximal, ~100 nT, at $\Phi \simeq 69$°S (A81), it has a minimum, ~20 nT, at geomagnetic latitude ~80°–83° (P4, VOS), and then grows to ~30 nT in the deep polar cap (P5).

[15] The spectral coherence between different pairs of stations (Figure 3) confirms a seeming decoupling of magnetic variations at polar cap and auroral latitudes. The coherence in the bandwidth around spectral power peak ($f \leq$ 1.7 mHz) is high, $\gamma \simeq 0.7$–0.9, for both components between high latitude pairs of observatories (P5-VOS, and VOS-P4), but it drops substantially for P4-A81 pair ($\gamma <$ 0.3).

3.1.2. Broadband noise

[16] An event recorded on 23 February 1998 (DOY = 054) is a good example of colored-noise type variations. During the time interval 2–4 UT (0–2 MLT), nonperiodic, but almost identical, oscillations are recorded in both H and D components in the high- latitude segment of the profile (Figure 4, left) with peak-to-peak amplitudes ~5–10 nT in both components. At the A81 station the oscillations have a larger amplitude, ~50 nT and show little resemblance to the variations at higher latitudes. No frequencies are dominant in the amplitude spectra (Figure 4, right).

[17] Although no spectral maxima is evident for this event, both visual inspection of the magnetograms and the analysis of spectral coherence (not shown) indicate that the variations at P5, VOS, and P4 are closely correlated ($\gamma \geq$ 0.8), whereas for the P4-A81 pair the coherence is low $\gamma \simeq$ 0.2–0.3. Thus although the spectral features of these two events are different, they demonstrate qualitatively similar meridional distributions of spectral power and coherence: low amplitude and spatially coherent variations at polar cap stations seem to be independent from those at the auroral station.

3.2. Meridional Distribution of the Pc5-6 Characteristics: Statistical Analysis

[18] Since there are no dramatic differences between the two groups of Pc5-6 variations, in the statistical analysis

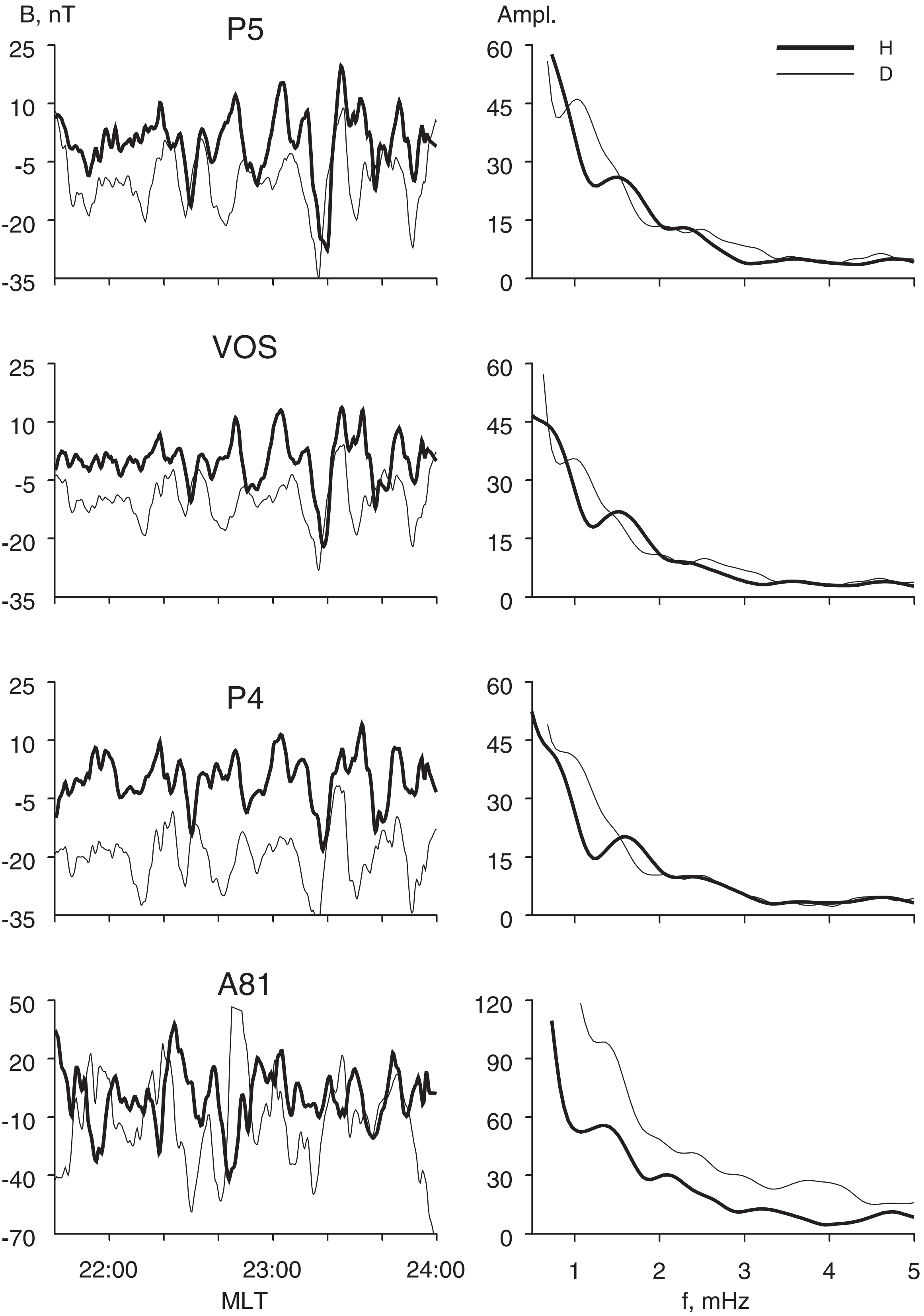

Figure 2. An example of the quasi-periodic oscillations observed on DOY = 048, 2140–2400 UT, along geomagnetic meridian 40°. The band filtered (0.5–5 mHz) magnetograms are shown on the left and the amplitude spectra (linear scale) on the right for both horizontal components (the vertical scale for A81 is different).

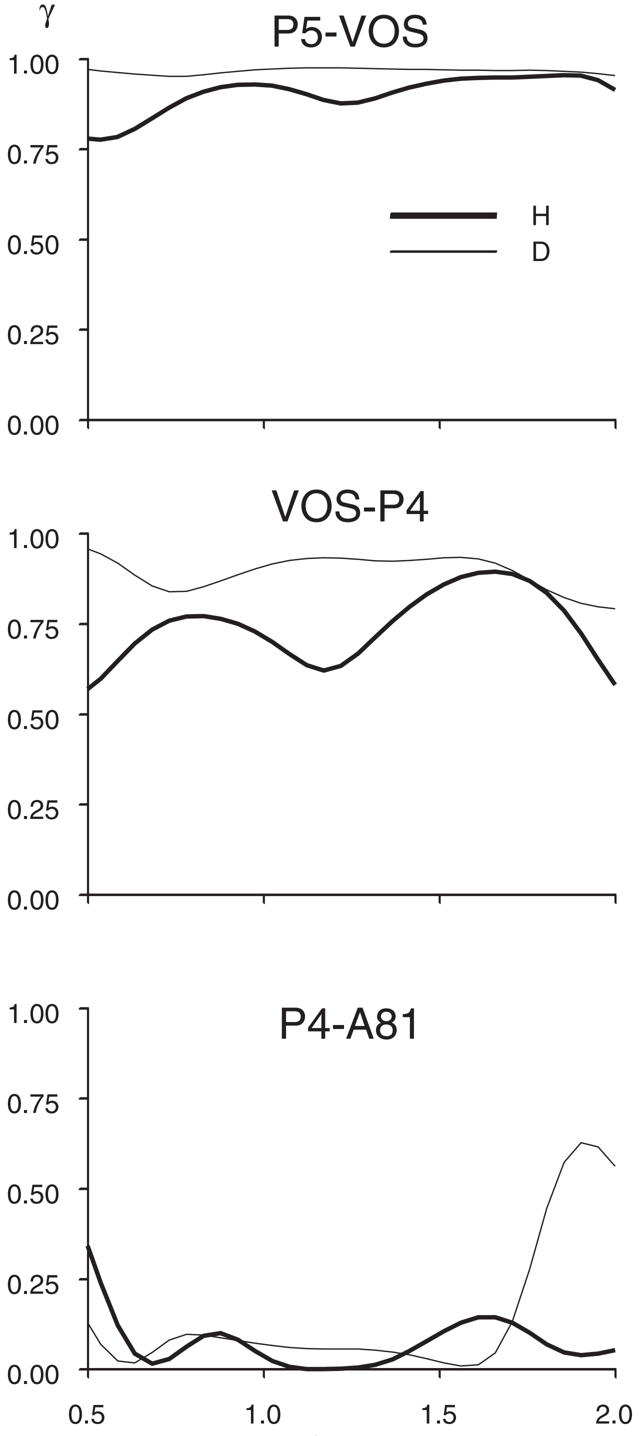

Figure 3. The spectral coherence γ between stations along the meridian (P5-VOS, VOS-P4, P4-A81) for the event on DOY = 048, 2140–2400 UT, shown in Figure 2.

we have made no separation between the band-limited and broadband variations. For the analysis we have chosen two months in 1998, February and March. In total, 37 days with good data coverage at all local times and at all stations during the two month period have been used for the statistical analysis. Diurnal variation of spectral parameters have been calculated in a moving time window with length of 512 samples, i.e., 10,240 s $\simeq$ 2 hours 50 min.

3.2.1. Diurnal variation of ULF intensity and coherence at different latitudes

[19] The diurnal variations of the average pulsation power (log power) for the two horizontal components from stations along meridian 40° are shown in Figure 5. At A81 the MLT dependence of the Pc5-6 amplitude is as expected for auroral latitudes: it has a broad maximum in the morning (~6–10 LT) hours, related to typical Pc5 activity [e.g., *Gupta*, 1973], and a maximum on the nightside, probably caused by a substorm activity. At P4 the nighttime maximum becomes weaker, and a near noon maximum emerges, likely associated with the ULF activity in the cusp region [see e.g., *Engebretson et al.*, 1995; *Lanzerotti et al.*, 1999].

[20] Two stations (VOS, P5) deep in the polar cap are characterized by a similar MLT dependence with two maxima: in the local morning and early afternoon for the H component, and postmidnight and prenoon for the D component.

[21] The diurnal variations of the average coherence in the Pc5-6 band for the two horizontal components are shown in Figure 6. High values of the coherence are found for the P5-VOS and VOS-P4 station pairs, especially at nighttime hours (~0.6–0.7), while for the P4-A81 pair the coherence is low (~0.1) at all local times. A weak enhancement of coherence at near-noon hours is probably associated with cusp-related Pc5 activity. The coherence between pulsations from polar cap station pairs is highest at night hours, whereas it decreases in the day time, especially at the lower latitude pair, VOS-P4.

[22] Thus the examination of the diurnal variation of Pc5-6 power and coherence show that at very high latitudes there exists a specific global ULF variation at magnetic local night hours. In the following we concentrate on the study of the meridional distribution of the average spectral parameters for local night hours (0100–0400 UT).

3.2.2. Spectral power meridional distribution

[23] Time-averaged, night time (0100–0400 UT) power spectral density at different latitudes is given in Figure 7 as log–log plots (top) for H (left) and D (right) components. Standard errors of mean values are less then 5% at 1 mHz and 10% at 6 mHz. Figure 7 (middle) shows the latitudinal distribution of the logarithm of the spectral power, log (*P*), integrated in the band 1–6 mHz. In Figure 7 (bottom), the variations of the spectral slope α (solid line) and S/N spectral index (dashed line) along the meridian are shown. Standard errors for the averaged spectral slope do not exceed 7% for all the stations; thus the differences between estimated parameters at different stations are statistically meaningful.

[24] At all stations the average spectra have colored-noise forms over the frequency band 1–6 mHz. The average spectral slope (solid line in Figure 7, bottom) weakly depends on latitude, increasing from $\alpha \sim 2.7$ at A81 to $\alpha \simeq 3.3$ at P5 and VOS. This indicates a relative dominance of shorter period, about few minutes, fluctuations (probably, Pc5 and Pi2) at auroral latitudes. The spectral slopes are consistent with the values found in a previous statistical analysis at the Antarctic station TNB ($\Phi \simeq -80°$) by *Lepidi et al.* [1996].

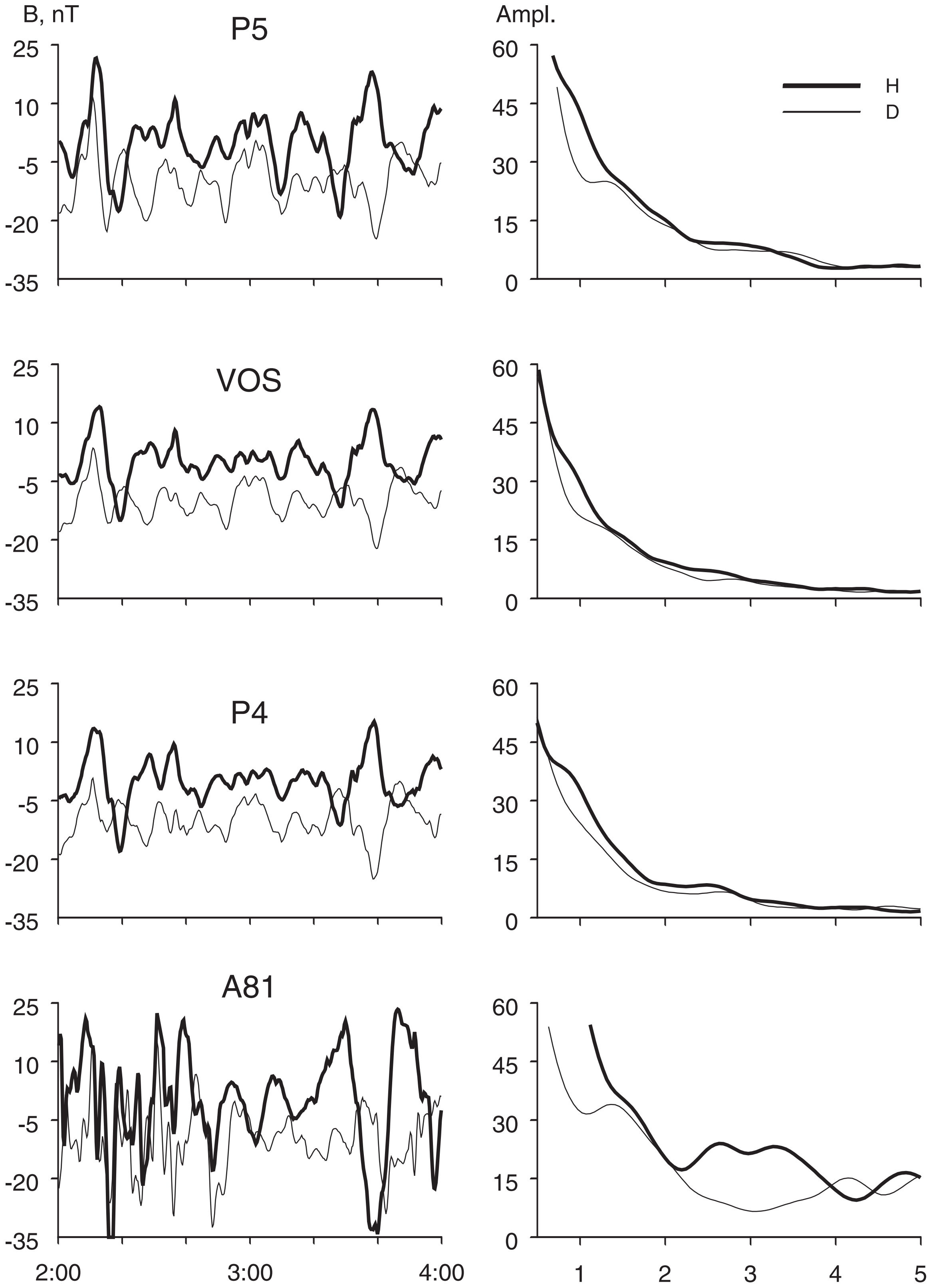

Figure 4. An example of colored-noise type variations recorded on DOY = 054 along meridian 40° profile during the time interval 2–4 UT (0–2 MLT): (left) H and D magnetograms and their (right) amplitude spectra.

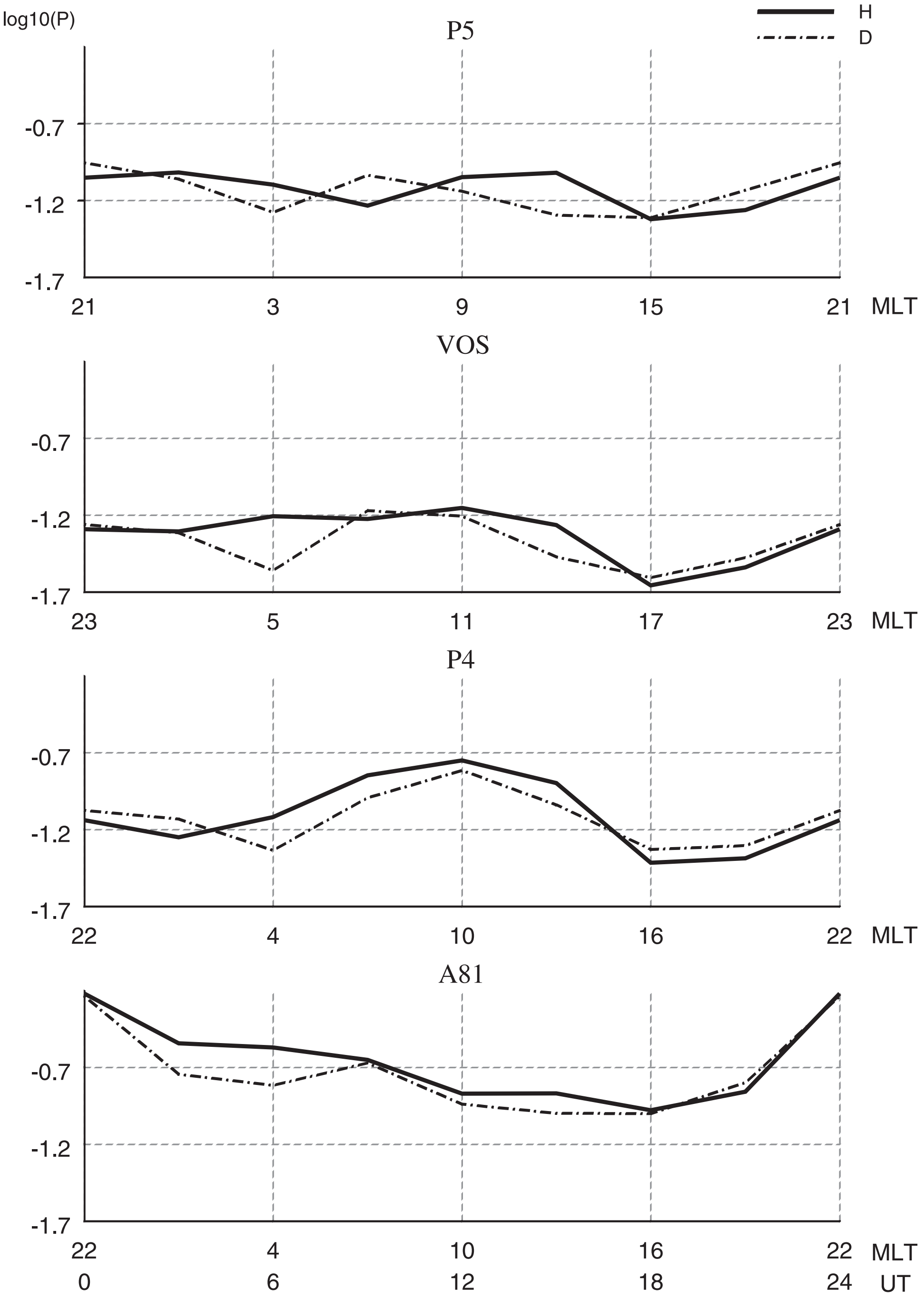

Figure 5. The MLT dependence of the Pc5-6 average decimal logarithm of spectral power for the two horizontal components at different stations.

[25] This statistical analysis confirms the results from the case studies in section 3.2.1: the variation of the ULF intensity along a meridian is nonmonotonic for both horizontal components. Enhanced Pc5-6 power at the auroral latitude station (A81) may be associated with substorm activity. The minimum in the meridional distribution of the power falls at a latitude ~ 80°–83° (P4, VOS), and then the pulsation power grows with latitude inside the polar cap (P5). Thus the nighttime Pc5-6 power enhancements occur at the auroral as well as at the polar cap latitudes.

[26] The average value of the S/N-index (dashed line in Figure 7, bottom) at polar cap latitudes is lower (~2 times) than that at the auroral station A81. This indicates that at auroral latitudes ULF variations are more regular and periodic than at polar cap latitudes. The behavior of the two horizontal components is similar but not identical.

3.2.3. Meridional distribution of spectral coherence

[27] The time-averaged spectral coherence $\gamma(f)$ in the band 1–6 mHz is presented in Figure 8 for the H (top) and D components (bottom) from different pairs of stations. Even the two-month averaged coherence is rather high,

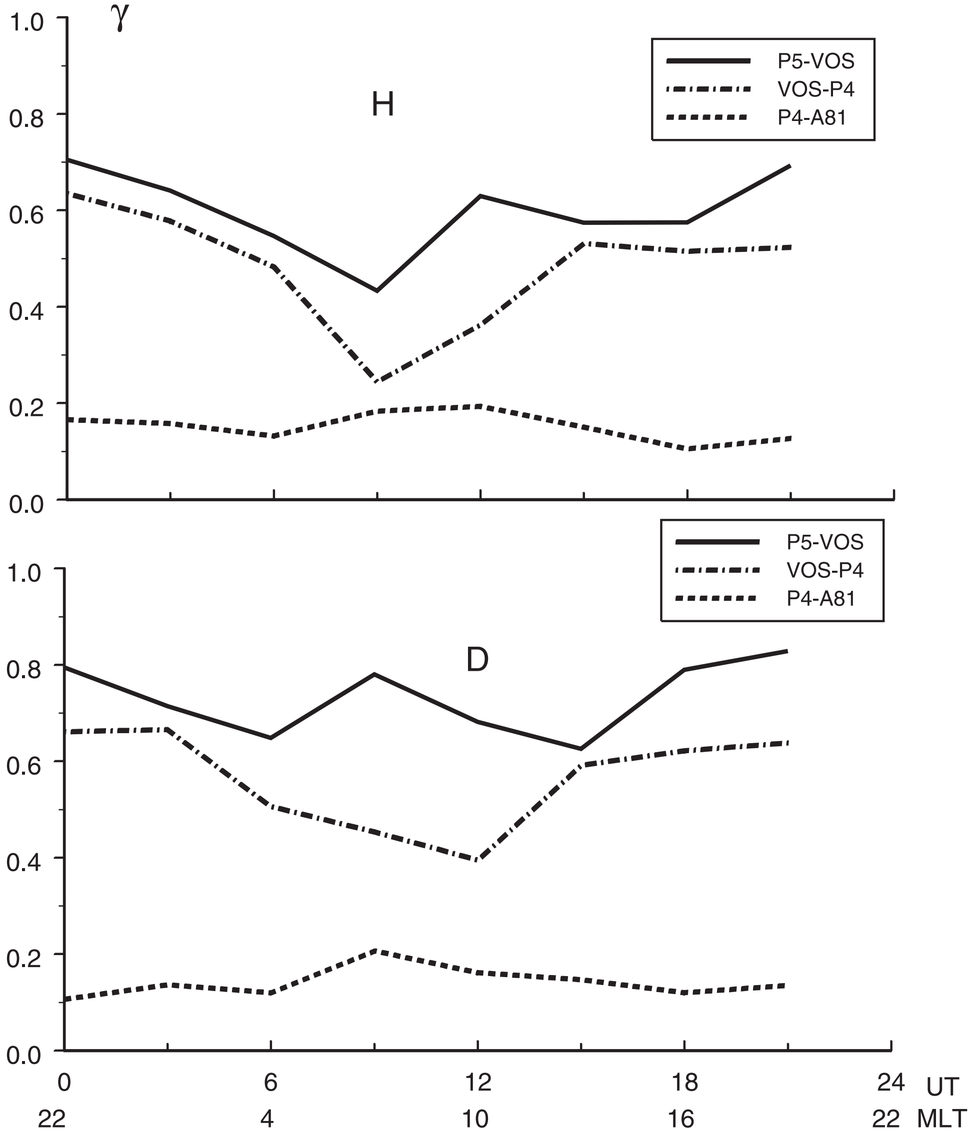

Figure 6. The MLT dependence of the Pc5-6 average spectral coherence for the two horizontal components from different pairs of stations.

between 0.6–0.8, for the cap-related P5-VOS and VOS-P4 pairs of stations. However, the coherence for the P4-A81 pair drops to low values, ~0.2–0.3. The standard error for the mean values of γ is less than 10%; that is, the difference between the coherency estimates is statistically meaningful. The substantial difference in spatial coherency inside the cap and between cap and auroral latitudes support the previously concluded fact that long-period ULF activity in the polar cap is largely decoupled from that at auroral latitudes.

4. Discussion

[28] In the following, we attempt to answer the question as to whether the long-period geomagnetic variations observed at very high latitudes have a source at auroral latitudes, where they are largely masked by stronger Pc5/Pi2 activity, or are they the result of some specific polar cap/magnetotail activity? The observational results support the basic conclusion that the sources of ULF waves in the Pc5-6 band (1–6 mHz) in the polar cap are different from those in the auroral oval. Both the statistical and the case studies reported here of magnetic variations in the Pc5-6 frequency band at the array of Antarctica magnetometers show that ULF activity inside the polar cap is decoupled from that at auroral latitudes.

[29] Thus it may be suggested that long-period nighttime magnetic activity in the polar cap is a result of wave activity in the magnetotail lobes. There are several oscillatory modes of the magnetotail, theoretically predicted by *Patel* [1966], *McKenzie* [1970], and *Ershkovich and Nusinov* [1972], which may be relevant to long-period oscillations in the polar cap. One of them is global oscillation of the entire tail, modeled as an oscillation of a "plasma cylinder" with radius R. If the typical Alfven velocity throughout the tail is assumed to be $V_A \sim 600$ km/s and $R \sim 15\ R_E$, then the expected periods of a flapping motion of the tail in the solar wind with a scale

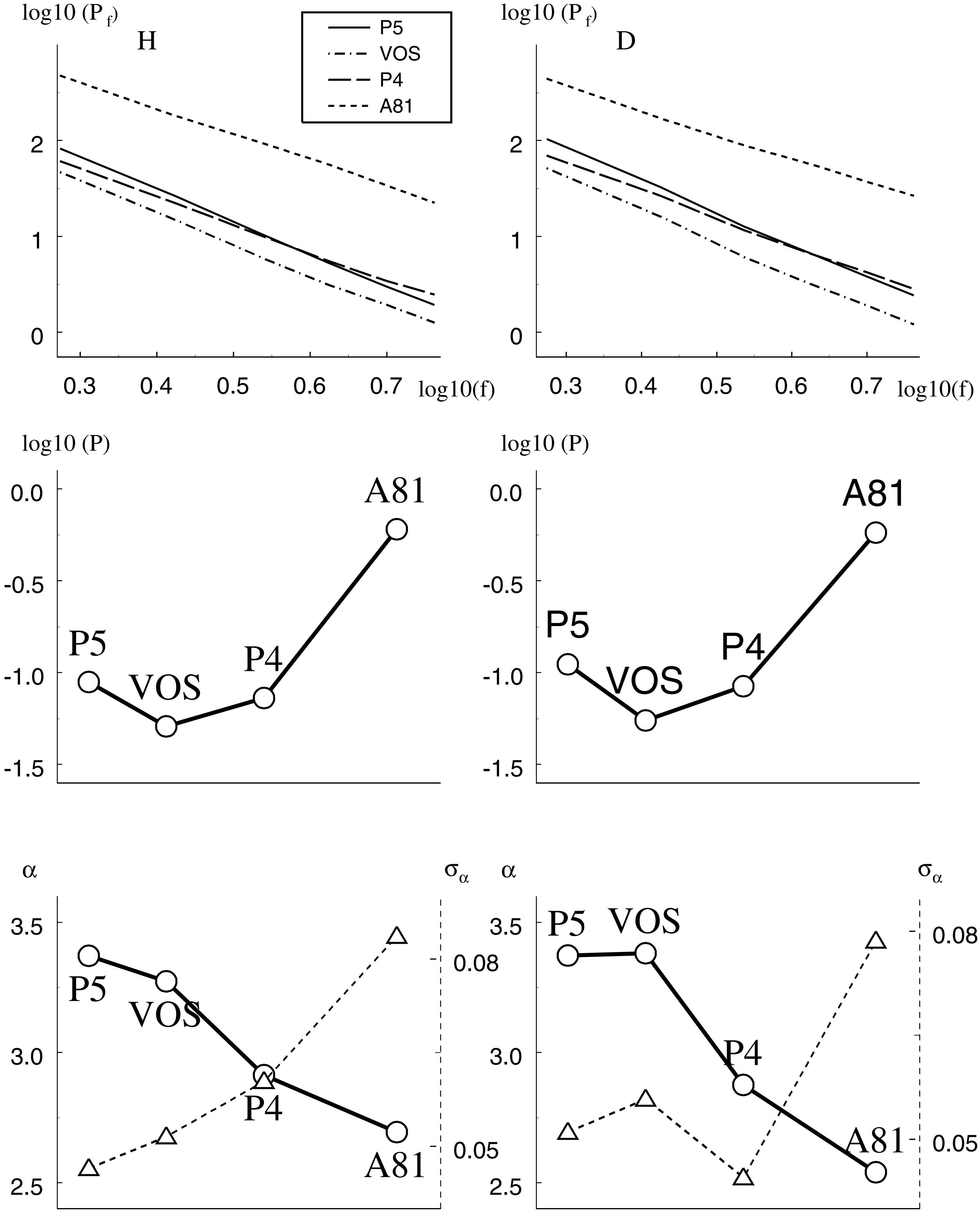

Figure 7. The time-averaged dependence of decimal logarithm of spectral power density P_f (upper panel) on decimal logarithm of frequency (mHz) and meridional distribution of averaged spectral parameters during nighttime hours (1–4 UT) for (left) H component and for (right) D component: logarithm of the spectral power integrated in the band 1–6 mHz (middle), and the spectral slope α and S/N-index (bottom).

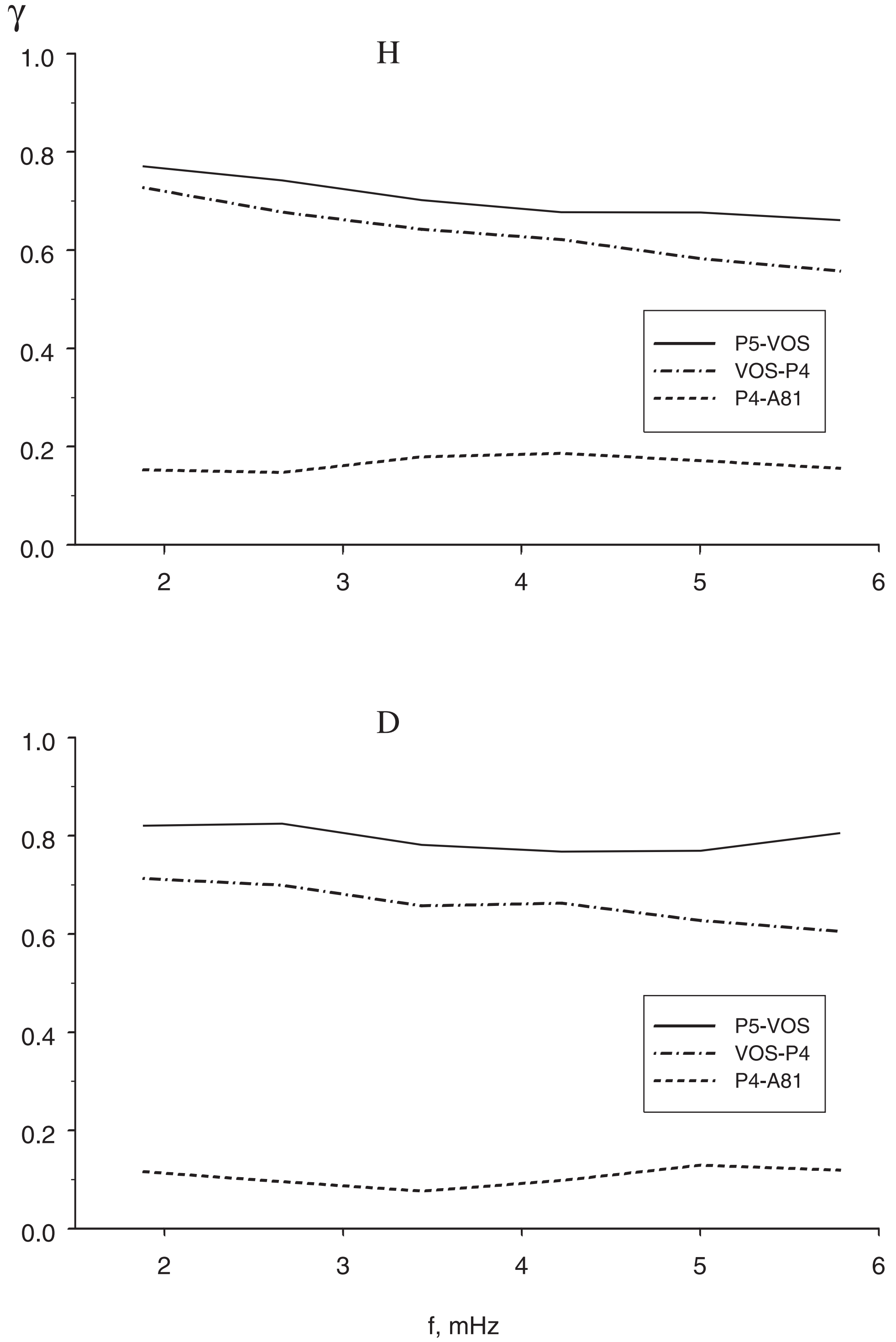

Figure 8. The frequency dependence of the time-averaged spectral coherence $\gamma(f)$ during nighttime hours (1–4 UT) for the (top) H component and the (bottom) D component between P5-VOS, VOS-P4 and P4-A81 stations.

comparable with the tail scale ($kR \sim 1$) is $T \simeq R/V_A \sim$ 20 min. These oscillations can probably be excited by enhanced solar wind flow via velocity shear instabilities at the tail boundary or as transient responses to solar wind pressure pulses. However, the mechanism by which such oscillations might be transferred to a ground observation site is still an unresolved problem. During this transport, a ground signal could be enhanced as compared with that in the tail lobe by a geometric factor, which is about the ratio between the scales of the lobe and polar cap.

[30] Large-scale disturbances propagating along the plasma sheet, with spatial scales comparable to the cross-tail size, can effectively penetrate into the lobe and excite

resonantly Alfven waves over a broad layer, including the tail lobe as well as plasma sheet boundary layer (PSBL). Numerical simulation by *Allan and Wright* [2000] showed, perhaps surprisingly, that amplitudes of Alfven waves excited in the lobe was just somewhat lower than those in the PSBL. While the waves in the lobe propagate both earthward and tailward from the source zone almost like plane waves, the PSBL Alfven waves experience significant phase mixing. As a result, their transverse scale upon reaching the ionosphere may become relatively small, and the ground ULF response be attenuated. This consideration is in qualitative agreement with the observed high coherence of Pc5-6 pulsations throughout the polar cap and decrease of ULF intensity near ~80°, the expected projection of PSBL. According to this scenario, observed ULF activity in the polar cap might be the manifestations of the dynamics of the middle magnetotail, which requires experimental validation.

[31] Satellite observations of ULF waves in the lobes are rare [e.g., *Siscoe*, 1969; *Sarafopoulos*, 1995]. Mostly, satellite observations within the magnetotail of magnetic fluctuations in the ULF band have shown low wave power in the lobes compared with that in the plasma sheet. ISEE-2 observations in the tail lobes of ULF waves with periods of 3–64 min showed that, commonly, wave amplitudes are below 0.8 nT and are weakly correlated with the *AE* index [*Chen and Kivelson*, 1991].

[32] Night time irregular auroral ULF activity, as observed at A81, may be related partially to poleward boundary intensifications near the separatrix, separating the auroral oval and the polar cap. Recently, the indications on possible coupling between poleward boundary intensifications and bursty flow in the plasmasheet were reported by *Lyons et al.* [1999]. Poleward boundary intensifications and accompanying Pi2 occurred repetitively, and these disturbances appeared to emerge during all levels of geomagnetic activity. Quasi-periodic variations near the poleward auroral boundary may be also related to oscillations of the plasma sheet. The latter can be modeled as oscillations of a "plasma slab" with thickness H [*McKenzie*, 1970]. The period of oscillations with $kH \sim 1$ is estimated to be $T \sim 8$ min for $H = 4R_E$. These oscillations can probably be excited by bursty processes in the magnetotail.

[33] The specific polar cap variations might be considered to be related to the irregular nature of the transpolar ionospheric current system. The suggestion that long-period ULF activity in the polar cap could be a manifestation of turbulent component of the ionospheric convection at very high latitudes requires further investigation.

[34] Another possible mechanism is a direct penetration of long period variations from the solar wind and boundary regions along reconnected field lines, convected with the solar wind flow across the polar cap into the distant magnetotail. To confirm this suggestion, a comparative analysis of observational data from magnetotail satellites and high latitude stations will be necessary.

5. Conclusion

[35] The statistical meridional distributions of spectral power in the Pc5-6 band (1–5 mHz) at the high latitude Antarctic stations demonstrate enhancements at auroral latitudes and deep within the polar cap, with a minimum around 80° geomagnetic latitude. The latitude dependence of the spectral slopes indicate a major content of higher frequency fluctuations at auroral latitudes with respect to polar cap latitudes. Despite their wideband and noisy looking spectra, the high-latitude oscillations are highly coherent along a magnetic meridian through the polar cap, while the correlation between auroral and polar cap latitudes is found to be poor. We conclude that ULF activity in the Pc5-6 frequency band inside the polar cap is decoupled from that at auroral latitudes.

[36] We further suggest that long-period nighttime magnetic activity in the polar cap is a result of wave or transient processes in the magnetotail lobes, though we do not exclude that this ULF activity is related to the turbulent nature of the ionospheric convection at very high latitudes. To understand the possible generation mechanisms, the distinctive features of ULF signatures, including their morphological characteristics, amplitude-phase spatial structures, and solar wind/IMF correlation, should be examined in greater detail.

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