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The Role of the Ionosphere in Coupling Upstream ULF Wave Power Into the Dayside Magnetosphere

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A series of recent studies of Pc 3 magnetic pulsations in the dayside outer magnetosphere has given new insights into the possible mechanisms of entry of ULF wave power into the magnetosphere from a bow shock related upstream source. In this paper we first review many of these new observational results by presenting a comparison of data from two 10-hour intervals on successive days in April 1986 and then present a possible model for transmission of pulsation signals from the magnetosheath into the dayside magnetosphere. Simultaneous multi-instrument observations at South Pole Station, located below the cusp/cleft ionosphere near local noon, magnetic field observations by the AMPTE CCE satellite in the dayside outer magnetosphere, and upstream magnetic field observations by the IMP 8 satellite show clear interplanetary magnetic field field magnitude control of dayside resonant harmonic pulsations and band-limited very high latitude pulsations, as well as pulsation-modulated precipitation of what appear to be magnetosheath/boundary layer electrons. We believe that this modulated precipitation may be responsible for the propagation of upstream wave power in the Pc 3 frequency band into the high-latitude ionosphere, from whence it may be transported throughout the dayside outer magnetosphere by means of an "ionospheric transistor." In this model, modulations in ionospheric conductivity caused by cusp/cleft precipitation cause varying ionospheric currents with frequency spectra determined by the upstream waves; these modulations will be superimposed on the Birkeland currents, which close via these ionospheric currents. Modulated region 2 Birkeland currents will in turn provide a narrow-band source of wave energy to a wide range of dayside local times in the outer magnetosphere.

1. INTRODUCTION

The long history of studies of Pc 3–4 pulsations has been reviewed in earlier papers [*Odera*, 1986; *Vero*, 1986; *Yumoto*, 1986; *Arnoldy et al.*, 1988; *Engebretson et al.*, 1989*a*,*b*]. Although a connection between upstream waves and observations of Pc 3–4 pulsation activity has been suggested for many years, it has been difficult to characterize the efficacy of the connection, and there has been considerable controversy over the range of terrestrial latitudes to which upstream Pc 3–4 pulsation activity can reach. In particular, interplanetary magnetic field (IMF) cone angle effects and pulsation frequency dependence on IMF field magnitude were clearer at low latitudes than at subauroral or auroral latitudes in several data sets [*Greenstadt et al.*, 1979; *Russell et al.*, 1983; *Yumoto et al.*, 1984, 1985; *Yumoto*, 1985].

Since 1982, however, studies of Pi 1 pulsations, which contribute significant power to the Pc 3 frequency band, have provided new insights into this connection. *Arnoldy et al.* [1982], *Engebretson et al.* [1983], *Oguti et al.* [1984], and *Oguti and Hayashi* [1984] showed that Pi 1 activity at auroral and subauroral latitudes was convincingly tied to variations in overhead auroral precipitation. Later studies at cusp/cleft latitudes by *Engebretson et al.* [1986*a*, 1989*b*] using both ground observations and low-altitude satellite data showed a similarly clear correlation between Pi 1 activity and levels of overhead auroral activity. Because of past ambiguities in interpreting high-latitude pulsation data in the Pc 3–4 frequency range, it is particularly important that the reader should be aware of these studies, which show clear morphological and physical distinctions between broadband Pi 1–2 activity at high latitudes and more band-limited Pc 3–4 activity.

Recent studies which separated narrow-band Pc 3–4 pulsation activity from the more broadband Pi 1 pulsation activity in this same frequency range showed clear IMF control of a narrow-band pulsation component [*Engebretson et al.*, 1986*a*, 1989*b*; *Slawinski et al.*, 1988] and thus gave support to the long-standing Soviet practice of distinguishing solar-wind-controlled pulsations from magnetospherically generated pulsations [e.g., *Plyasova-Bakounina et al.*, 1986]. In addition, several studies have shown that Pc 3 pulsations are most intense in the dayside cleft regions [*Bol'shakova and Troitskaya*, 1984; *Plyasova-Bakounina et al.*, 1986; *Morris and Cole*, 1987], and recent observations indicate that they are at times associated with simultaneous pulsations in overhead auroral luminosity [*Engebretson et al.*, 1990*a*].

Perhaps because of the clearer correlation between upstream waves and low-latitude observations, nearly all previous theoretical efforts to model the transport of wave signals from the solar wind/magnetosheath toward Earth have concentrated on physical processes near the equator or, equivalently, have incorporated a theoretical framework which neglects the role of the ionosphere or the ionospheric foot of magnetopause/cusp/cleft field lines. However, the several observational developments cited above make it appropriate to reevaluate our understanding of how Pc 3–4 pulsations propagate into the magnetosphere. As a specific example of some of these recent observational results, we will first show in section 2 multi-instrument observations from two successive days in April 1986 during which the IMF conditions were favorable for the generation of upstream waves for extended periods. In section 3 we will present a review of earlier proposed mechanisms for entry of upstream waves. In section 4 we present a new model of wave entry in which the cusp/cleft ionosphere plays a simple but essential role.

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2. OBSERVATIONS

In each of the two cases below we will show Interplanetary Monitoring Platform (IMP) 8 observations of IMF conditions, magnetic pulsation data for a full orbit of AMPTE CCE (Active Magnetospheric Particle Tracer Explorers/Charge Composition Explorer) through the dayside equatorial magnetosphere, and 10 hours of simultaneous magnetometer, photometer, and ELF-VLF data from South Pole, Antarctica, near local magnetic noon. Fortuitous differences in IMF magnitudes during these two days are used to show IMF magnitude control of the frequency envelope of Pc 3 pulsations both in the outer magnetosphere, where harmonic pulsations are excited, and below the high-latitude ionosphere, where band-limited pulsations are observed in auroral light as well as in magnetic fields. Apart from the unusually prolonged extent of radial IMF orientation, however, these observations are typical of Pc 3 pulsation events studied over a 3-year period at South Pole near local noon and on AMPTE CCE in the dayside outer magnetosphere.

Information about the interplanetary magnetic field (IMF) was obtained by the IMP 8 satellite, located in a nearly equatorial 30- to 40-R_E elliptical orbit roughly upstream during the two days studied here. IMP 8 data used here are 15-s vector samples.

The AMPTE CCE satellite is part of an international three-satellite program to perform active experiments in space. AMPTE CCE was launched into a near-equatorial, highly elliptical orbit with 15.6 hour period and 8.8 R_E apogee on August 16, 1984. Its magnetic fields experiment [*Potemra et al.*, 1985] utilized a three-axis flux gate magnetometer digitally recorded at 8.06 samples/s. Data to be used in this report are 6.2-s median samples and are rotated into a geomagnetic spherical coordinate system. Components to be displayed are *BR*, radially outward from the Earth, *BE*, magnetically eastward, and *BN*, magnetically northward. At the low magnetic latitudes traversed by AMPTE CCE, the *BN* unit vector lies very nearly parallel to the nominal field direction.

South Pole Station, at the Earth's south geographic pole, is located at an invariant latitude of 74°, near the nominal foot point of the dayside cusp/cleft region. It is equipped with a variety of instruments to study ionospheric and magnetospheric processes, including magnetometers, riometers, photometers, and ELF-VLF receivers. 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 magnetometer. This instrument consists of two identical search coil units mounted orthogonally in magnetically northward and eastward directions [*Taylor et al.*, 1975]. Measurements of *D* and *E* region ionization were obtained using the University of Maryland 30-MHz riometers, and optical measurements of auroral brightness were obtained 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 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 narrow-band filter outputs covering the range from 0.5 to 38 kHz. Each of these signals is digitized at a rate of 1 sample/s.

2.1. *April 25, 1986*

Figure 1*a* shows a full day's 15-s IMF data from the IMP 8 satellite, located almost directly upstream from Earth (GSE coordinates 37.3 R_E, 0.25 R_E, and 3.8 R_E at 1200 UT). The upper three panels display Cartesian components of the field in solar magnetospheric coordinates, and the lower three panels show field magnitude, cone angle (with 0° indicating a field aligned with the *X* axis, away from the Earth, and 180° indicating a field aligned antiparallel to the *X* axis), and elevation angle (with 90° indicating a field aligned with the *Z* axis and –90° indicating a field aligned antiparallel to the *Z* axis), respectively.

The IMF cone angle was near 180° for most of the period from 0500 to 2000 UT on this day; the field magnitude was nominally 4 nT and decreased from 6 to less than 2 nT during the interval. During the intervals when the *By* component was centered at zero, there was considerable scatter in all field components and in field magnitude. Intervals of nonzero average *By* and *Bz* components, such as from 0550 to 0645, 1140 to 1215, and 1320 to 1335, are characterized by considerably lower scatter in component values and in IMF magnitude. This suggests that IMP 8 was in the ion foreshock region and observed upstream wave turbulence at times when the *By* and *Bz* components were small.

Figure 1*b* is a local magnetic time–invariant latitude plot of the location of South Pole Station and the magnetic foot point of the AMPTE CCE satellite from 0800 to 1600 UT on this day. Note that local magnetic noon at South Pole is 1530 UT. The local times of the two stations were roughly similar during this period, although AMPTE CCE changed local time more slowly than South Pole when it was was near the apogee of its highly elliptical orbit (from 0800 to 1100 UT) and changed local time more quickly than South Pole from 1400 to 1600 UT.

Plate 1*a* is a color Fourier spectrogram of AMPTE CCE magnetic fields data for a full orbit from 0110 to 1650 UT, April 25, 1986. Apogee is at the center of the figure. The frequency scale, shown on the left, ranges from 0 to 80 mHz, and power levels of the three magnetic field components are displayed at each time and frequency according to the color bar legend at the right edge of the figure. The narrow bottom panel displays variations in field magnitude from the International Geomagnetic Reference Field (IGRF) 1980 model value. The three scales at the bottom of the figure denote the *L* shell, magnetic local time, and magnetic latitude of the satellite. Spectrograms such as this are described in greater detail by *Engebretson et al.* [1986*b*, 1987].

The most prominent feature of this spectrogram is the simultaneous occurrence of harmonically related frequencies in the azimuthal (*BE*) component from 0430 until after 1400 UT. The first, second, and third harmonics are excited during this entire interval, and a fourth harmonic is clearly visible from 0900 until after 1300 UT. Wave power is generally greater in the frequency band from 15 to 30 mHz than at higher or lower frequencies throughout the pass, regardless of *L* shell.

On the basis of other, similar spectrograms [*Engebretson et al.*, 1986*b*] we interpret the absence of the fourth harmonic near 0800 and the relative weakening of the second harmonic near 1100 UT to be related to the nodal structure of the resonant harmonics. These variations during the gradual passage of the AMPTE CCE spacecraft to increasing magnetic latitudes are consistent with the *Cummings et al.* [1969] model of the nodes and antinodes of ULF field line resonances, but only if nodes of even harmonics are located somewhat closer to the geomagnetic equator than predicted by the model. Although one would expect the amplitude of the fundamental to increase significantly as the satellite moves latitudinally away from the magnetic equator, this effect is usually offset in the AMPTE CCE data by local time effects: fundamental mode (Pc 5) oscillations peak near dawn and appear to have a quite different driving source than the second and higher harmonics [*Anderson et al.*, 1990].

From 0430 until after 0730 UT, power in the locally resonant fundamental mode is evident in the northward (*BN*) component as well as in the azimuthal (*BE*) component. The appearance of power in this component, usually associated with compressional waves, is

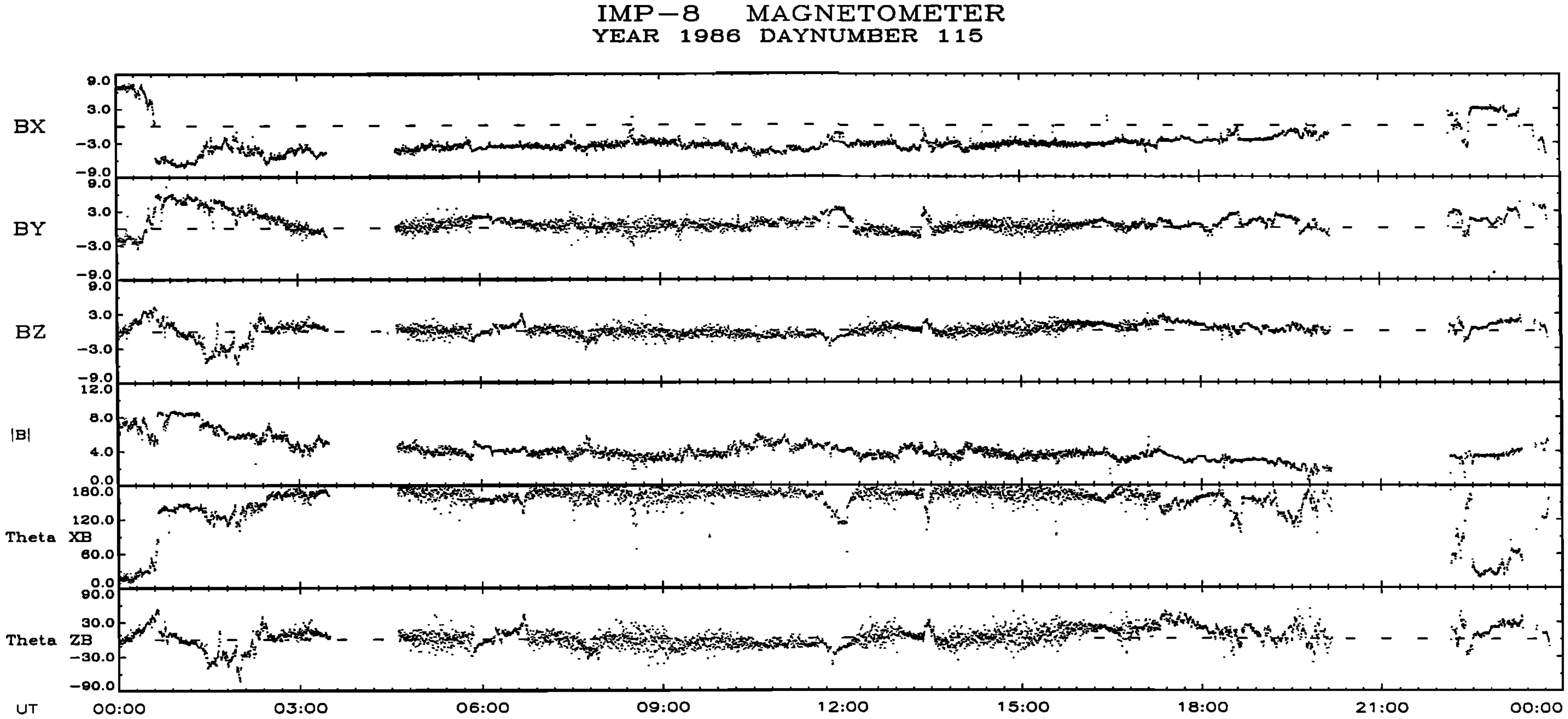

Fig. 1*a*. Plot of interplanetary magnetic field (IMF) data obtained by the IMP 8 spacecraft during April 25, 1986. The top three panels show the magnetic field components in a geocentric solar magnetospheric coordinate system. The lower panels display field magnitude, cone angle, and elevation angle, respectively.

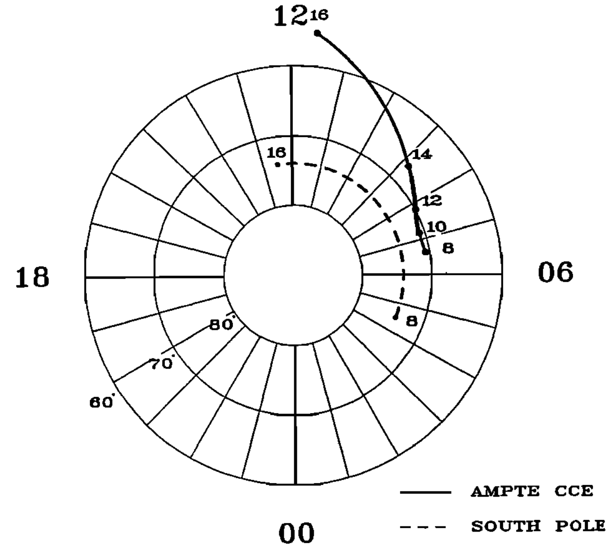

Fig. 1*b*. Schematic diagram showing the trajectories of South Pole Station (dashed line) and the magnetic foot point of the AMPTE CCE satellite (solid line) on a local time–invariant latitude dial, for the interval 0800 to 1600 UT, April 25, 1986. Solid circles show the location of the AMPTE CCE satellite at 2-hour intervals. During this period, AMPTE CCE was at nearly the same local time as South Pole Station, but always at lower invariant latitudes.

most likely caused by distortion of the quiet-time field in the near-dawn outer magnetosphere and is thus probably not a true compressional resonance.

Weaker, broadband power with a similar frequency envelope is evident in the northward component, especially from 0630 to 1030 UT. This power has an upper limit near 40 mHz and lower limit near 5 mHz. The radial component shows a still weaker envelope during the same time interval. Although its apparent bandwidth is narrower and it appears to have a lower center frequency, the power evident in this component most closely matches the frequency range of maximum power in the *BE* component. We suspect that the apparently narrower bandwidth of the radial component is an artifact resulting from both the 16-color display used and the low signal levels in the presence of background.

Data from South Pole Station from 1000 to 2000 UT are presented in a similar format in Plate 1*b*. From top to bottom are shown Fourier spectrograms of the north-south component of the wave magnetometer (YBB), the 427.8-nm photometer (PHO2), and the 500- to 1000-Hz ELF-VLF receiver (VLF1). The larger frequency range used in this spectrogram, 0–250 mHz, was chosen to show the presence of both broadband (Pi 1–2) and band-limited (Pc 3–4) pulsation activity, as is typical of ground-based data at cusp/cleft latitudes during daytime hours [*Engebretson et al.*, 1986*a*, 1989*b*].

Band-limited power in the 5- to 40-mHz range is evident in the top panel during all but the last hour shown and is relatively intense from 1100 UT (0730 MLT) to 1800 UT (1430 MLT). Broadband activity is also evident and is most prominent from 1100 to shortly after 1200 UT and near 1400 and 1730 UT. Band-limited and broadband signals in the 427.8-nm photometer data (middle panel) are similar to those in the magnetometer data (top panel) during most of the 6-hour interval centered near local noon. ULF modulations in the ELF-VLF signals, known as quasi-periodic (QP) variations (bottom panel), are evident in the bottom panel sporadically from 1400 to 1900 UT. Both broadband and band-limited modulations occur only during periods when similar signals are evident in the magnetic field spectrogram.

In Figure 1*c* we display logarithmic power spectra of 2048 one-second samples from these and other instruments at South Pole Station for a 34-min period beginning at 1800:20 UT. From top to bottom are shown the east-west and north-south components of the wave magnetometer signal in nanoteslas per hertz (XBB and YBB), the raw signal from the 30-MHz riometer (RIO3), the 427.8-nm photometer (PHO2), and the 500- to 1000-Hz and 1000- to 2000-Hz ELF-VLF receivers (VLF1 and VLF2). A vertical dotted line has been drawn at 17.4 mHz, the expected frequency for upstream Pc 3–4 pulsations based on elementary theory [*Gul'elmi*, 1974] using the formula

$$f = 0.006\, |B|\ (\mathrm{nT}) \tag{1}$$

which is consistent with many observations [*Gul'elmi*, 1988]. (An estimated delay time of 470 s, based on the hourly averaged solar wind velocity of 520 km/s during this time, was incorporated into the calculation of the average IMF magnitude of 2.9 nT during this interval.) The frequency of this line lies near the center frequency of the observed increases in power in five of the six traces shown. A calculation of the expected frequency was also made using the theoretically based formula of *Takahashi et al.* [1984*a*],

$$f = 0.0076\, |B|\ (\mathrm{nT}) \cdot \cos^2(\theta_{xB}) \tag{2}$$

with a resulting value of 19 mHz, or ~10% higher than the frequency calculated using the empirical formula.

The vertical error bar in Figure 1*c* indicates the 99% confidence level according to Fisher's test for a power spectrum based on 2048 data points. It is apparent that the broad peaks in five of the six traces shown lie above the background levels by an amount on the order of or larger than this level. Power is conspicuously absent only in the riometer trace. For further details of these multi-instrument data and of the statistical significance of the spectral peaks, refer to *Engebretson et al.* [1990*a*].

Figure 1*a* indicated a sharp, temporary deviation of the IMF cone angle from the radial direction from 1140 to 1215 UT, with the angle deviating from radial by more than 45° from 1148 to 1205 and reaching 60° or more from radial from 1154 to 1204 UT. According to the usual cone angle–pulsation relationship, this interval of time should be quite unfavorable for the observation of Pc 3 activity in the magnetosphere. However, band-limited Pc 3 pulsations at South Pole and resonant harmonics at AMPTE CCE continue with essentially undiminished amplitude through this interval (this was also verified with detailed waveform plots). Although it is possible that IMP 8 and the Earth's magnetosphere observed considerably different IMF conditions for this brief interval, it is also possible that the 20-min time interval of unfavorable IMF orientation is simply too short to turn off the extended upstream wave source. We note that in an earlier study of upstream waves and IMF orientation using the AMPTE IRM satellite and simultaneous magnetospheric pulsations using the AMPTE CCE satellite, *Engebretson et al.* [1987] found minimum switching times on the order of tens of minutes for Pc 3 pulsations controlled by IMF reorientations.

2.2. *April 24, 1986*

Figure 2*a* shows IMP 8 magnetometer data for the previous day, April 24, 1986. Each component of the field showed considerably more variation on short time scales than on April 25, and the IMF magnitude was considerably higher, varying between 5 and 8 nT during the latter part of the day. It is evident that the IMF was again predominantly radial during much of the day, with the cone angle above 150° almost continuously from 1045 until 1455 UT and again from 1640 to 1745 UT. The IMF was roughly transverse to the *X* axis (cone angle near 90°) for short periods near 1530, 1600, and 1800 UT and for a ~25-min interval shortly before 1930 UT.

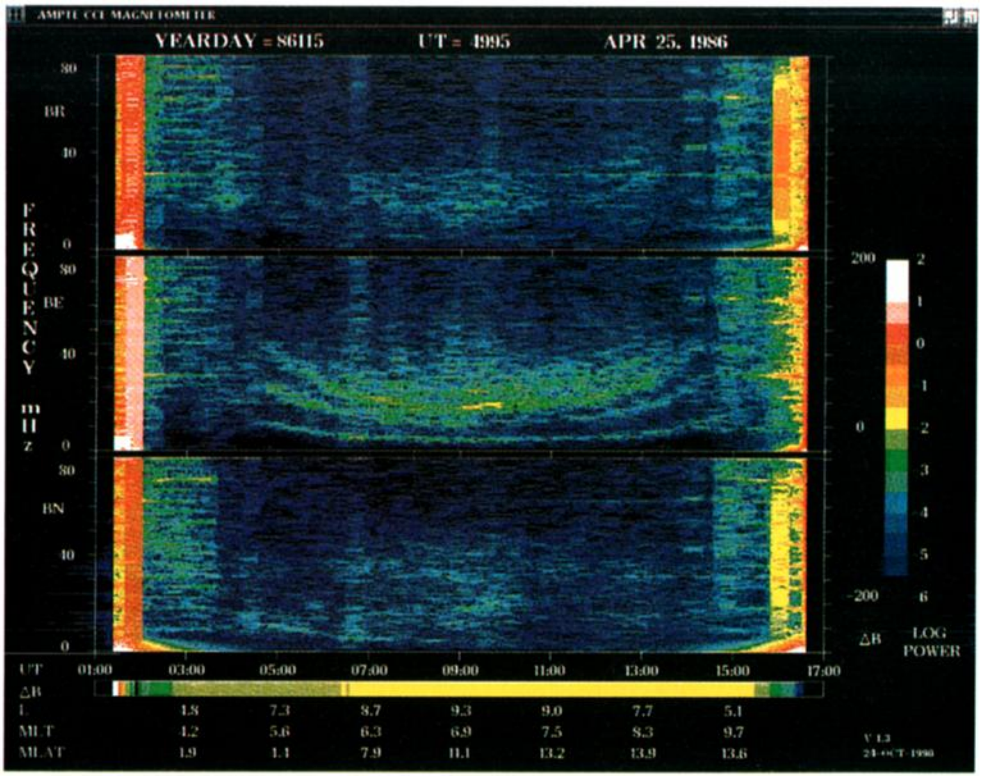

Plate 1*a*. Three component dynamic power spectra of magnetic field data from the AMPTE CCE satellite for a full orbit from 0110 to 1650 UT, April 25, 1986. Apogee is at the center of the figure. The components shown are in a geomagnetic spherical coordinate system, with *BR* radially outward, *BE* eastward (azimuthal), and *BN* magnetically northward. The narrow bottom panel indicates deviations of the total field from IGRF 1980 model values.

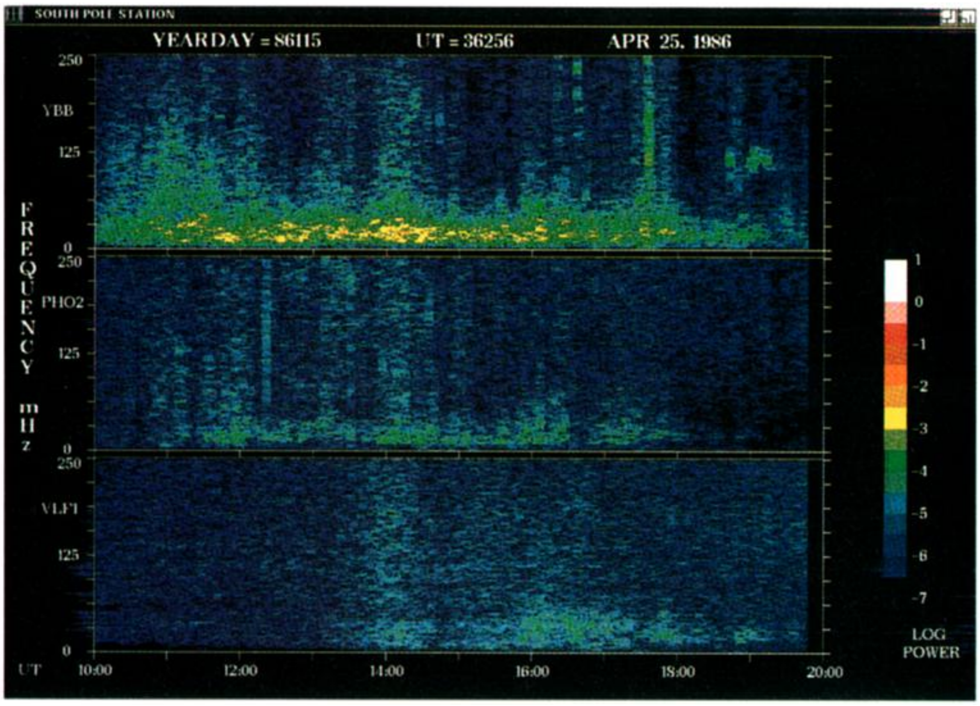

Plate 1*b*. Dynamic power spectra of ULF wave activity from three instruments at South Pole, Antarctica, from 1000 to 2000 UT, April 25, 1986. From top to bottom are color-coded power levels for the *Y* (magnetically northward) component of the wave magnetometer (YBB), 427.8-nm photometer (PHO2), and 0.5- to 1.0-kHz ELF-VLF receiver (VLF1). Local time at South Pole Station is UT minus 3.5 hours.

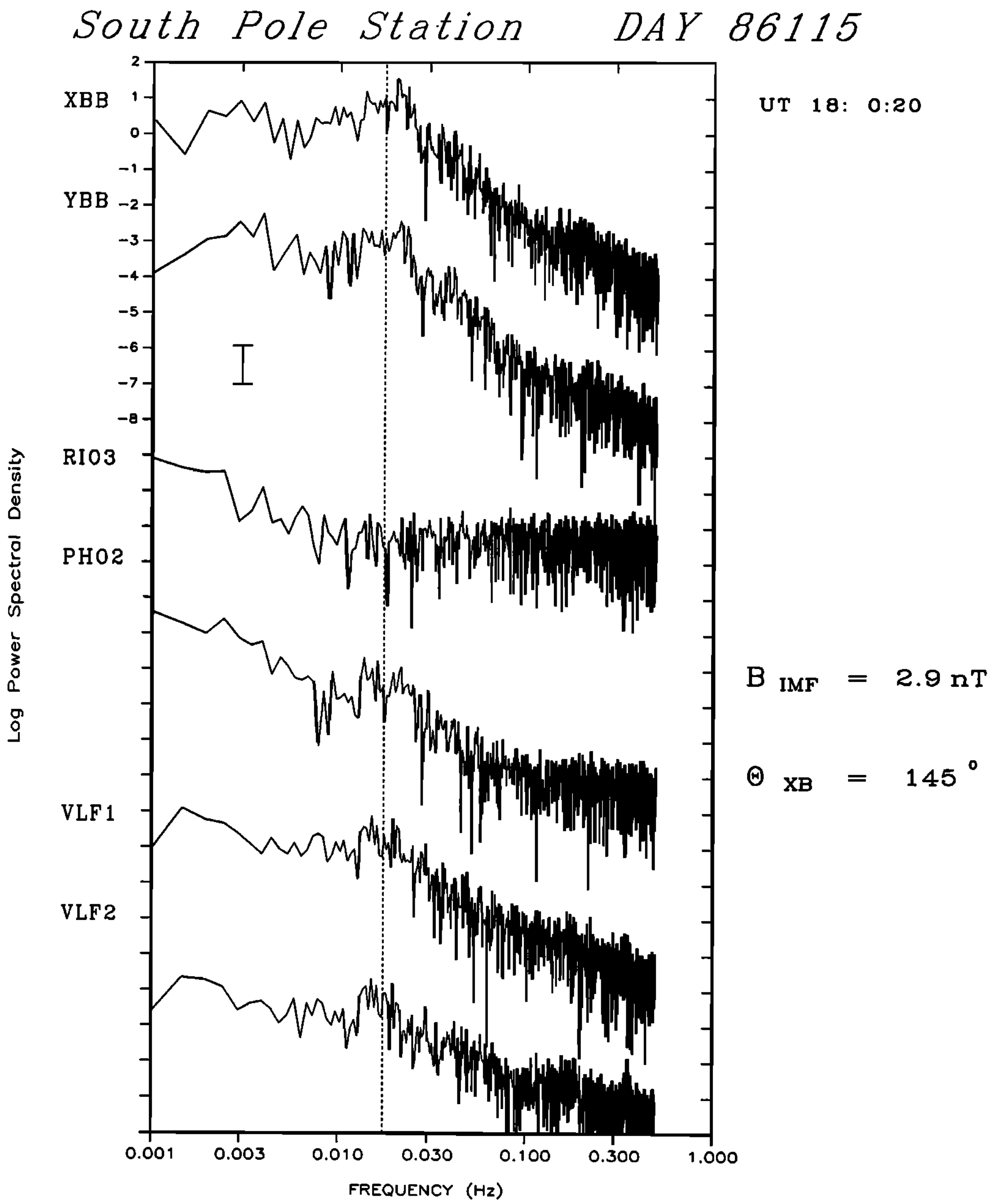

Fig. 1c. Logarithmic power spectra of data obtained at South Pole Station, Antarctica, from 1800 to 1834 UT, April 25, 1986. The traces from top to bottom are from east-west and north-south oriented wave magnetometers (XBB and YBB), 30-MHz riometer (RIO3), 427.8-nm photometer (PHO2), and 0.5- to 1.0-kHz and 1.0- to 2.0-kHz ELF-VLF receivers. The vertical error bar indicates the 99% confidence level according to Fisher's test for a power spectrum based on 2048 data points. Also shown are the hourly average magnitude and cone angle of the interplanetary magnetic field (IMF). The vertical line represents the predicted center frequency of upstream waves, determined by the IMF magnitude according to equation (1).

Figure 2*b* is a local magnetic time–invariant latitude plot of the location of South Pole Station and the magnetic foot point of the AMPTE CCE satellite from 1100 to 2000 UT on this day. The satellite and South Pole Station were clearly never close to the same flux tubes during this interval.

Plate 2*a* is a color Fourier spectrogram of AMPTE CCE magnetic field data for the previous orbit, from 0930 UT, April 24, 1986, to 0110 UT, April 25, 1986. Resonant harmonic pulsations are apparent in the *BE* component even before the magnetic fields experiment changed to a more sensitive range at 1200 UT, and they continue until after 2100 UT at varying power levels. As expected for resonant harmonics, the fundamental and third harmonic have much lower power than the even harmonics (second and fourth) near the time the satellite crosses the magnetic equator (1900 to 2100 UT). Broadband power is again evident in the compressional component, especially for larger *L* values, with power levels varying with those in the azimuthal component. Power in all three components is clearly at a minimum near 1930 UT, consistent with the IMF data in Figure 2*a* which show a 25-min interval of IMF orientation unfavorable for upstream wave generation at this time. As was the case in Plate 1*a*, the resonant harmonics appear to be stimulated only within the bandwidth of the more broadband power enhancement. In contrast to Plate 1*a*, however, the frequency range of azimuthal and compressional broadband power goes up to at least 50 or 60 mHz.

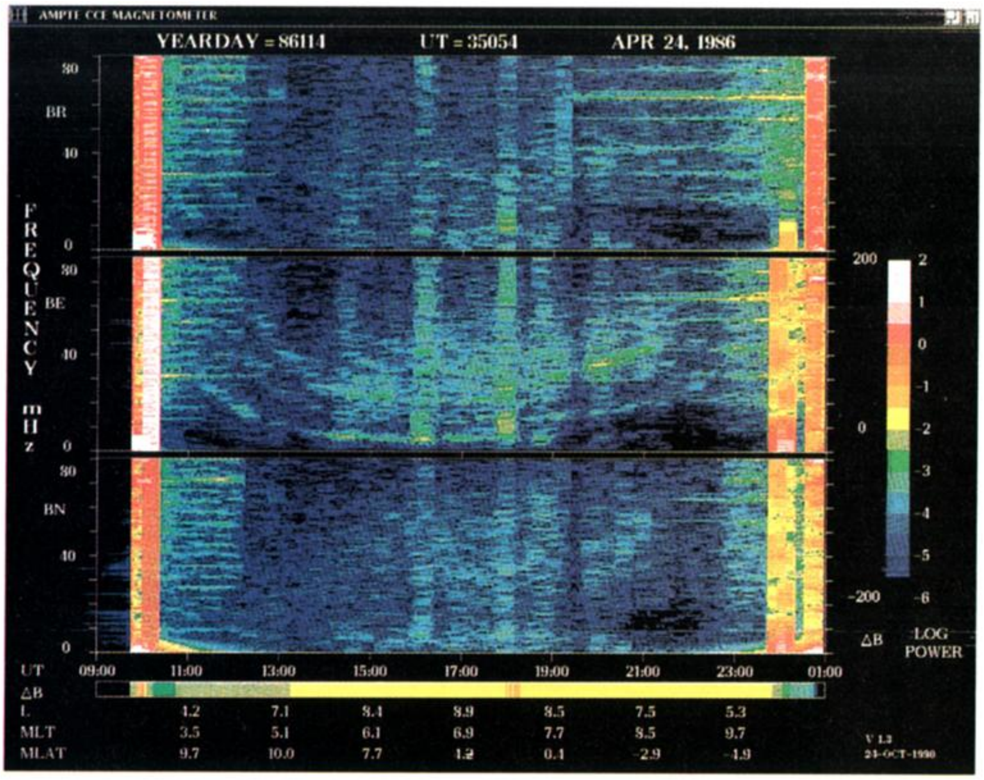

Plate 2*a*. Three component dynamic power spectra of magnetic field data from the AMPTE CCE satellite for a full orbit from 0930 UT, April 24, 1986, to 0110 UT April 25, 1986, as in Plate 1*a*.

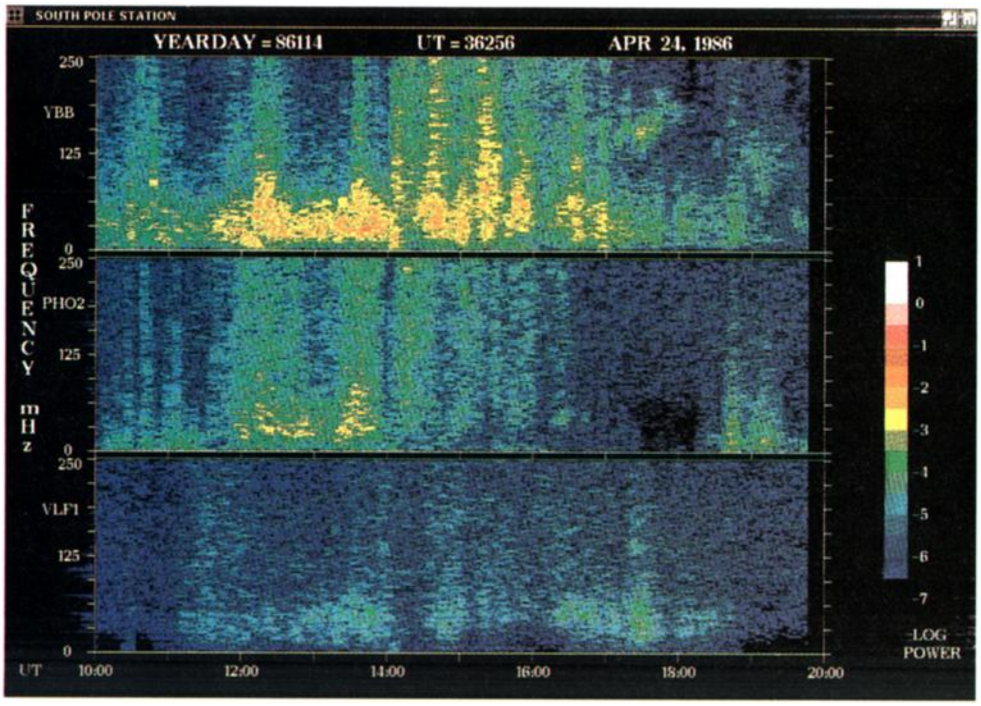

Plate 2*b*. Dynamic power spectra of ULF wave activity from three instruments at South Pole, Antarctica, from 1000 to 2000 UT, April 24, 1986, as in Plate 1*b*.

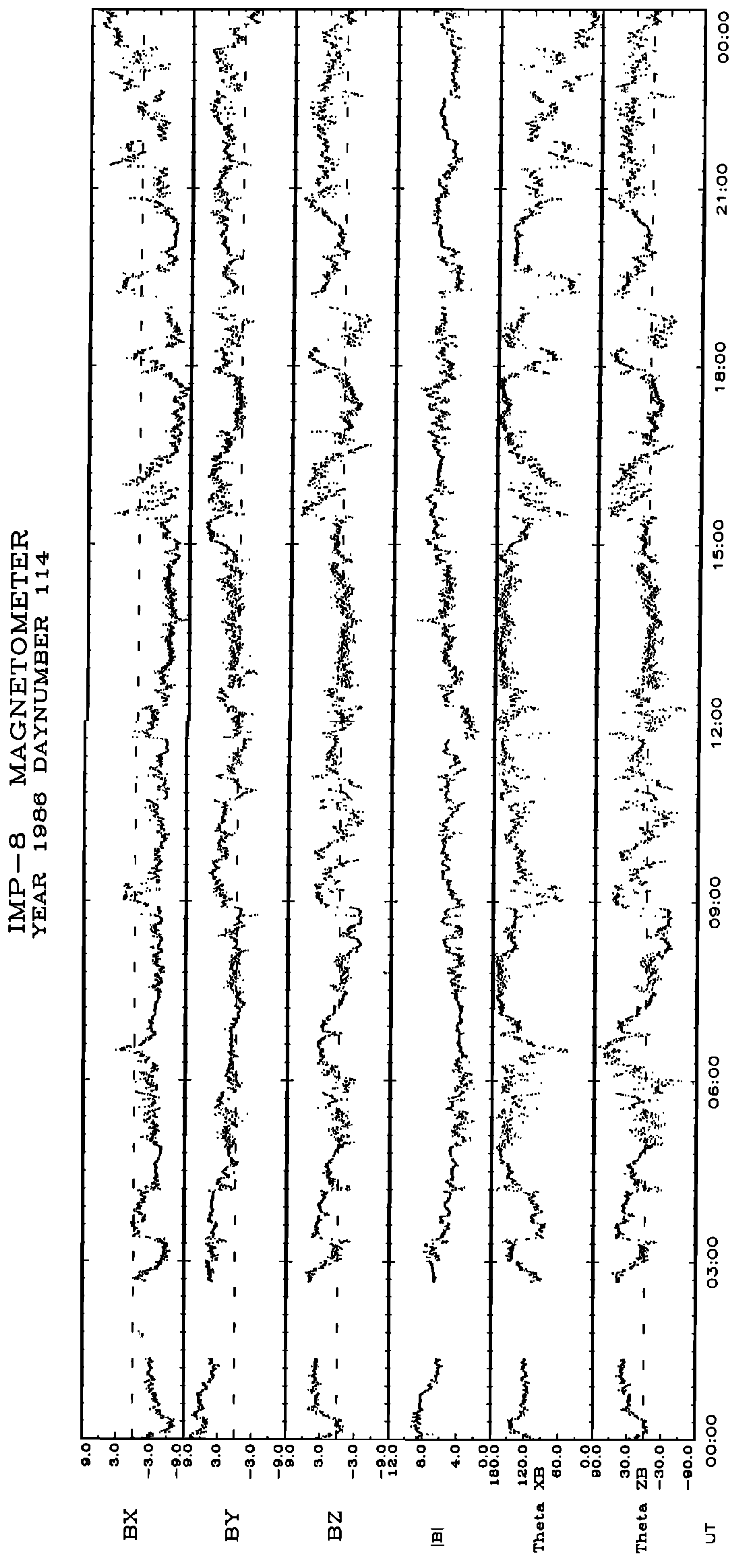

Fig. 2*a*. Plot of interplanetary magnetic field data obtained by the IMP 8 spacecraft during April 24, 1986, as in Figure 1*a*.

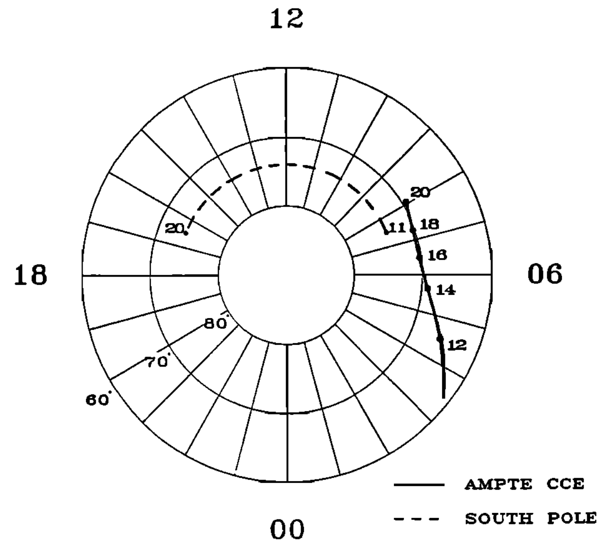

Fig. 2*b*. Local time–invariant latitude dial plot of the trajectories of South Pole Station and AMPTE CCE from 1100 to 2000 UT, April 24, 1986, as in Figure 1*b*. During this interval the satellite and South Pole Station were clearly never close to the same flux tubes.

Data from South Pole Station from 1000 to 2000 UT, April 24, 1986, are presented in Plate 2*b*. Again band-limited power is superposed on broadband signals of highly varying amplitude. On this day, however, the frequency range of the band-limited component is from ~10 mHz to 60–70 mHz, considerably higher than that shown in Plate 1*b*. As in that figure, band-limited Pc 3 pulsations occur in photometer and ELF-VLF receiver signals during subsets of the times they appear in the magnetic field spectrogram, and with identical frequency envelopes.

In Figure 2*c* we display logarithmic power spectra from six instruments at South Pole Station during the interval from 1620 to 1654 UT, as in Figure 1*c*. We again calculated the expected average frequency for upstream Pc 3–4 pulsations using IMP 8 magnetic field data and including a time delay corresponding to the observed ~600-km/s solar wind velocity. The frequency shown in the figure, 42 mHz, was calculated using equation (1); use of equation (2) in this case gave a ~3% lower frequency. The vertical dotted line again lies near the center frequency of the observed increases in power in five of the six traces shown, and again only the riometer trace is devoid of power. During this interval, enhancements in the magnetic field include both broadband and band-limited components (refer to Plate 2*b*), so the spectral enhancements are less clear near the upstream wave frequency. The spectral peaks in the lower three bars, however, again meet or exceed the 99% confidence level.

2.3. *Summary of Observations*

1. Magnetic pulsations in the Pc 3 period range are observed simultaneously at South Pole Station and at the AMPTE CCE satellite in the outer dayside magnetosphere during times of low IMF cone angle. The pulsations in space occur simultaneously over a wide range of dayside local times and outer magnetospheric *L* shells. Pulsations at South Pole are strongest near local noon, when it is situated under the nominal footpoint of the dayside cusp/cleft region, but extend throughout the local time region identified as the ionospheric foot of the low-latitude boundary layer [*Newell and Meng*, 1988].

2. Pulsations in auroral light at 427.8 nm wavelength are often observed with magnetic pulsations at South Pole, and Pc 3 period modulations of the ELF-VLF signal are occasionally observed at South Pole in the 0.5- to 1.0-kHz and 1.0- to 2.0-kHz frequency ranges as well. Whereas ground magnetometers are sensitive to ionospheric currents at considerable distances, the South Pole photometer's 55° full width field of view allows detection of only overhead auroral activity. We thus infer that localized regions of modulated auroral pulsations occur on the dayside at very high geomagnetic latitudes and that they were overhead at South Pole more often on April 25 than on April 24.

The interpretation of the ELF-VLF data is not as clear, because quasi-periodic emissions of the sort shown here ("polar chorus") have been observed over a range of high latitudes on the dayside. Although at least some of the modulated ELF-VLF signal appears to be produced on closed outer magnetospheric field lines (near the magnetopause) by interactions with compressional field perturbations [*Gail et al.*, 1990], these signals could be produced at locations with varying *L* shell and local time and then propagate to South Pole after exiting the ionosphere. Modulated ELF-VLF signals are observed over 50% of the time magnetic pulsations occur, and they appear to correlate with at least moderately enhanced levels of geomagnetic activity ($Kp > 1$), suggesting a threshold effect based on the density of trapped magnetospheric electrons. A further study of the occurrence and spatial distribution of the ELF-VLF modulations is in progress.

3. The IMF magnitude appears to control the frequency of Pc 3 pulsations in all South Pole instruments except the riometer. The frequency envelope of compressional broadband and azimuthal harmonic pulsations at AMPTE CCE varies in the same way.

4. Although not shown here, 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 [*Engebretson et al.*, 1990*a*], but no riometer variations are noted during periods of band-limited Pc 3 activity. Because riometers are sensitive to electrons with energies of several keV and above [*Matthews et al.*, 1988] while the 427.8-nm photometer is sensitive to precipitation with much lower energies, *Engebretson et al.* [1990*a*] interpreted these observations as showing that those precipitating electrons responsible for the auroral emissions at Pc 3 frequencies probably had energies less than 1 keV and originated in the magnetosheath or boundary layer.

3. REVIEW OF MODELS OF UPSTREAM WAVE ENTRY

The ion foreshock region of the solar wind, upstream of the Earth's bow shock, has been considered a major candidate for the source of dayside Pc 3–4 pulsations for nearly two decades. In this region, solar wind ions (mostly protons) reflected upstream from the bow shock interact with the bulk plasma of the solar wind via an ion cyclotron instability to generate Alfvén waves in the interplanetary medium [*Fairfield*, 1969; *Thomsen*, 1985]. The frequency of these waves, as seen in a frame of reference traveling with the Earth, is in the Pc 3–4 period range (20 to 120 s), with a typical period varying as $160/B$ s, for B in nanoteslas [*Troitskaya et al.*, 1971]. The ion foreshock region develops upstream of the subsolar bow shock when the interplanetary magnetic field (IMF) is oriented in an approximately radial direction, i.e., when the IMF cone angle, $\theta_{xB} = \cos^{-1}(Bx/|B|)$, is closer to 0° or 180° than to 90°. Under these conditions the bow shock upstream of the Earth is in a quasi-parallel shock geometry, favorable for the reflection of solar wind ions and thus for the generation of these waves [*Paschmann et al.*, 1979; *Russell and Hoppe*, 1983; *Yumoto*, 1985]. For cone angles very close to 0°or 180°, waves appear to form directly at the subsolar shock itself [*Greenstadt*, 1986].

Pc 3 pulsations observed on the ground and in space inside the

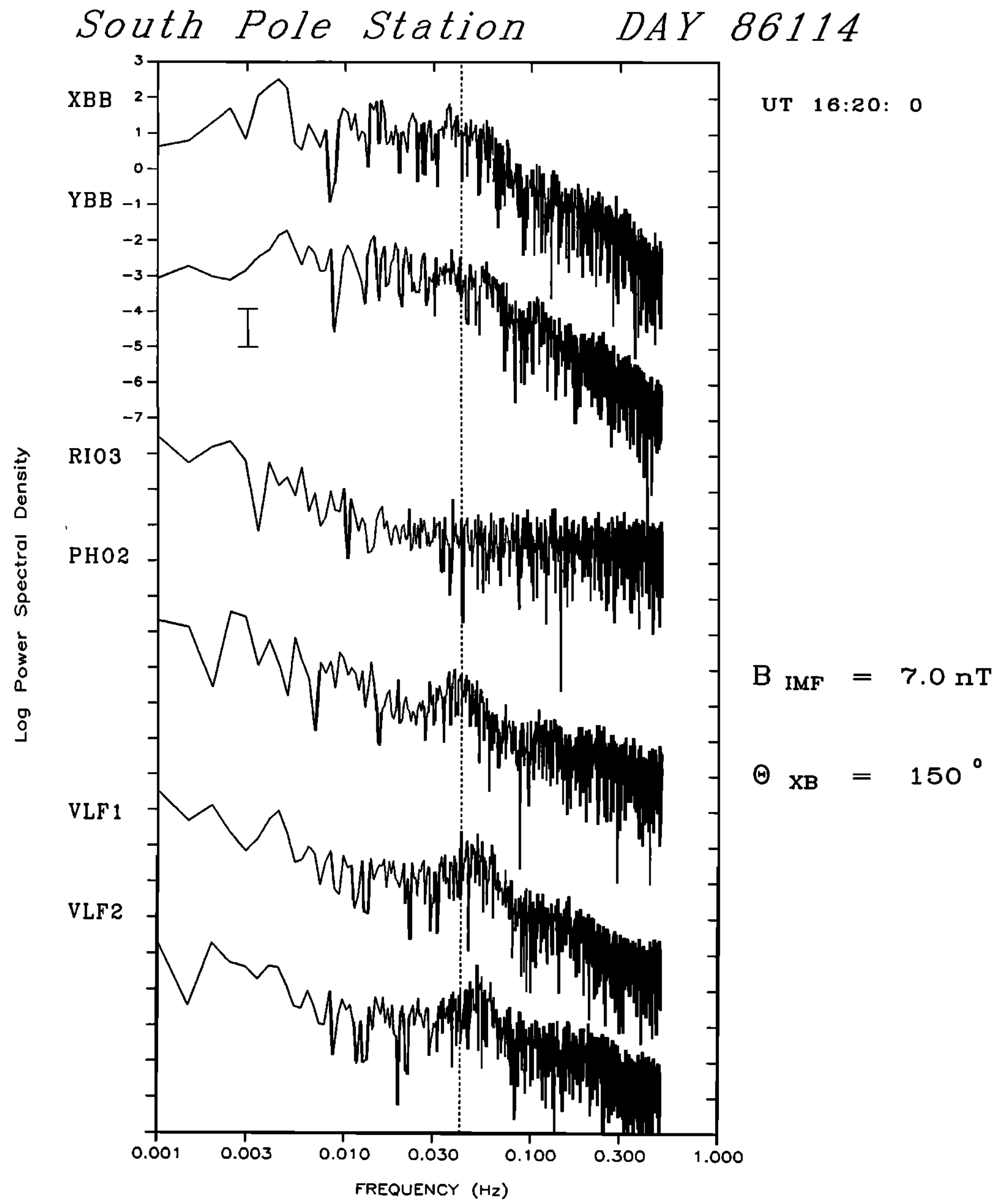

Fig. 2*c*. Logarithmic power spectra of data obtained at South Pole Station, Antarctica, from 1620 to 1654 UT, April 24, 1986, as in Figure 1*c*.

magnetosphere have been tied to waves generated in this upstream region by several studies, ranging from the pioneering work of *Troitskaya et al.* [1971] and *Greenstadt* [1972] to recent studies by *Greenstadt et al.* [1980], *Yumoto et al.* [1984, 1985], and *Engebretson et al.* [1986*a*, 1987].

Fairfield and Ness [1970] established that the quasi-parallel shock is a dominant source of dayside magnetosheath field fluctuations, and *Greenstadt* [1972] appears to have been the first to make the suggestion that magnetosheath turbulence originating on streamlines near the subsolar bow shock will bathe the dayside magnetopause. *Russell et al.* [1983] built on this concept in developing a simple geometrical model explaining the influence of the IMF cone angle in determining the propagation of waves generated in the ion foreshock region to the magnetosheath and magnetopause. *Crooker et al.* [1981] and *Luhmann et al.* [1986] used ISEE data to provide experimental support for these ideas by showing a clear correlation between the IMF direction and the presence of energetic ions in the magnetosheath, and between the IMF direction and levels of magnetosheath turbulence, respectively.

Recent multisatellite studies by *Engebretson et al.* [1990*b*] and *Lin et al.* [1990] have verified and extended these earlier studies. *Engebretson et al.* [1990*b*] compared ISEE 1/2 upstream magnetic field data, AMPTE IRM plasma and magnetic field data in the subsolar magnetosheath, and AMPTE CCE magnetic fields data in the dayside outer magnetosphere. They found, both on a statistical and on a case-by-case basis, that IMF cone angles allowing a quasi-parallel shock to form at the subsolar bow shock correlated well with extremely turbulent magnetosheath plasma and fields and with simultaneous excitation of harmonic Pc 3–4 pulsations in the dayside outer magnetosphere. *Lin et al.* [1990], in an extension of this work, quantified the magnetosheath turbulence and found greatly increased and variable kinetic and thermal beta values, disordered magnetic fields, and the presence of an energetic (> 8 keV) plasma component in the magnetosheath to be associated with low cone angle and simultaneous magnetospheric harmonic Pc 3–4 activity. The observed thermal beta values, often >> 1, indicate that during these periods the convecting subsolar magnetosheath plasma, or at least its high - energy portion, is not well constrained by magnetic fields (consistent with the much earlier conclusion of *Asbridge et al.* [1978]), and thus plasma processes at the magnetosheath/magnetopause/boundary layer interface will be much more complicated than is assumed by many models of such boundary processes.

Theoretical studies of the transport of solar wind generated wave energy into the magnetosphere have until recently focused on direct entry of wave energy across the magnetopause, usually near the equator, followed by mode conversion to generate resonant transverse pulsations. The earliest mechanism, suggested by *Verzariu* [1973], was transmission of compressional wave power, but with severe attenuation, directly across tangential discontinuities at the equatorial subsolar magnetopause. A small fraction of the wave energy in the magnetosheath penetrates a tangential magnetopause discontinuity near the subsolar equatorial point at normal incidence and propagates in the compressional mode into the magnetosphere. Refraction effects spread the wave energy somewhat. The waves are expected to attenuate gradually as they pass into the magnetosphere, coupling some of their energy into transverse modes.

Wolfe and Kaufmann [1975] found support for Verzariu's model in data from Explorer 12 near the subsolar magnetopause, and *Greenstadt et al.* [1983], using ISEE 1 and 2 data on either side of the magnetopause, confirmed Verzariu's prediction of a roughly 2 orders of magnitude attenuation of power across the subsolar magnetopause. Several studies of the penetration of such waves deep into the magnetosphere, however, indicated considerable disagreement between the expected wave attenuation and the observed wave amplitudes at different L shells [*Lanzerotti et al.*, 1981, 1989; *Wolfe et al.*, 1989]. Primarily because of this disagreement, *Lanzerotti et al.* [1981] were the first to suggest that pulsations observed at low latitudes might be transmitted via the ionosphere from cusp latitudes by some as yet unknown mechanism.

One-fluid MHD calculations nearly a decade later by *Kwok and Lee* [1984] suggested that ULF waves of all polarizations could propagate across rotational discontinuities, in association with the reconnection process. They also showed that, in contrast to the severely attenuated transmission of Verzariu's mechanism, wave power could even be amplified across a rotational (open) magnetopause boundary. In their model, waves reaching the magnetopause enter and are amplified at rotational discontinuities (sites of reconnection). Compressional waves are launched in all directions into the magnetosphere, and transverse waves are guided along cusp and low-latitude boundary layer (LLBL) field lines toward low altitudes. Compressional waves will couple and attenuate as they travel inward as in the Verzariu model.

The only restriction in the *Kwok and Lee* [1984] model, of course, is that reconnection must occur in order for such wave transmission to take place. Although the elusive nature of the reconnection process makes it difficult to test the validity of their model, there is some evidence that reconnectionlike events and the presence of Pc 3 activity near the foot point of the cusp/cleft/LLBL are related. A study of magnetic field signatures at cusp latitudes by *Olson* [1986] found associations between Pc 3 pulsations and irregular pulses in the Pc 5 period in the cusp region. *Sandholt et al.* [1986] found intense Pc 3 pulsation activity during the times they observed auroral signatures consistent with flux transfer events [*Russell and Elphic*, 1979], but they did not comment on the significance of these pulsations. Unpublished data from search coil magnetometers at South Pole Station, Antarctica, also at times showed the presence of strong Pc 3 activity in conjunction with these signatures.

Our observations at South Pole have shown that the occurrence and amplitude of Pc 3–4 pulsations have little if any dependence on the sign of IMF Bz or, when the IMF is radial, on the sign of Bx. This suggests little dependence on the IMF directions usually associated with reconnection. However, studies of magnetosheath fields during times of upstream wave activity by *Engebretson et al.* [1990*b*] and *Lin et al.* [1990] showed a large (often 30 nT or more), rapidly fluctuating Z component of the magnetosheath field specifically when the IMF was largely radial, regardless of the sign of the small upstream Bz component. Although the duration of the large southward magnetosheath fields thus produced was usually quite short (typically 1 min or less), available data cannot rule out a possibly significant role for reconnection, and hence the Kwok and Lee mechanism, in the process of wave transmission.

The MHD treatments above support a direct transmission of upstream wave energy into the magnetosphere, but many data sets have suggested a more complex transmission mechanism. *Singer et al.* [1977], *Greenstadt et al.* [1979], *Golikov et al.* [1980], *Dowden and Fraser* [1984], and *Vero* [1986], for example, viewed the generally good correlation between Pc 3–4 pulsation amplitude and solar wind velocity as supportive of the role of Kelvin-Helmholtz instabilities, which convert the energy of relative bulk plasma flow into vortex kinetic energy and magnetic turbulence [*Miura and Pritchett*, 1982].

Because of the importance of a large velocity shear, most studies indicate a larger growth rate for this instability in the flanks and/or high-latitude regions of the magnetosphere than near the subsolar point, where the relative flow velocity is low [*D'Angelo*, 1977, *Yumoto*, 1984]. *Anderson et al.* [1990], in a statistical study of ULF pulsations in the Pc 3–5 period range based on data from the equatorially orbiting AMPTE CCE satellite, found that fundamental mode resonances and harmonic Pc 3–4 pulsations are two independent but at times overlapping phenomena, with quite different occurrence distributions in local time and L shell. In particular, *Anderson et al.* [1990] found that the most intense harmonic resonance events were observed on the dayside from 0600 to 1600 MLT, while intense fundamental resonance events were observed from 0300 to 0900 MLT, consistent with the existence of a source of energy for Pc 5 pulsations (but not for higher harmonics) in the flanks of the magnetosphere. In addition, the radial distributions of harmonic and fundamental events were markedly different. Harmonic events were observed with nearly uniform occurrence at all L values from $L = 5$ to 9, while the fundamental events displayed a prominent and consistent trend of increasing occurrence with increasing L: the occurrence frequency for $L = 8$ to 9 was approximately double that for $L = 6$ to 7. This suggests that the Kelvin-Helmholtz instability may be a major source for Pc 5 pulsations, but not for Pc 3-4 activity in the outer equatorial magnetosphere.

Earlier results from studies of azimuthal phase velocities also support a distinction between generation mechanisms for Pc 5 pulsations and the higher-frequency Pc 3–4 activity. The field line resonance models of *Chen and Hasegawa* [1974*a*] and *Southwood* [1974] assumed a large azimuthal wave number m for their models of field line resonance. Such large wave numbers were observed for Pc 5 pulsations, and their azimuthal phase velocities appeared to be consistent with those expected for a Kelvin-Helmholtz source on the flanks of the magnetosphere [*Takahashi and McPherron*, 1984]. The observations of *Green* [1976], *Hughes et al.* [1978], *Mier-Jedrzejowicz and Southwood* [1979], and *Takahashi et al.* [1984*b*], however, indicated that pulsations in the Pc 3–4 period range have relatively small east-west phase variations, inconsistent with both a Kelvin-

Helmholtz instability on the flanks of the magnetosphere and with the above models of wave coupling leading to field line resonances. These observations contributed to suggestions by *Kivelson and Southwood* [1985, 1986] of the existence of global compressional mode resonances, with $m = 0$, which might couple to the transverse waves commonly observed in the magnetosphere. The mechanism we will suggest below is also consistent with the observed small east-west phase variation in Pc 3–4 pulsations.

We remind readers that harmonic Pc 3–4 transverse pulsations in the outer magnetosphere ($L \geq 4$) are local resonances [*Takahashi and McPherron*, 1982; *Engebretson et al.*, 1986*b*, 1987], with periods governed by plasma densities and path lengths along individual magnetic field lines [*Hasegawa et al.*, 1983]. Although compressional pulsations observed simultaneously with the transverse harmonics by *Engebretson et al.* [1987] did appear to match the period of upstream waves observed simultaneously by the AMPTE IRM satellite, the compressional pulsations appeared to have a different time history than the transverse pulsations.

Engebretson et al. [1987] noted that while both azimuthal and compressional power at Pc 3–4 frequencies appeared near local noon at equatorial latitudes when the IMF was oriented radially, only azimuthal power was observed at large L values when the local time was near dawn or dusk. This difference in local time variation argued against the idea that azimuthal wave power is transmitted earthward from the subsolar equatorial magnetopause by compressional waves. A qualitative examination of the set of AMPTE CCE spectrograms also showed that at and shortly before dawn, compressional pulsations seldom if ever accompanied transverse harmonics.

The statistical results of *Anderson et al.* [1990] also provide evidence regarding entry for Pc 3–4 wave power: the occurrence rate of intense Pc 3–4 harmonic events was found to drop from a uniform dayside value to near zero from 0600 to 0400 MLT and from 1600 to 1800 MLT, implying that the energy source for Pc 3–4 pulsations has a sharp transition shortly before local dawn and at dusk from nearly uniformly distributed dayside power levels to near-background nightside power levels. A similar sharp onset of harmonic Pc 3–4 activity at local dawn was reported earlier by *Takahashi et al.* [1984*b*] using multisatellite data from synchronous orbit.

According to a compressional wave propagation mechanism, however, one would expect to observe a gradual attenuation of wave power from the subsolar magnetosphere earthward and toward both flanks, and also across local dawn. The observations cited above thus imply that compressional waves do not couple significant power into dayside transverse Pc 3–4 pulsations in the outer magnetosphere, even though compressional pulsations are often observed near local noon when transverse pulsations are also observed. Taken together, these data suggest that mode conversion from equatorially transmitted compressional waves is a surprisingly inefficient process in at least some locations in the outer magnetosphere (but may still be important near or inside the plasmapause [*Chen and Hasegawa*, 1974*b*]).

We mention, finally, that the only location where solar-wind-controlled pulsations are observed on the nightside is in the polar cap [*Engebretson et al.*, 1989*b*]. This observation would seem to be in direct contradiction to models of equatorial wave entry in the compressional mode, as there is no clear reason why compressional waves would propagate into the polar caps and not across the equatorial dawn meridian.

4. THE "IONOSPHERIC TRANSISTOR" ENTRY MODEL

We have noted that until recently studies of the entry of upstream wave energy into the Earth's magnetosphere have focused on direct entry of wave energy across the magnetopause, followed by mode conversion to generate resonant transverse pulsations. To the extent that these models have incorporated the high-latitude ionosphere at all, they have usually considered it as a passive reflecting boundary. In two recent theoretical studies of the response of the magnetosphere to solar wind pressure variations impinging on the magnetopause, however, there is explicit mention of the need to include more realistic models of the effects of magnetosheath plasma variations [*Southwood and Kivelson*, 1990], and the observation that pressure variations contribute nonlinear transport of momentum from the solar wind into the magnetospheric cavity [*Kivelson and Southwood*, 1990]. Both of these studies predicted the existence of large perturbations in the cusp/cleft latitude ionosphere as a result of these pressure variations.

The observations presented in this paper indicate that outer magnetospheric harmonic Pc 3–4 activity is accompanied by strong cusp–cleft activity in both magnetic fields and in electron precipitation. Instead of assuming that waves enter directly into the magnetosphere as waves, perhaps changing modes in the process but at all times propagating as wave-disturbances, these observations lead us to suggest that transmission across the magnetosheath may be an indirect process, involving particle and current modulations and cusp/cleft precipitation. Transverse Pc 3–4 pulsations in the outer magnetosphere can in this way be driven by high-latitude perturbations in a manner analogous to the bowing of a violin string, which occurs not near the center but near the end.

A schematic diagram of our proposed model is shown in Figure 3. According to this model, no wave mode coupling is required, and the waves do not propagate across field lines at any point in the outer magnetosphere. Rather, momentum or pressure fluctuations in a high-beta magnetosheath (associated with upstream waves) impinge on the magnetopause and cause (1) modulated precipitation of otherwise trapped electrons [*Gail et al.*, 1990] and/or (2) the launching of quasi-periodic transient field-aligned currents (arrows) along cusp/cleft/LLBL field lines [*Kivelson and Southwood*, 1990]. These precipitating electrons and/or currents convey wave information to the near-cusp ionosphere. Either indirectly (via modulated Pedersen conductivity) or directly (as modulated region 1 currents) they cause ac variations in ionospheric Pedersen currents and region 2 field-aligned currents at lower latitudes. These varying currents cause transverse distortions of magnetospheric field lines and launch waves with frequency content matching those upstream.

In Figure 4 we show the "transistor action" at the ionospheric foot of the proposed wave entry path in more detail. Dayside region 1 and region 2 currents are coupled by ionospheric currents at cleft/cusp latitudes. Periodic precipitation of particles will modulate the ionization and conductivity of the cusp/cleft ionosphere and thus modulate ionospheric and region 1–2 current flow, in a manner analogous to the way in which a small, variable base current in a transistor modulates a much larger variable flow of current from collector to emitter. In both cases a small "base current" modulates the electrical properties of a region of relatively low conductivity connecting two regions of relatively high conductivity.

In this model, current continuity near the polar cusps forces ac currents to flow in the ionosphere and out into the magnetosphere along outer magnetospheric field lines. These currents, with frequency spectra determined by the upstream waves, provide a narrowband source of wave energy to a wide range of latitudes in the outer magnetosphere. To the extent that these current fluctuations are extended in longitude/local time, as suggested by the spectrograms discussed in section 2, the magnetic deflections they cause will be azimuthal (perpendicular to the plane of the figure), consistent with polarizations observed by spacecraft in the outer magnetosphere.

The concept of pulsations being intimately related to magnetospheric and ionospheric currents is not new. *Heacock and Chao*

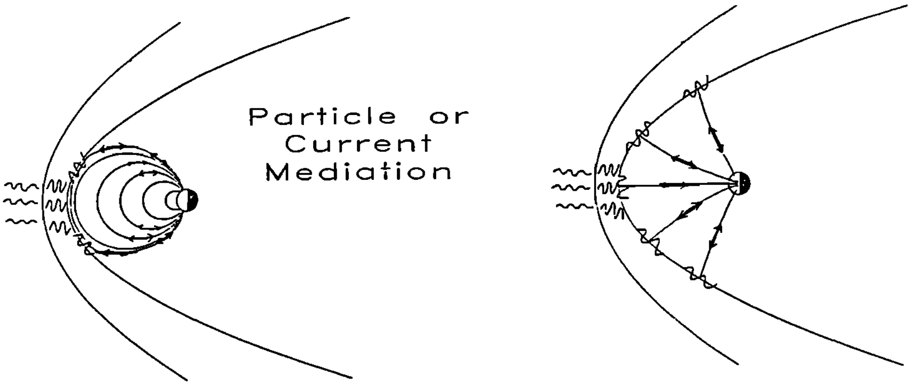

Fig. 3. A sketch of the proposed ac current model of entry of upstream wave signals. Magnetosheath turbulence impinging on the magnetopause causes (1) modulated precipitation of otherwise trapped electrons and/or (2) modulated flow of field-aligned currents (arrows) along boundary layer/cleft/cusp field lines. These electrons and/or currents convey wave information to the near-cusp ionosphere. Either indirectly, via modulated Pedersen conductivity, or directly, this causes ac variations in ionospheric Pedersen currents and region 2 field-aligned currents at lower latitudes. These currents cause transverse distortions of magnetospheric field lines and launch waves with frequency content matching those upstream. The left side presents a view from the dusk meridian, and the right side a view from magnetic north.

[1980] invoked three-dimensional currents to explain features of very high latitude Pi 1 activity they observed. They introduced the idea of dual driving functions for Birkeland currents, with a dc source driven by the solar wind-magnetosphere dynamo and an ac source related to near-Earth convection variations. They also noted that the response of such current loops to imposed emf variations is strongly dependent on the conductivity in the *E* region portion of the loop. Thus, Pi 1 amplitudes were observed to be larger on the dayside, in summer, and in locations where auroral precipitation was enhanced. *Rostoker and Lam* [1978] and *Lam and Rostoker* [1978], on the basis of detailed analyses of morning sector Pc 5 pulsations and the auroral westward electrojet, also invoked oscillations of three-dimensional magnetosphere-ionosphere current systems as the origin of the observed pulsations. Even earlier, *Maltsev et al.* [1974] pointed out that a change in ionospheric conductivity in the presence of an externally imposed ionospheric electric field can launch an Alfvén wave up a field line.

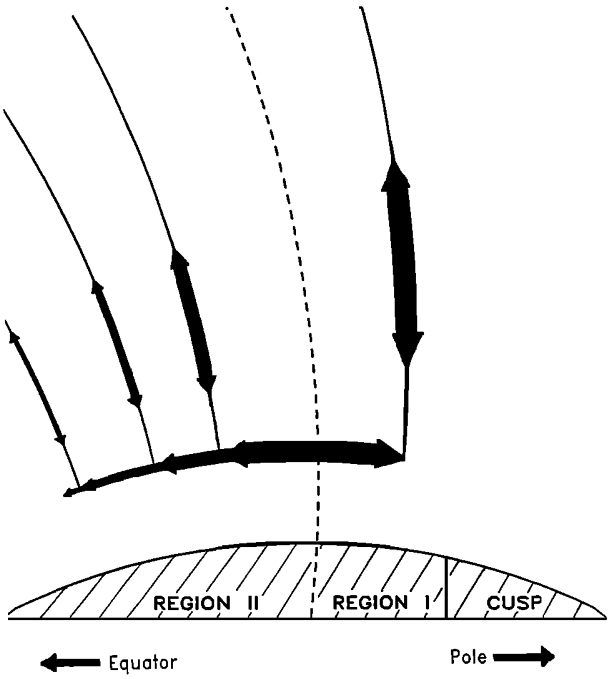

Fig. 4. Ionospheric detail of the proposed ac current model of entry of upstream wave signals. Dayside region 1 and region 2 currents are coupled by ionospheric conductivity at cleft/cusp latitudes. Modulated precipitation in the cleft region (near the dashed line) will cause modulated ionospheric and region 1–2 current flow. To the extent that these current fluctuations are extended in longitude, the magnetic deflections they cause will be azimuthal (perpendicular to the plane of the figure).

Although the instrumentation at South Pole is insufficient to determine the conductivity variations or ac ionospheric currents associated with the observed auroral and magnetic pulsations, we can use observed equatorial pulsation amplitudes and simple geometrical arguments to provide an order-of-magnitude estimate of the ionospheric and field-aligned currents required in this model. A simple geometrical argument indicates that a longitudinally extended ac current sheet which produces a typical Pc 3 magnetic perturbation of 1 nT at the equator at $L = 9$ will produce a perturbation of ~ 35 nT at the foot of this field line in the polar ionosphere. This perturbation corresponds to a changing field-aligned sheet current amplitude of roughly 5×10^{-2} A/m at ionospheric altitudes, roughly an order of magnitude lower than typical ionospheric currents near the cusp when $Bz = 0$ [*Friis-Christensen et al.*, 1985]. If this region 2 sheet current has a latitudinal thickness of 2.5°, the average current density is ~ 2×10^{-8} A/m^2, which is roughly an order of magnitude lower than typical values of dc field-aligned currents observed near the dayside cusp when $Bz = 0$ [*Friis-Christensen et al.*, 1985].

We now discuss several ways in which this model reproduces known features of Pc 3–4 pulsation morphology. First, this model can naturally explain the sharp transition from large, nearly uniformly distributed dayside power levels to negligible nightside power levels. There is growing consensus that the dayside and nightside sections of the region 1 and 2 Birkeland currents may be separated and may be produced by different sources [*Friis-Christensen et al.*, 1985]. If pulsation signals are transmitted through cusp/cleft/LLBL field lines, we would naturally observe a rather sharp transition from dayside field lines (those whose Birkeland currents are connected to the LLBL) to nightside field lines (those whose Birkeland currents are connected to the plasma sheet boundary layer). The fact that the near-dawn amplitude transition appears to be swept toward slightly earlier times (approximately 0500 MLT) in the AMPTE CCE data set near $L = 9$ than in the ATS 6 data set at synchronous orbit (L ~ 6.6) can be understood as a consequence of outer magnetospheric field draping in conjunction with this high-latitude entry mechanism.

Second, modulations of region 2 currents in a given bandwidth will be able to excite all available harmonics within that bandwidth. This is consistent with AMPTE CCE observations here and elsewhere [*Engebretson et al.*, 1986*b*, 1987] that show little difference in excitation between odd and even harmonics if nodal structure is taken into account.

Although synchronous orbit data on harmonic pulsations compiled by *Takahashi and McPherron* [1984] showed that the third harmonic was statistically dominant at 10° magnetic latitude, we believe this dominance is related primarily to the rough coincidence between the frequency of the third harmonic at this L value and the typical frequencies of upstream waves. (Because typical IMF field magnitudes are 5–6 nT, the frequencies of maximum upstream wave power will be 30–36 mHz.) In addition, at those times when the Earth's magnetic poles are equidistant from the equatorial magnetopause, one might expect both in this model and in earlier equatorial wave transmission models a slight preference for generating latitudinally symmetric disturbances. According to our model, upstream waves will in this case tend to drive modulated currents in opposite hemispheres in the same sense, i.e., into or out of the ionosphere at the same time at both poles. This will in turn lead to preferential excitation of odd harmonics (with opposite azimuthal magnetic field perturbations in opposite hemispheres). Because of the varying angle between the Earth's dipole axis and the Sun-Earth line, however, this effect should not be dominant.

An additional result of this model, because of its proposed high-latitude/low-altitude entry point for wave energy, is that it can better satisfy the observational constraint of small east-west phase variation referred to earlier. The longitudinal phase velocity of the resonant pulsations is no longer constrained by the Alfvén speed near the equatorial midpoint of field lines, but is determined by the azimuthal propagation speed of modulated currents in the cusp/cleft ionosphere. (We presently have no quantitative estimate of this speed, however.)

Although Pedersen conductivity may play the largest role in coupling region 1 and 2 currents in the cusp/cleft ionosphere, Hall conductivity is likely to cause a longitudinal spreading of ionospheric currents, allowing a (possibly) more localized region of enhanced conductivity to stimulate pulsations in an extended local time range in the dayside magnetosphere.

One might object that since cusp/cleft ULF power is dominated by Pi 1 activity rather than Pc 3, this driving mechanism should produce strong field line resonances that depend on auroral activity rather than on the IMF cone angle. We suggest, however, that any geomagnetic power observed at cusp latitudes that is irregular and spatially incoherent, as is the case for the Pi 1 pulsations produced as a result of substorm-related activity, will not be able to launch coherent Birkeland currents over large longitudinal ranges. Transient power from a line or point source will drop off quickly, while the more coherent power from a (finite) sheet source will drop off much less rapidly with distance. This argument also explains why ground-based pulsation data from auroral or subauroral stations, such as were used by *Greenstadt et al.* [1979], *Russell et al.* [1983], and *Yumoto et al.* [1984, 1985], could be contaminated by irregular Pi 1 pulsation activity, while AMPTE CCE data, taken at L values from 4 out to 9 but at equatorial latitudes, did not contain such irregular pulsations.

Finally, a longitudinally extended sheetlike perturbation in the region 2 currents will produce an azimuthal magnetic field deflection, which is exactly the polarization observed for resonant harmonic pulsations in the outer dayside magnetosphere [*Takahashi and McPherron*, 1982; *Takahashi et al.*, 1984*b*; *Engebretson et al.*, 1986*b*, 1987].

5. SUMMARY

We have given the qualitative outline of a new mechanism, the "ionospheric transistor," for the entry of upstream ULF wave energy into the Earth's dayside magnetosphere. Instead of assuming that waves cross the magnetopause directly into the magnetosphere as waves, perhaps changing modes in the process but at all times propagating as wave disturbances, we have suggested that transmission into the magnetosphere may also occur as an indirect process involving modulations of the three-dimensional dayside Birkeland current system.

Our model is based on several recent and some long-known observational results: (1) Pc 3–4 observations on the ground have for years been characterized as predominantly a dayside phenomenon: other than in a few early studies at equatorial latitudes which reported an evening occurrence maximum in association with increases in equatorial ionospheric disturbance currents [*Hutton*, 1960, 1962], Pc 3–4 activity can be observed during nighttime only in the polar cap. More recent studies have shown that pulsations associated with low IMF cone angles are a dayside phenomenon, with sharp cutoffs in local time in the outer magnetosphere near dawn and dusk. Unfortunately no comparison can be made between Hutton's observations and the IMF orientation. (2) The band of frequencies within which dayside harmonically resonant Pc 3–4 pulsations appear in space is the same as the band of enhanced Pc 3–4 activity observed at cusp/cleft latitudes on the ground. (3) Greatly increased magnetosheath turbulence in both particles and magnetic fields, including large beta values and increased densities of energetic particles, is associated with upstream waves and a quasi-parallel shock structure. Such turbulence might drive transient dayside reconnection, inpulsive antisolar momentum transfer, and/or modulated magnetopause/boundary layer (region 1) currents. (4) Localized, modulated precipitation of electrons with magnetosheath or boundary layer energies occurs in the cusp/cleft region, with frequencies identical to those of simultaneously observed Pc 3–4 magnetic pulsations.

We have suggested that this precipitation, because it changes the conductance of the ionospheric foot of the dayside Birkeland current circuit, will modulate the region 2 currents. (If this precipitation is a result of driven reconnection processes, these will directly modulate the region 1 currents as well.) These modulated currents, whose frequency spectra are determined by the upstream waves, provide a band-limited source of wave energy to a wide range of dayside local times in the outer magnetosphere. As with other Birkeland sheet currents, these Region 2 currents set up transverse magnetic perturbations, hence launching transverse magnetic pulsations on closed field lines. In this manner, magnetosheath turbulence will be transmitted inward to L shells in the dayside magnetosphere to the extent of the inner edge of the region 2 current sheet, i.e., in a region covering most of the magnetosphere outside of the plasmapause. No mode conversion of ULF wave power is required in this model.

We remind readers that the study of *Engebretson et al.* [1987] showed evidence that some Pc 3–4 wave power does appear to enter the magnetosphere by a mechanism consistent with that described by *Verzariu* [1973] and *Yumoto et al.* [1984, 1985]. We do not claim that the entry mechanism presented here acts to the exclusion of other mechanisms. In particular, we have noted that this model provides no means to transmit power inside the plasmapause to sites at low L shells, where many studies have observed clear solar wind control of pulsation activity. Although we believe this model satisfactorily explains recent observations of solar-wind-controlled pulsations at high dayside latitudes and azimuthally polarized resonant harmonics in the equatorial outer magnetosphere, further studies are needed to determine the relative importance of this model and earlier wave-wave propagation models.

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