JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 95, NO. A3, PAGES 2447–2456, MARCH 1, 1990

Ionospheric Signatures of Cusp Latitude Pc 3 Pulsations

M. J. ENGEBRETSON,[1] B. J. ANDERSON,[1,2] L. J. CAHILL, JR.,[3] R. L. ARNOLDY,[4]
T. J. ROSENBERG,[5] D. L. CARPENTER,[6] W. B. GAIL,[7] AND R. H. EATHER[8]

We have compared search coil magnetometer, riometer, photometer, and ELF-VLF receiver data obtained at South Pole Station and McMurdo, Antarctica (at invariant latitudes of -74° and -79°, respectively), during selected days in March and April 1986. Narrow-band magnetic pulsations in the Pc 3 period range are observed simultaneously at both stations in the dayside sector during times of low interplanetary magnetic field (IMF) cone angle, but are considerably stronger at South Pole, which is located at a latitude near the nominal foot point of the dayside cusp/cleft region. Pulsations in auroral light at 427.8 nm wavelength are often observed with magnetic pulsations at South Pole, but such optical pulsations are not observed at McMurdo. We have occasionally observed Pc 3 period modulations of the ELF-VLF signal at South Pole in the 0.5- to 1.0-kHz and 1.0- to 2.0-kHz frequency ranges as well. When Pc 3 pulsations are present, they exhibit nearly identical frequencies, proportional to the magnitude of the IMF, in magnetometer, photometer, and ELF-VLF receiver signals at South Pole Station and in magnetometer signals at McMurdo. Signals from the 30-MHz riometer at South Pole are modulated in concert with the magnetic and optical variations during periods of broadband pulsation activity, but no riometer variations are noted during periods of narrow-band activity. Because riometers are sensitive to electrons of auroral energies (several keV and above), while the 427.8-nm photometer is sensitive to precipitation with much lower energies, we interpret these observations as showing that precipitating magnetosheathlike electrons (with energies ≤ 1 keV) at nominal dayside cleft latitudes are at times modulated with frequencies similar to those of upstream waves. We suggest that these particles may play an important role, via modification of ionospheric currents and conductivities, in the transmission of upstream wave signals into the magnetosphere and in the generation of dayside high-latitude Pc 3 pulsations.

INTRODUCTION

It has been well established that many of the disturbances in the Earth's magnetosphere, such as auroral substorms, are a response to variations in the solar wind that continually sweeps from the Sun past the Earth and other planets. Studies over the past several years, most recently reviewed by *Odera* [1986] and *Arnoldy et al.* [1988], have shown that Pc 3 pulsations, a class of ULF waves in the Earth's magnetic field with periods between 15 and 40 s, are also directly related to activity in the ion foreshock region of the solar wind just upstream of the Earth's bow shock and magnetosphere.

There has been ample evidence that plasmas from interplanetary space can penetrate to ionospheric altitudes in the cusp region [*Heikkila and Winningham*, 1971; *Frank*, 1971]. Numerous studies at high-latitude sites, beginning with *Troitskaya et al.* [1971], and most recently *Morris and Cole* [1987], *Bol'shakova and Troitskaya* [1984], *Plyasova-Bakounina et al.* [1986], and *Olson* [1986], have noted the presence of large-amplitude Pc 3 pulsation activity peaking at cusp/cleft latitudes.

We present in this report new observations from South Pole Station, Antarctica, which during certain hours every day is located under the nominal position of the magnetospheric cleft/cusp region.

[1]Augsburg College, Minneapolis.
[2]Now at The Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland.
[3]University of Minnesota, Minneapolis.
[4]University of New Hampshire, Durham.
[5]Institute for Physical Science and Technology, University of Maryland, College Park.
[6]Space, Telecommunications, and Radioscience Laboratory, Stanford University, Palo Alto, California.
[7]The Aerospace Corporation, Los Angeles.
[8]Boston College, Chestnut Hill, Massachusetts.

Paper number 89JA02898.
0148-0227/90/89JA-02898$02.00

Two earlier papers based on South Pole data [*Lanzerotti et al.*, 1986; *Engebretson et al.*, 1986*a*] noted that large-amplitude narrow-band Pc 3 magnetic pulsations occurred at South Pole Station when the interplanetary magnetic field (IMF) was aligned near the Earth-Sun direction (low IMF cone angle). We have now found evidence of these pulsations in data from other South Pole instruments as well.

The observations to be reported here were obtained as a follow-up to a multistation case study of high-latitude pulsation activity during spring 1986 [*Engebretson et al.*, 1989], hereafter referred to as paper 1. In this study, observations from South Pole and McMurdo, Antarctica, were compared to data from three satellites: DMSP F7, in a low-altitude polar orbit, AMPTE CCE in the dayside equatorial magnetosphere, and IMP 8 in the solar wind. Paper 1 confirmed the observations of *Engebretson et al.* [1986*a*] that band-limited Pc 3 pulsations (20-40 s period) at cusp/cleft locations have occurrence/intensity controlled by the cone angle of the IMF and frequency controlled by the IMF magnitude:

$$f\,(\text{Hz}) = 0.006 \times |B|\,(\text{nT}) \qquad (1)$$

Recently, *Slawinski et al.* [1988] used an automated, statistical approach to analyze data from the AT&T Bell Laboratories flux gate magnetometer at South Pole and found a nearly identical relation between IMF magnitude and the frequencies of narrow-band Pc 3 activity.

We note that *Russell et al.* [1987] cautioned against too naive a use of equation (1). They pointed out that the spectrum of upstream waves observed by ISEE and AMPTE UKS was usually characterized by both spectral peaks in the Pc 3-4 frequency range and a broad power maximum covering much of the ULF period range. Perhaps consistent with the disordered state of plasma in the ion foreshock region, simultaneous observations of spectral peaks at different locations in this region at times showed different frequency maxima and/or different peak structure toward the low-frequency side. However, the plots and tabulated data presented by *Russell et al.* [1987] indicate that weighted average frequencies were usually proportional to the average local IMF field strength according to equation (1) whenever either (or both) of the satellites was in the ion foreshock region.

Whereas *Engebretson et al.* [1986*a*] confined their attention to a 1-hour period in local time around noon, paper 1 showed examples of IMF control of cusp latitude pulsation activity over approximately a 6-hour range of local times usually centered shortly before local noon. Simultaneous observations at McMurdo indicated that such pulsations can propagate into the polar cap (with reduced intensity) even to predawn local times.

Paper 1 also confirmed the findings of earlier studies that broadband Pi 1-2 magnetic activity (5 - 500 s period) is related to overhead ionospheric currents, and is linked to the precipitation of energetic auroral electrons [*Arnoldy et al.*, 1982; *Engebretson et al.*, 1983; *Oguti et al.*, 1984; *Oguti and Hayashi*, 1984]. In the cases studied in paper 1, Pi 1 (broadband) pulsation activity occurs at cusp/cleft locations when the IMF *Bz* component is negative, indicating a relationship to substormlike activity.

Successful characterization of irregular high-latitude Pi 1 pulsations in earlier studies was facilitated by the use of a variety of sensors, including riometers, photometers and/or other optical sensors as well as magnetometers [*Arnoldy et al.*, 1982; *Engebretson et al.*, 1983; *Oguti et al.*, 1984]. Although both magnetic field and ELF-VLF sensors were used by *Lanzerotti et al.* [1986] to characterize the Pc 3 pulsations they observed, we believe this is the first report of modulations in auroral light synchronized with narrowband magnetic pulsations in this frequency range. We believe the presence of these optical pulsations, and the modulated precipitation of energetic particles of which they give evidence, may play a key role in the transmission of wave energy from the upstream region to the high-latitude ionosphere.

Instrumentation

The ground-based data used in this study were obtained at South Pole Station, Antarctica (geographic latitude -90°, invariant latitude -74°, local magnetic noon 1530 UT), and at McMurdo, Antarctica (geographic latitude -77.9°, geographic longitude 166.7°, invariant latitude -79°, local magnetic noon 2030 UT).

Magnetic fluctuations in the 0.001- to 5-Hz range were obtained at a rate of 10 samples/s using the University of New Hampshire/University of Minnesota wave magnetometers. Instruments at both sites consist of two identical search coil units mounted orthogonally in magnetically northward and eastward directions [*Taylor et al.*, 1975]. A search coil's output is proportional to the derivative of the ambient field, and not the field itself. It is hence susceptible to high-frequency interference, and must be outfitted with a suitable low-pass filter to prevent aliasing effects. Data to be shown here are calibrated in nanoteslas per second for the dominant frequency detected in the appropriate interval. Further description of these sensors and of the data format used in this paper may be found in paper 1.

Measurements of *D* and *E* region ionization were obtained at each station using the University of Maryland 30-MHz riometers, and optical measurements of auroral brightness were obtained at each station using the Boston College zenith-pointing photometers at 427.8 nm wavelength. The 55° field of view of the photometers is approximately the same as that of the riometer antennas [*Rosenberg et al.*, 1987]. ELF-VLF data used in this study (available at South Pole only) are from the Stanford University ELF-VLF receiver, which includes a vertical loop antenna oriented for maximum sensitivity in the local magnetic north-south direction with five narrowband filter outputs covering the range from 0.5 to 38 kHz. Each of these signals is digitized at a rate of 1 sample/s.

Observations

Figure 1 shows stacked waveform plots for a 1-hour period on April 27, 1986, from several instruments at South Pole Station. From top to bottom are signals from wave magnetometers oriented east-west and north-south, respectively (XBB and YBB), 30-MHz riometer (RIO3), 427.8-nm photometer (PHO2), and 0.5- to 1.0-kHz and 1.0- to 2.0-kHz ELF-VLF receivers (VLF1 and VLF2) at South Pole Station. The magnetic signals are 1-s averages of 0.1-s samples; the remaining data are shown at their actual 1-s sampling rate.

Wave packets with Pc 3 pulsations are clearly evident in the top two (wave magnetomer) panels, for example between 1320 and 1330 UT, and waves of similar period are evident in the ELF-VLF signals shown in the bottom panels. The largest peak-to-peak amplitude wave packet shown in the XBB search coil trace near 1322 UT in Figure 1 is 0.2 nT/s, which is equivalent to a 1-nT p-p variation in *B*. Similarly, the largest packets in the YBB trace, near 1325 UT, have amplitudes near 0.3 nT/s, equivalent to a 1.3-nT p-p variation in *B*. The ELF-VLF modulations range from 5 to over 10 μV/m.

The photometer, sensitive to auroral light generated in the upper ionosphere (including that caused by electrons with energy below 1 keV), shows variations similar in frequency to those of the magnetic field sensors during the first half of the hour, as well as a larger-amplitude slow variation. The amplitude of the Pc 3 pulsations in auroral light during the first 25 min shown ranges from 0.15 to 0.25 kR. The riometer, which is sensitive to variations in charge density in the lower ionosphere caused by much more energetic (≥ 5-10 keV) electrons [*Matthews et al.*, 1988], exhibits broadband noise but little or no coherent variation in this frequency range.

In order to analyze the frequency characteristics of these traces more quantitatively, we prepared Fourier spectra based on 2048 one-second data points from each instrument. Figure 2 displays a logarithmic frequency spectrum for each instrument during roughly the first half of the time interval shown in Figure 1, from 1300 to 1334 UT. For each of the six traces shown, the vertical scale indicates the relative base 10 logarithm of the power spectral density, or wave power per unit frequency, as a function of frequency. The increases in five of the six traces near 0.03 Hz indicate increased wave power in the Pc 3 frequency range during this time period. The vertical bar shows the 99% confidence level above background for a 2048-point spectral estimate, based on Fisher's test [*Fuller*, 1976]. This figure more clearly shows that the riometer has no significant wave power at these frequencies, but that broad increases in each of the other five panels appear to be significant at or above the 99% level.

A vertical dotted line has been drawn in Figure 2 at the expected frequency for upstream Pc 3 pulsations (equation (1)), based on the hourly averaged IMF field magnitude measured by the IMP 8 satellite, located at this time more than 20 R_E upstream from the Earth, in the solar wind. The frequency of this line is in excellent agreement with the center frequency of the observed increases in power in magnetometer and ELF-VLF traces, but the enhancement in the photometer spectrum peaks at a slightly higher frequency. The spectral enhancements shown in the figure (and those observed upstream of the bow shock by *Russell et al.* [1987]) have bandwidths of approximately 20-30 mHz, while individual resonant Pc 3 harmonics observed in the dayside outer magnetosphere typically have bandwidths of order 2-5 mHz [*Takahashi and McPherron*, 1982; *Engebretson et al.*, 1986*b*].

Although detailed IMP 8 IMF data for April 27, 1986 (shown in Figure 9 of paper 1), suggested that the frequency offset in the photometer spectrum might be caused by a slight decrease in IMF magnitude during the 34-min interval included in the spectral estimate, more detailed analysis showed that this was not the case. Spectral analysis using shorter interval lengths (using 512-point, ~8-min spectra offset by 4 min rather than a single 32-min spectrum) showed that the spectral peak in the photometer data was consistently 0.005 Hz higher than the peak in the VLF channels. In one other case studied we found the photometer spectral peak to be ~0.005 Hz lower

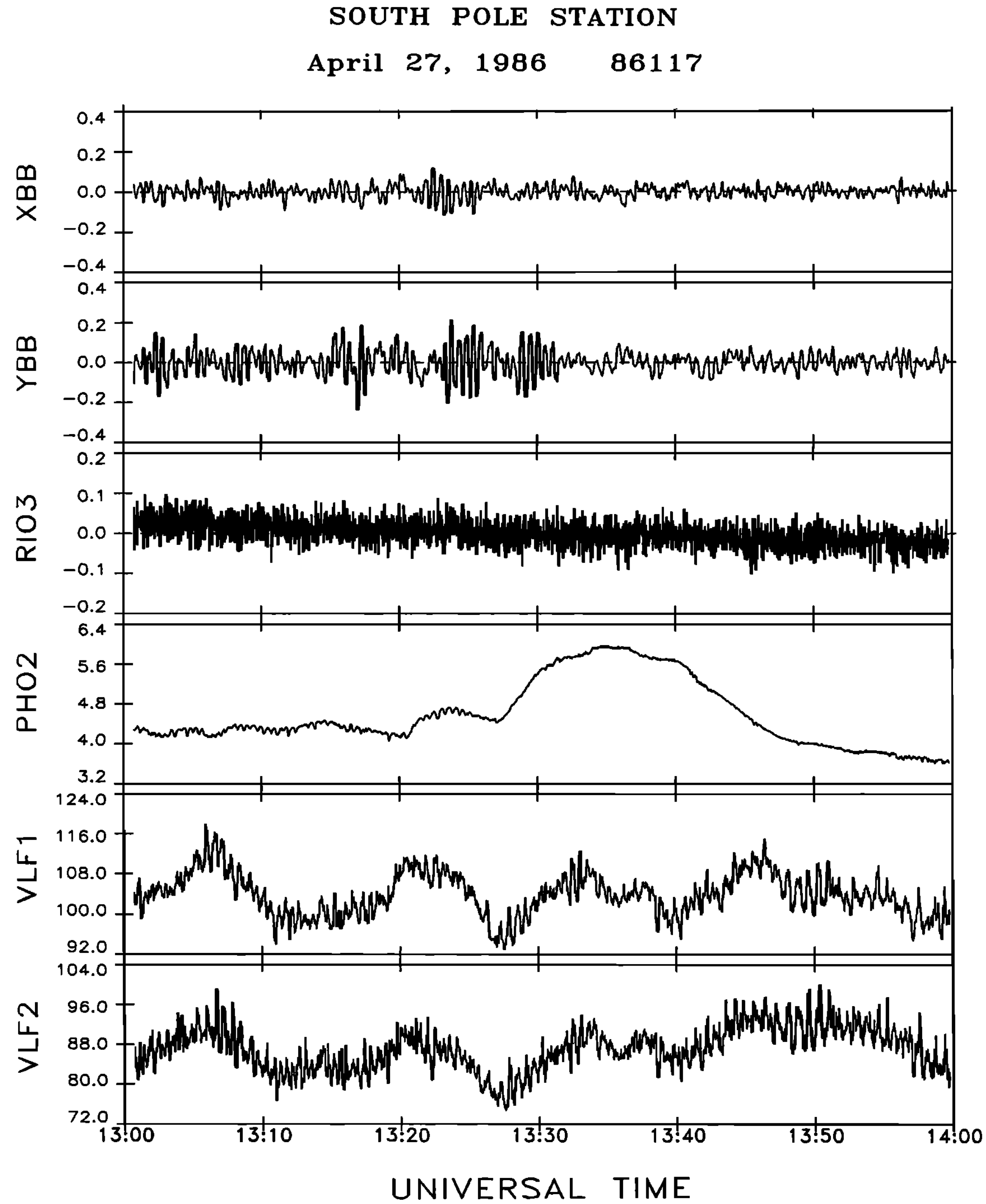

Fig. 1. Stacked plot of data from South Pole Station from 1300 to 1400 UT, April 27, 1986, during a time when narrow-band Pc 3-4 pulsations were observed. The traces from top to bottom are east-west (XBB) and north-south (YBB) magnetic field components (in nanoteslas per second) from the search coil magnetometer, relative ionospheric absorption (in decibels) from the 30-MHz riometer (RIO3), auroral brightness (in kilorayleighs) from the 427.8-nm photometer (PHO2), and ELF-VLF electric field intensity (in microvolts per meter) from receivers in the 0.5- to 1.0-kHz and 1.0- to 2.0-kHz frequency ranges (VLF1 and VLF2).

in frequency than the VLF peak; in most cases (and in that to be shown in Figure 4), however, there was no evident difference in spectral peaks between magnetometer, photometer, and VLF signals. It is possible that these frequency variations between instruments are related to the differing fields of view of photometer, ELF-VLF receiver, and magnetometers, but we have at present no satisfactory explanation for this difference.

We also generated Lomb-Scargle normalized periodograms [*Press and Teukolsky*, 1988] for these same signals, and verified both the frequency peaks and their significance. The riometer signal above 0.01 Hz had an estimated probability of over 0.99 of being random, while the next most random signal shown, XBB, had a probability of randomness of ~10^{-22}. Lomb-Scargle analysis also showed a weaker but still highly significant (P random = 2×10^{-10}) spectral peak in the signal from the South Pole 630.0-nm photometer (not shown), at the same frequency found for the 427.8-nm photometer ($f = 0.036$ Hz). (The low signal to noise ratio of the 630.0-nm signal is physically plausible because the time constant for radiation from this metastable state is comparable to the period of the pulsations.)

We used several methods (hodograms, cross correlations, and

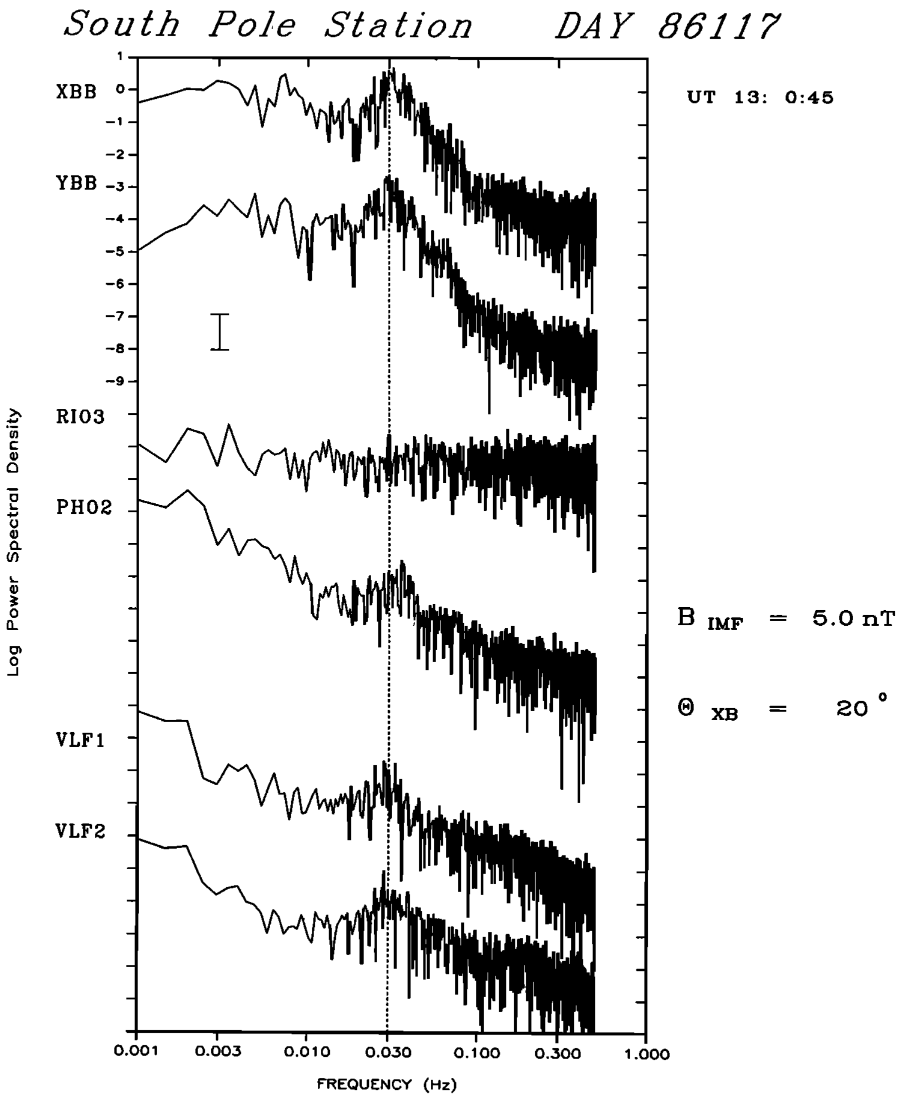

Fig. 2. Relative logarithmic power spectra of data obtained at South Pole Station, Antarctica, from 1300 to 1334 UT, April 27, 1986. Traces shown correspond to waveforms shown in the first part of Figure 1. Also shown are the hourly average magnitude and cone angle of the interplanetary magnetic field (IMF). The vertical line at 30 mHz represents the predicted center frequency of upstream waves, determined by the IMF magnitude. The vertical bar indicates the 99% confidence level.

detailed line plots) to study the phase relationships between the five traces showing Pc 3 pulsation activity, and found a consistent relationship only between the two ELF-VLF traces. Although pulsations in the Y (northward) wave magnetometer signal were at times nearly in antiphase with pulsations in the photometer signal (e.g., 1308-1311 and 1323-1325 UT), at other times there was little coherence between the Y magnetometer signal and the 427.8-nm photometer signal, or even between the Y and X (eastward) magnetometer signal. A similar lack of coherence between horizontal components of magnetic Pc 3 wave packets was evident in several examples shown by *Engebretson et al.* [1986*a*]. We speculate that the highly linear polarization of such wave packets, as well as their only sporadic coherence with optical pulsations, may be related to the filamentary structures often observed in the cusp/cleft region [*Meng and Candidi*, 1985].

Spectra obtained simultaneously at McMurdo, closer to the southern magnetic pole, are shown in Figure 3. Local time at McMurdo during this interval is 0430-0500 MLT, compared to 0930-1000 MLT at South Pole. Magnetometer spectra from McMurdo reveal an enhancement in wave activity in the same frequency range observed at South Pole, but no such enhancement is evident in either riometer or photometer data at this site.

We provide two more examples of South Pole spectra to characterize the range of ionospheric variations coincident with the presence of cusp/cleft latitude magnetic pulsations.

Figure 4 shows spectra for the interval 1800 to 1834 UT, April 25, 1986, during another interval of moderately radial IMF ($\theta_{xB} = 145°$) and with modest fluctuations about an hourly average magnitude of only 2.9 nT. Broad enhancements of power are evident in five of the six spectra shown, with nearly identical frequency. Only the riometer signal is again devoid of power enhancements. In this case too, the McMurdo magnetometer signals (not shown) are enhanced at the same frequency observed at South Pole, and no such variations are visible in McMurdo riometer or photometer data.

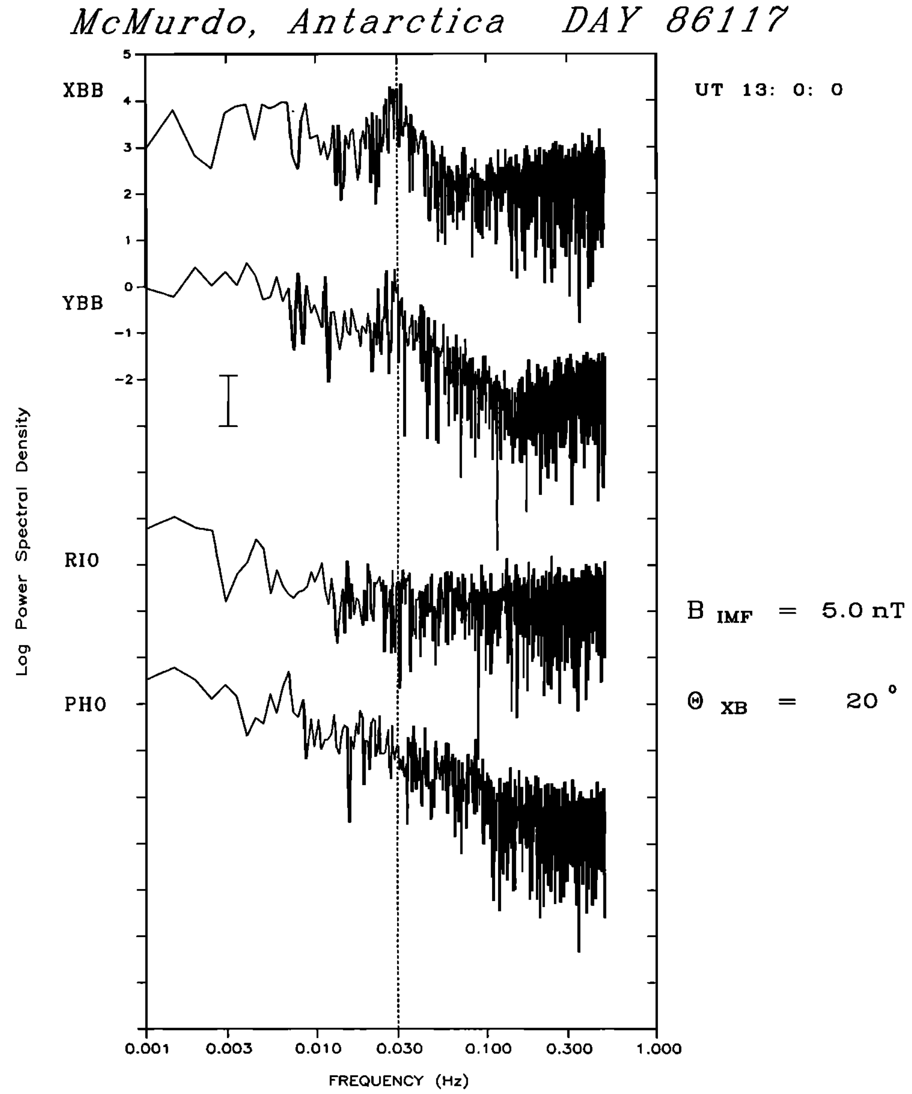

Fig. 3. Logarithmic power spectra of data from McMurdo, Antarctica, from 1300 to 1334 UT, April 27, 1986, as in Figure 2.

Figure 5 shows stacked waveform plots for the interval 1400 to 1500 UT, four hours earlier that same day. All six instruments show substantial pulsation activity, and photometer and riometer traces are clearly correlated during the largest pulsations. The magnetic field traces in the top two panels show large, often one-sided pulsations with sharp phase shifts [*Engebretson et al.*, 1983], and some of the largest of the magnetic pulsations correlate with riometer and photometer pulsations. This is consistent with the photometer and riometer having nearly identical fields of view, both much smaller than that of the magnetometers.

The variations shown in Figure 5 are typical of Pi 1-2 activity, the statistically dominant and largest-amplitude class of pulsation activity observed at South Pole on the dayside [*Engebretson et al.*, 1986*a*]. Both *Engebretson et al.* [1986*a*] and paper 1 showed that this class of pulsation activity was correlated well with the presence of precipitation of energetic electrons with energies typical of those found in the plasma sheet ($E > 20$ keV). We note that such electrons will penetrate to the low altitudes necessary to cause riometer absorption, and will of course generate simultaneous optical pulsations when the precipitation is impulsive and/or irregular.

Spectra from the first half of the interval shown in Figure 5, from 1400 to 1434 UT, are presented in Figure 6. One can observe nearly identical spectral enhancements in the riometer and photometer traces near 0.01 Hz, and related (but weaker) features in the magnetometer and ELF-VLF traces, between 0.004 and 0.015 Hz. The magnetometer spectra show a broad plateau from below ~0.01 to ~0.03 Hz, with Pi 1-2 (broadband) signatures dominating both components. Indeed, although the average IMF cone angle was 170° during this time period, there is almost no evidence of narrow-band pulsation activity near the frequency expected for upstream wave-generated Pc 3.

In all but the last figure, Pc 3 pulsations evident in magnetic field data also appear in photometer and ELF-VLF receiver signals. More numerous cases in which pulsations appear only in the magnetic field data have not been shown. Comparisons of data from the several instruments over a period of several days reveal the following characteristics for the degree of coordination between instruments:

Occurrences of modulations of auroral light at Pc 3 frequencies are highly localized in time (on the scale of individual wave packets), as in Figure 1, and there is a general trend for greater occurrence

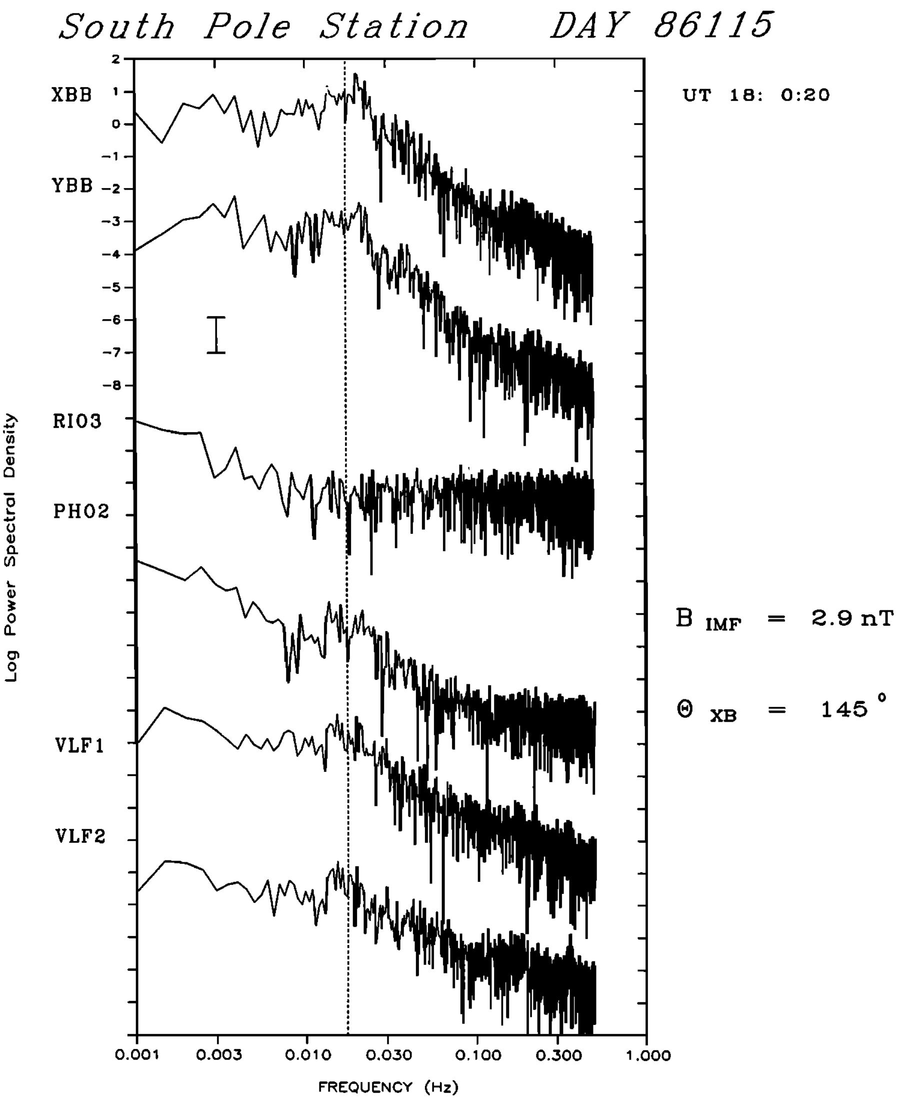

Fig. 4. Logarithmic power spectra from 1800 to 1834 UT, April 25, 1986, as in Figure 2. The IMF magnitude is considerably lower during this interval.

frequency as the amplitude of the magnetic pulsations becomes larger. Both of these effects are consistent with the narrower field of view of the photometer, as explained above, and with a varying location and/or latitude for the precipitation responsible for the auroral emissions.

The occurrence of modulations of ELF-VLF signals varies more from day to day; when ELF-VLF modulations are observed they are continuous over periods of several hours. This steady signal is consistent with the ability of the ELF-VLF receiver to view emissions associated with a wide range of L shells and local times [*Walker*, 1974; *Tsuruda et al.*, 1982], but there is no clear relationship between the absence of ELF-VLF modulation and the presence or absence of optical variations or the polarity of the IMF, for example.

In summary, we have found that highly polarized, narrow-band Pc 3 magnetic pulsations observed at South Pole, near the nominal latitude of the low-altitude cusp/cleft region, (1) are also observed in the polar cap (at McMurdo), (2) are also seen often in auroral light at cleft latitudes (South Pole) but not in the polar cap (McMurdo), (3) are often associated with oscillations in the amplitude of ELF-VLF emissions, and (4) do not correspond to discernible variations in D or E region ionization at either cleft/cusp or polar cap locations. We suggest that variations in spectral features are likely due to the different fields of view of the respective instruments, with the ELF-VLF receivers sensing signals produced throughout a wide region of the magnetosphere, the magnetometers sensing ionospheric electric currents down to low zenith angles, and the photometer and riometer sensing only those variations within their limited field of view.

DISCUSSION

The observations presented here and in paper 1 indicate that Pc 3-4 magnetic pulsations are observed simultaneously at both South Pole and McMurdo, Antarctica, during local daytime hours when the IMF cone angle is low, but are considerably stronger at South Pole, which is located at a latitude near the nominal foot point of the dayside magnetic cusp/cleft region. During some events, pulsations are also observed in overhead auroral light and/or in ELF-VLF signals. During these times, signals from all of these instruments display enhancements at frequencies proportional to the magnitude of the IMF. We consider the importance of the data from each instrument in turn.

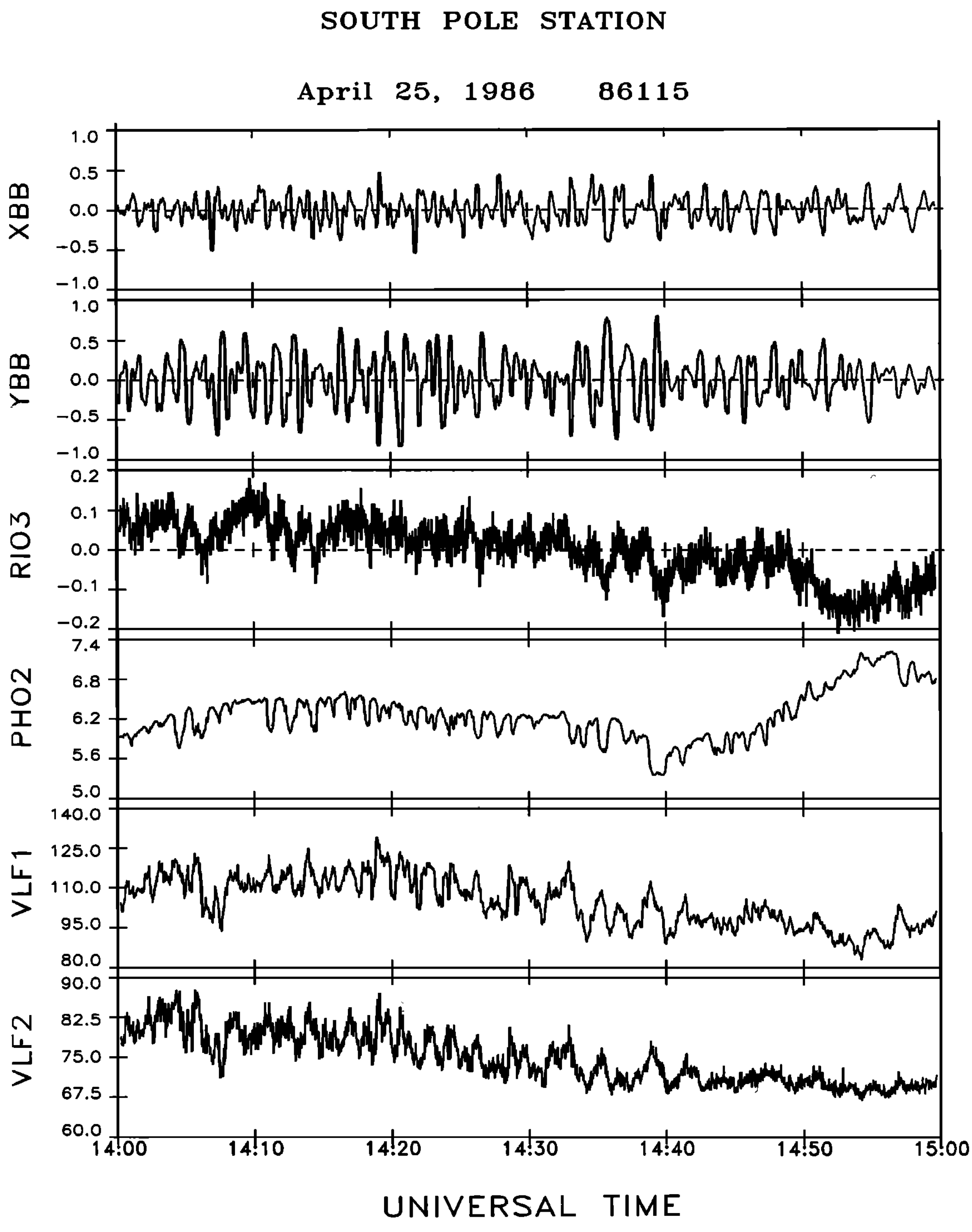

Fig. 5. Stacked plot of data from South Pole Station from 1400 to 1500 UT, April 25, 1986, as in Figure 1, during a period when broadband Pi 1-2 activity was dominant.

Pulsations in Magnetic Field

The wave magnetometer data presented here are in agreement with many earlier studies which have noted that the dayside cusp/cleft region is a significant source of Pc 3 pulsation energy [*Bol'shakova and Troitskaya*, 1984; *Plyasova-Bakounina et al.*, 1986; *Olson*, 1986; *Engebretson et al.*, 1986*a*; *Morris and Cole*, 1987] . Our observations are also in agreement with those earlier studies at very high latitudes which have distinguished broadband from narrowband pulsation activity [*Bol'shakova and Troitskaya*, 1984, *Plyasova-Bakounina et al*, 1986, *Engebretson et al.*, 1986*a*, *Slawinski et al.*, 1988] in finding that Pc 3 pulsation frequencies are correlated with IMF magnitude. The often nearly linear polarization observed for these signals, however, demands further investigation.

Pulsations in Auroral Light

We have observed bursts of optical pulsations at Pc 3 frequencies at South Pole during 30-40% of the times when magnetic Pc 3 pulsations are also observed, but have never observed them at McMurdo. This suggests that such auroral optical pulsations and the electron precipitation which causes them are spatially confined "near" the cleft/cusp region. We have observed auroral pulsations from before 1200 until after 1800 UT, indicating that the cusp,

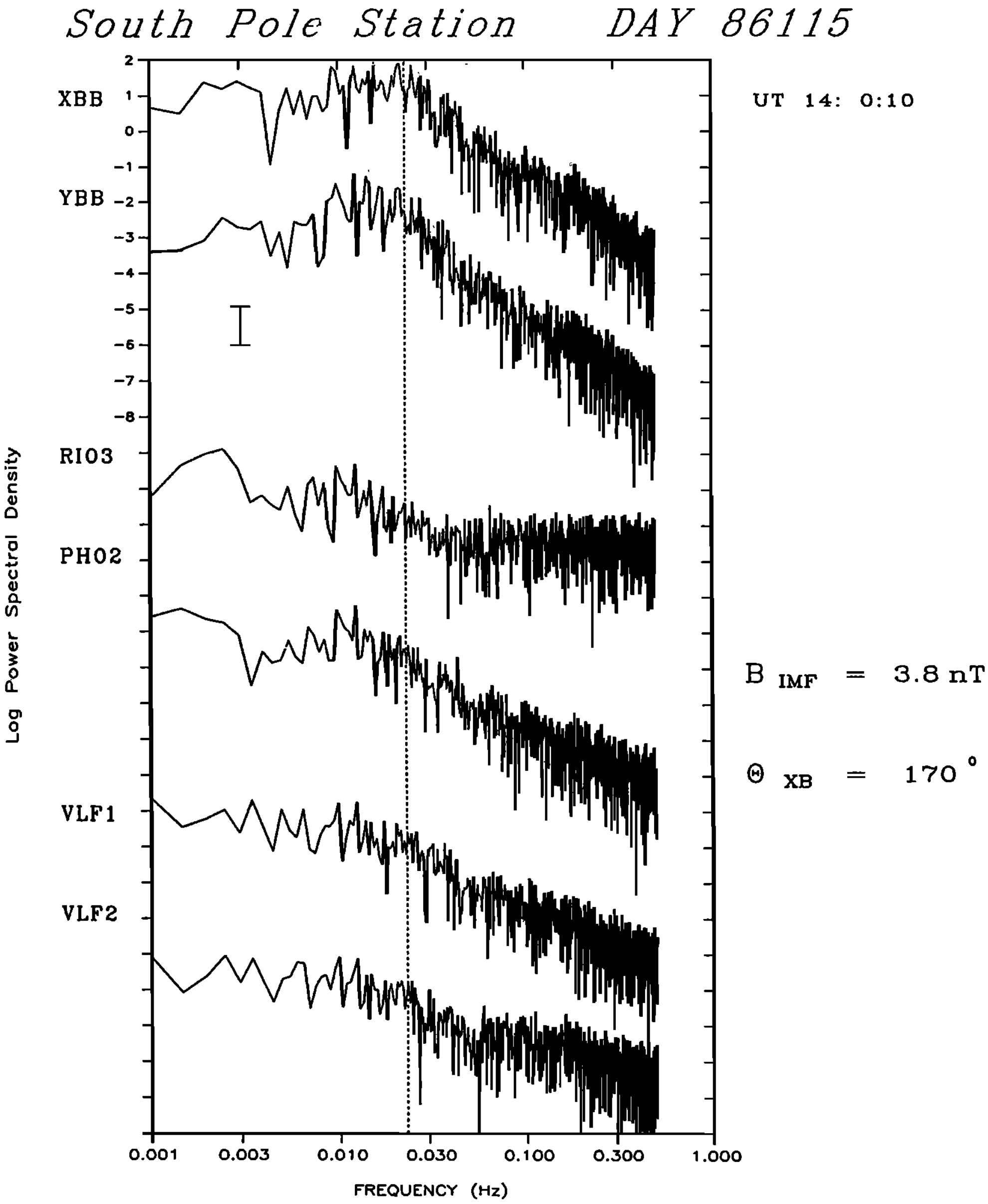

Fig. 6. Logarithmic power spectra from 1400 to 1434 UT, April 25, 1986, as in Figure 2. Traces shown correspond to waveforms shown in Figure 5.

defined as that localized region near noon in which magnetosheath plasma has direct entry to low altitudes, is not the unique source of these optical pulsations. Our observations suggest that the pulsations in auroral light are correlated better with the more longitudinally extended cleft region, as defined with low-altitude satellite (DMSP) data by *Newell and Meng* [1988] as a region of less intense but somewhat more energetic precipitating electrons.

Pulsations in ELF-VLF Signals

The ELF-VLF modulations, which are similar to those reported earlier by *Lanzerotti et al.* [1986] also using instruments at South Pole Station, appear to be examples of type I quasi-periodic emissions or QP/GP events [Kimura, 1974]. These have been observed for many years on the ground and in space (see for example *Kimura* [1974], *Gendrin* [1980], *Tixier and Cornilleau-Wehrlin* [1986], and *Gail et al.* [1990]). Such events mainly involve ULF waves in the Pc 3-4 period range, and their diurnal occurrence maximizes shortly before local noon; the events reported here are consistent with both of these characteristics. Most early studies reported that QP/GP events were generally observed in the recovery phase of geomagnetic storms. Although the observed diurnal occurrence pattern was clearly consistent with a cusp/cleft related source, *Lanzerotti et al.* [1986] were apparently the first to suggest that these events could be associated with upstream wave activity rather than with auroral sources. The apparent limitation of the ULF modulations of ELF-VLF emissions to the 0.5- to 2-kHz bands is common at South Pole, and is evidence that the emissions are polar chorus. This probably originates well outside the plasmapause, possibly near the magnetopause on the dayside.

Coroniti and Kennel [1970] proposed a modification of the quasilinear theory of *Kennel and Petschek* [1966] to explain ULF modulation of ELF-VLF emissions. In this model, the compressional components of ULF waves preferentially affect the perpendicular energy of gyrating electrons through betatron acceleration, changing the pitch angle anisotropy and thus modifying the ELF-VLF growth rate. The ELF-VLF waves scatter electrons into the loss cone, resulting in electron precipitation into the ionosphere which is modulated at the ULF frequency. The amplitudes of the ELF-VLF and precipitated flux modulations, however, depend critically on the characteristics of the ambient energetic plasma distribution. The unexplained absence of ELF-VLF modulation on some days is consistent with a dependence on the state of the particle distribution as well as on the presence or absence of pulsations.

Theoretical and experimental work has suggested that the effect of ULF modulation on the generation of ELF-VLF waves may be strongest in the outer dayside region. *Perona* [1972] developed a theory which predicts that the ELF-VLF growth rate during magnetic compressions associated with sudden commencements (SC) maximizes near noon. *Olson and Lee* [1983] obtained similar results at ULF frequencies for the growth of ion cyclotron waves during SC. *Gail et al.* [1990] and *Gail and Inan* [1990] provided experimental support for these theoretical predictions, showing that ELF-VLF emissions are commonly associated with SC magnetic compressions and that the wave growth is observed simultaneously with the inferred passage of the SC disturbance through the outer dayside magnetosphere.

Studies of Pc 3-4 pulsations observed in the dayside outer magnetosphere by the AMPTE CCE satellite [*Engebretson et al.*, 1986*b*, 1987] have shown that these ULF waves are consistently present when the IMF cone angle is low, as is the case for all the events shown in this study. Although these last papers focused on purely azimuthal resonant harmonics, near local noon these harmonics are often accompanied by compressional pulsations (noted earlier at synchronous orbit by *Yumoto et al.* [1984]). These compressional Pc 3-4 pulsations are usually weaker and more broadbanded than the azimuthal resonant harmonics (see the examples in *Engebretson et al.* [1987]), but could contribute to the observed VLF modulation by the above mechanism.

Because of the evident correlation of the VLF modulation frequency with the magnitude of the IMF (and, by inference, with the influence of upstream waves), we must consider also the role these waves might play as they enter the magnetosphere from the magnetosheath. Analyses of ISEE data in the magnetosheath have shown that (1) highly disturbed magnetosheath plasma conditions are linked to regions of quasi-parallel bow shock structure [*Crooker et al.*, 1981], now considered an integral part of the upstream wave source, and (2) magnetic field fluctuations in the magnetosheath are greatly enhanced during times of nearly radial IMF [*Luhmann et al.*, 1986]. Preliminary results of a comparison of AMPTE IRM passes through the magnetosheath and AMPTE CCE passes in the dayside outer magnetosphere show a similar relationship: harmonically structured Pc 3-4 activity was observed in the dayside magnetosphere at AMPTE CCE during more than 80% of the periods when disturbed plasma conditions and strong magnetic field fluctuations ($\Delta B / B \geq 0.1$) were observed in the magnetosheath, and no harmonic Pc 3-4 activity was observed during times when magnetosheath plasmas and magnetic fields were steady. If such magnetosheath fluctuations are able to cause compressional variations at the magnetopause or boundary layer, they could well enhance electron pitch angle anisotropies sufficiently to increase the ELF-VLF growth rate on flux tubes near or overhead of South Pole during daytime hours. This mechanism, if confirmed, would also be one source of the precipitating electrons responsible for generating the observed auroral pulsations.

We emphasize that the lack of detailed correlation between pulsations in the VLF signals and the magnetic field signals noted above (and shown in Figure 1) suggests that the VLF signals observed may not originate predominantly in flux tubes that map to overhead of South Pole. The large viewing area of the South Pole ELF-VLF receiver means that the observed waves could have been generated anywhere within a wide range of L shells and local times. *Helliwell et al.* [1980] found that similar QP emissions could induce precipitation measurable with photometers at Siple, Antarctica ($L = 4.2$). The QP emissions observed at South Pole during these events could be associated with source regions that vary considerably in L shell and local time during the course of an event as well as from event to event.

Lack of Evidence for Pulsations in Riometer Absorption

The absence of riometer variations during periods of Pc 3 activity places an upper limit on the energy of the precipitating electrons causing the auroral light sensed by the photometers. High-latitude ULF pulsation activity is dominated by irregular broadband magnetic fluctuations, with periods covering the range of 5 to 500 s, which are related to precipitation of energetic ($E > 20$ keV) auroral electrons [*Engebretson et al.*, 1986*a*]. We have shown that for such activity photometer and riometer responses are very similar (Figure 5). The consistent difference between the response of the South Pole photometer and riometer signals during intervals of Pc 3 pulsation activity, however, provides evidence that these pulsations are related to precipitation of electrons with much lower energies. On the basis of DMSP overflight data (taken with typically a 2-hour separation in local time, as documented in paper 1), it appears that South Pole was under the ionospheric foot point of the cleft/boundary layer region during some, but not all, of the times auroral Pc 3 pulsations were observed. We thus suggest that these precipitating electrons come from the magnetospheric boundary layer, and that these particles have energies of 1 keV or lower, but further study using imaging photometers and/or comparisons with low-altitude satellite particle data will be needed to verify this.

In summary, we have shown several examples of simultaneous observations of Pc 3-4 pulsations in magnetic field, auroral light, and VLF signal modulation data at cleft/cusp latitudes. These multi-instrument observations provide important clues to the mechanism for transmitting Pc 3-4 pulsations, believed to originate in the solar wind upstream from a quasi-parallel bow shock structure, deep into the Earth's magnetosphere. The frequent observation of "patches" of auroral Pc 3 pulsations at cusp/cleft latitudes suggests that spatially confined regions of modulated precipitating particles "near" the cleft/cusp are associated with these pulsations. We speculate that these regions are in the magnetospheric boundary layer, and on the basis of their inferred low energies, that the precipitating particles originate in the magnetosheath. The localized nature of the auroral patches may further reflect a localized, perhaps impulsive, transfer of momentum and/or wave information from the magnetosheath into the magnetosphere. Further study of this possible transfer mechanism is in progress.

Acknowledgments. We are grateful to the two referees for helpful suggestions and criticisms. We thank Scott Carlson, Jon Webster, Chad McCartney, David Murr, and Shawn Rounds of Augsburg College for their assistance in data analysis and display, P. T. Newell of The Johns Hopkins University Applied Physics Laboratory for helpful comments, and R. P. Lepping of NASA/Goddard Space Flight Center for permission to use IMP 8 magnetometer data. This research was supported by National Science Foundation grant DPP-86-13272 to the University of New Hampshire and by subcontracts to Augsburg College and the University of Minnesota, by NASA under task I of contract N00024-85-C-5301 to The Johns Hopkins University Applied Physics Laboratory and by subcontract to Augsburg College, by National Science Foundation grant DPP-86-10061 to the University of Maryland, and by National Science Foundation grant DPP-86-13783 to

Stanford University. Computational support at Augsburg College was provided by National Science Foundation grant ATM-86-06388.

The Editor thanks J. V. Olson and J. Watermann for their assistance in evaluating this paper.

REFERENCES

Arnoldy, R. L., K. Dragoon, L. J. Cahill, Jr., S. B. Mende, T. J. Rosenberg, and L. J. Lanzerotti, Detailed correlations of magnetic field and riometer observations at $L = 4.2$ with pulsating aurora, *J.. Geophys. Res.*, *87*, 10449, 1982.

Arnoldy, R. L., L. J. Cahill, Jr., M. J. Engebretson, L. J. Lanzerotti, and A. Wolfe, Review of hydromagnetic wave studies in the Antarctic, *Rev. Geophys.*, *26*, 181, 1988.

Bol'shakova, O. V., and V. A. Troitskaya, The relation of the high-latitude maximum of Pc 3 intensity to the dayside cusp, *Geomagn. Aeron.*, Engl. Transl., *24*, 633, 1984.

Coroniti, F. V., and C. F. Kennel, Electron precipitation pulsations, *J. Geophys. Res.*, *75*, 1279, 1970.

Crooker, N. U., T. E. Eastman, L. A. Frank, E. J. Smith, and C. T. Russell, Energetic magnetosheath ions and the interplanetary magnetic field orientation, *J. Geophys. Res.*, *86*, 4455, 1981.

Engebretson, M. J., L. J. Cahill, Jr., R. L. Arnoldy, S. B. Mende, and T. J. Rosenberg, Correlated irregular magnetic pulsations and optical emissions observed at Siple Station, Antarctica, *J. Geophys. Res.*, *88*, 4841, 1983.

Engebretson, M. J., C.-I. Meng, R. L. Arnoldy, and L. J. Cahill, Jr., Pc 3 pulsations observed near the south polar cusp, *J. Geophys. Res.*, *91*, 8909, 1986*a*.

Engebretson, M. J., L. J. Zanetti, T. A. Potemra, and M. H. Acuna, Harmonically structured ULF pulsations observed by the AMPTE/CCE magnetic field experiment, *Geophys. Res. Lett.*, *13*, 905, 1986*b*.

Engebretson, M. J., L. J. Zanetti, T. A. Potemra, W. Baumjohann, H. Luehr, and M. H. Acuna, Simultaneous observation of Pc 3-4 pulsations in the solar wind and in the Earth's magnetosphere, *J. Geophys. Res.*, *92*, 10053, 1987.

Engebretson, M. J., B. J. Anderson, L. J. Cahill, Jr., R. L. Arnoldy, P. T. Newell, C.-I. Meng, L. J. Zanetti, and T. A. Potemra, A multipoint case study of high-latitude daytime ULF pulsations, *J. Geophys. Res.*, *94*, 17143, 1989.

Frank, L. A., Plasma in the Earth's polar magnetosphere, *J. Geophys. Res.*, *76*, 5202, 1971.

Fuller, W. A., *Introduction to Statistical Time Series*, pp. 283-285, John Wiley, New York, 1976.

Gail, W. B., and U. S. Inan, Characteristics of wave-particle interactions during sudden commencements, 2, Spacecraft observations, *J. Geophys. Res.*, in press, 1990.

Gail, W. B., U. S. Inan, R. A. Helliwell, D. L. Carpenter, S. Krishnaswamy, T. J. Rosenberg, and L. J. Lanzerotti, Characteristics of wave-particle interactions during sudden commencements, 1, Ground-based observations, *J. Geophys. Res.*, in press, 1990.

Gendrin, R., Some aspects of ULF waves observed onboard GEOS related to convection, heating, and precipitation processes, in *Exploration of the Polar Upper Atmosphere*, edited by C. S. Deehr and J. A. Holtet, pp. 337-354, D. Reidel, Hingham, Mass., 1980.

Heikkila, W. J., and J. D. Winningham, Penetration of magnetosheath plasma to low altitudes through the dayside magnetospheric cusps, *J. Geophys. Res.*, *76*, 883, 1971.

Helliwell, R. A., S. B. Mende, J. H. Doolittle, W. C. Armstrong, and D. L. Carpenter, Correlations between λ 4278 optical emissions and VLF wave events observed at $L \sim 4$ in the Antarctic, *J. Geophys. Res.*, *85*, 3376, 1980.

Kennel, C. F., and H. E. Petschek, Limit on stably trapped particle fluxes, *J. Geophys. Res.*, *71*, 1, 1966.

Kimura, I., Interrelation between VLF and ULF emissions, *Space Sci. Rev.*, *16*, 389, 1974.

Lanzerotti, L. J., C. G. Maclennan, L. V. Medford, and D. L. Carpenter, Study of a QP/GP event at very high latitudes, *J. Geophys. Res.*, *91*, 375, 1986.

Luhmann, J. G., C. T. Russell, and R. C. Elphic, Spatial distributions of magnetic field fluctuations in the dayside magnetosheath, *J. Geophys. Res.*, *91*, 1711, 1986.

Matthews, D. L., T. J. Rosenberg, J. R. Benbrook, and E. A. Bering III, Dayside energetic electron precipitation over the South Pole λ = 75 degrees), *J. Geophys. Res.*, *93*, 12941, 1988.

Meng, C.-I., and M. Candidi, Polar cusp features observed by DMSP satellites, in *The Polar Cusp*, edited by J. A. Holtet and A. Egeland, pp. 177-192, D. Reidel, Hingham, Mass., 1985.

Morris, R. J., and K. D. Cole, Pc 3 magnetic pulsations at Davis, Antarctica, *Planet. Space Sci.*, *35*, 1437, 1987.

Newell, P. T., and C.-I. Meng, The cusp and the cleft/boundary layer: Low-altitude identification and statistical local time variation, *J. Geophys. Res.*, *93*, 14549, 1988.

Odera, T. J., Solar wind controlled pulsations, a review, *Rev. Geophys.*, *24*, 55, 1986.

Oguti, T., and K. Hayashi, Multiple correlation between auroral and magnetic pulsations, 2, Determination of electric currents and electric fields around a pulsating auroral patch, *J. Geophys. Res.*, *89*, 7467, 1984.

Oguti, T., J. H. Meek, and K. Hayashi, Multiple correlation between auroral and magnetic pulsations, *J. Geophys. Res.*, *89*, 2295, 1984.

Olson, J. V., ULF signatures of the polar cusp, *J. Geophys. Res.*, *91*, 10055, 1986.

Olson, J. V., and L. C. Lee, Pc 1 wave generation by sudden impulses, *Planet. Space Sci.*, *31*, 295, 1983.

Perona, G. E., Theory on the precipitation of magnetospheric electrons at the time of a sudden commencement, *J. Geophys. Res.*, *77*, 101, 1972.

Plyasova-Bakounina, T. A., V. A. Troitskaya, J. W. Muench, and H. F. Gauler, Super-high-latitude maximum of Pc 2-4 intensity, *Acta Geod. Geophys. Montanistica Hung.*, *21*, 143, 1986.

Press, W. H., and S. A. Teukolsky, Search algorithm for weak periodic signals in unevenly spaced data, *Comput. Phys.*, *1*(6), 77, 1988.

Rosenberg, T. J., D. L. Detrick, P. F. Mizera, D. J. Gorney, F. T. Berkey, R. H. Eather, and L. J. Lanzerotti, Coordinated ground and space measurements of an auroral surge over South Pole, *J. Geophys. Res.*, *92*, 11123, 1987.

Russell, C. T., J. G. Luhmann, R. C. Elphic, D. J. Southwood, M. F. Smith, and A. D. Johnstone, Upstream waves simultaneously observed by ISEE and UKS, *J. Geophys. Res.*, *92*, 7354, 1987.

Slawinski, R., D. Venkatesan, A. Wolfe, L. J. Lanzerotti, and C. G. Maclennan, Transmission of solar wind hydromagnetic energy into the terrestrial magnetosphere, *Geophys. Res. Lett.*, *15*, 1275, 1988.

Takahashi, K., and R. L. McPherron, Harmonic structure of Pc 3-4 pulsations, *J. Geophys. Res.*, *87*, 1504, 1982.

Taylor, W. W. L., B. K. Parady, P. B. Lewis, R. L. Arnoldy, and L. J. Cahill, Jr., Initial results from the search coil magnetometer at Siple, Antarctica, *J. Geophys. Res.*, *80*, 4762, 1975.

Tixier, M., and N. Cornilleau-Wehrlin, How are the VLF quasi-periodic emissions controlled by harmonics of field line oscillations? The results of a comparison between ground and GEOS satellites measurements, *J. Geophys. Res.*, *91*, 6899, 1986.

Troitskaya, V. A., T. A. Plyasova-Bakounina, and A. V Gul'elmi, Relationship between Pc 2-4 pulsations and the interplanetary magnetic field, *Dokl. Akad. Nauk SSSR*, *197*, 1312, 1971.

Tsuruda, K., S. Machida, T. Terasawa, A. Nishida, and K. Maezawa, High spatial attenuation of the Siple transmitter signal and natural VLF chorus observed at ground-based chain stations near Roberval, Quebec, *J. Geophys. Res.*, *87*, 742, 1982.

Walker, A. D. M., Excitation of the Earth-ionosphere waveguide by downgoing whistlers, II, Propagation in the magnetic meridian, *Proc. R. Soc. London, Ser. A*, *340*, 1974.

Yumoto, K., T. Saito, B. T. Tsurutani, E. J. Smith, and S.-I. Akasofu, Relationship between the IMF magnitude and Pc 3 magnetic pulsations the magnetosphere, *J. Geophys. Res.*, *89*, 9731, 1984.

B. J. Anderson, The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20707.

R. L. Arnoldy, Institute for the Study of the Earth, Oceans, and Space, University of New Hampshire, Durham, NH 03824.

L. J. Cahill, Jr., Space Science Center, University of Minnesota, Minneapolis, MN 55455.

D. L. Carpenter, Space, Telecommunications, and Radioscience Laboratory, Stanford University, Palo Alto, CA 94305.

R. H. Eather, Department of Physics, Boston College, Chestnut Hill, MA 01167.

M. J. Engebretson, Department of Physics, Augsburg College, Minneapolis, MN 55454.

W. B. Gail, The Aerospace Corporation, P. O. Box 92957, Los Angeles, CA 90009.

T. J. Rosenberg, Institute for Physical Science and Technology, University of Maryland, College Park, MD 20742.

(Received March 29, 1989;
revised July 20, 1989;
accepted September 5, 1989.)