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Study of a QP/GP Event at Very High Latitudes

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We report on the observation and analysis of a quasi periodic (QP) VLF emission and geomagnetic pulsation (GP) event, a QP/GP event, observed for several hours around local noon at high geomagnetic latitudes at the South Pole station. We believe that this is the highest latitude QP/GP event reported. The narrow-band magnetic pulsation ($f \sim 30$ mHz) suggests that at this time the dayside magnetic field lines connecting South Pole to the magnetosphere were closed. This conclusion is supported by an investigation of the interplanetary magnetic field (IMF) conditions at the time of the event and modeling of the polar cap region of the magnetosphere. The results show that the South Pole location would be expected to be inside the boundary for closed magnetic field lines. The polarizations of the observed hydromagnetic wave were primarily right-handed throughout the interval, changing slowly to left-handed beginning approximately 2 hours after local noon. The polarizations and the orientation of the IMF (essentially radial) suggest that the hydromagnetic energy source was upstream waves.

INTRODUCTION

Investigations related to high geomagnetic latitudes in the cusp and polar cap regions in the earth's magnetosphere have significantly increased in number in recent years. The importance of this region of the earth's magnetosphere, where the separation occurs between dayside magnetospheric magnetic field lines and those which extend into the geomagnetic tail, has been noted by a number of researchers and explicitly discussed in a recent advisory committee report [*Polar Research Board*, 1982]. Research has been carried out in a variety of areas, including studies of field-aligned currents and convection patterns and examination of particle precipitation patterns in order to delineate the dayside cusp region. Many of these investigations are summarized in a recent volume edited by *Holtet and Egeland* [1985]. Observations of shorter period ($\tau \lesssim 45$ s) hydromagnetic waves in the cusp region have been reviewed by *Fraser-Smith* [1982]. In particular, studies of hydromagnetic wave phenomena in this region of the magnetosphere can be exceedingly important for understanding energy transfer processes into the earth's magnetosphere.

Flux transfer events at the dayside magnetopause [e.g., *Russell and Elphic*, 1978, 1979; *Paschmann et al.*, 1982; *Daly et al.*, 1984] may be indicative of multiple x line reconnection at the magnetopause [*Fu and Lee*, 1985] which produces Alfvén waves and field-aligned currents. These should be evident in the high latitude ionosphere. As *Fraser-Smith* [1982] notes, however, there has been relatively little contribution from United States scientists to scientific investigations concerning ULF hydromagnetic wave phenomena in high latitude regions of the earth's magnetosphere. A recent paper by *Gurnett et al.* [1984] draws specific attention to auroral zone and higher latitude electric and magnetic noise in the Alfvén wave regime ($f < 100$ Hz) observed on the Dynamics Explorer 1 (DE 1) satellite. These satellite observations in many instances are likely to be related to small scale fluctuations frequently observed in field-aligned currents and to some ground-based measurements of magnetic field fluctuations corresponding to hydromagnetic frequencies. Unfortunately, the speed with which most spacecraft cross the cusp and polar cap regions of interest for delineating the important boundary regions, combined with the low frequencies of the waves, usually precludes detailed definition and study of specific individual events. In situ measurements of plasmas and plasma waves by satellites are important for interpreting the remote sensing measurements made from the ground, measurements which more readily can differentiate between spatial and temporal effects, given appropriate siting of the ground instruments.

The amplitudes of the magnetic field fluctuations measured on the ground at high latitudes in the cusp and polar cap regions are often quite large compared to those seen at subauroral and middle latitudes. As such, the results of studies of high latitude geomagnetic phenomena in the literature are frequently devoted to examinations of the morphology of longer period (several minutes or more) variations and their possible relationship to the geomagnetic cusp region [e.g., *Troitskaya and Bolšhakova*, 1977; *Kovner and Kuznetsova*, 1977; *Bolšhakova and Troitskaya*, 1977]. *Rostoker et al.* [1972] have provided evidence that the spectrum of magnetic fluctuations (as measured on the ground) in the cusp region is much broader than that at lower latitudes.

Finally, to the best of our knowledge, no quasi-periodic (QP) VLF event with accompanying geomagnetic pulsations (GP), a QP/GP event, has been reported at latitudes as high as that of the South Pole station. Such events are seen frequently at lower geomagnetic latitudes, where the geomagnetic field lines are definitely closed [e.g., *Troitskaya and Kleimenova*, 1972; *Ho*, 1973; *Kimura*, 1974; *Sato et al.*, 1974, 1985; *Korotova et al.*, 1975; *Sato and Kokubun*, 1980].

EXPERIMENT

Plotted in local time coordinates in Figure 1 are the locations of South Pole station (SP) and a number of other Antarctic research stations. Shown by the shaded region is the nominal auroral oval under average geomagnetic disturbances [*Akasofu*, 1968]. As indicated by the figure, during local daytime conditions South Pole can be close to the dayside auroral region and, depending upon geomagnetic conditions, can be either on open or closed magnetic field lines, finding itself on field lines connected inside the magnetosphere or connected to polar cap field lines extending into magnetotail.

Magnetic field and VLF measurements are made at South

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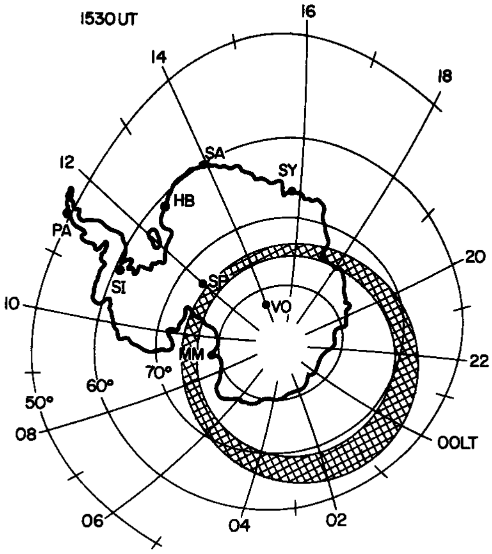

Fig. 1. Location of selected Antarctic research stations at South Pole local magnetic noon. SP, South Pole; VO, Vostok; MM, McMurdo; SI, Siple; PA, Palmer, HB, Halley Bay; SA, SANAE; SY, Syowa.

Pole station using instrumentation established at that location in connection with the U.S. Antarctic geomagnetic cusp program. Magnetic field data are acquired using a three-axis flux gate magnetometer oriented to measure the magnetic field fluctuations in the geomagnetic north-south (*H* component), east-west (*D* component), and vertical (*V* component) directions. The instrument at South Pole has an inherent noise level of ~0.25 nT. The VLF data are acquired using a loop antenna and associated preamplifier and amplifier circuitry. The VLF data are recorded in a broad band format and are also put through a series of eight narrow-band filters ranging from ~0.5 to 20 kHz. The analog outputs from the three magnetometer axes and the VLF filters are fed through a multiplexer and analog-to-digital converter and are written in computer compatible format on magnetic tape at 1 s intervals. In addition, housekeeping parameters from these two instruments and from other instrumentation are written periodically in order to monitor the system performance.

RESULTS

Plotted in Figure 2 are gray shade-coded digital dynamic spectra of two of the magnetometer channels and the lowest frequency VLF channel for the final 12 hours of January 5, 1982. The dynamic spectra are produced by calculating power spectra for successive 30 min intervals, each interval shifted from the previous one by 5 min. The spectra are calculated using a fast Fourier transform algorithm after first applying a Thomson window [*Thomson et al.*, 1976] to the data in the time domain.

These spectra show clearly that a broad band enhancement in the ULF and VLF signals began between hours 1200–1300 UT. This enhancement increased in frequency until there was essentially a steady strong signal in both the ULF and VLF frequency band spectra at a frequency of ~30 mHz. This continued until ~1700 UT when an intensity decrease occurred. The decrease in intensity in the ULF and VLF frequency bands at this time was accompanied by a short burst of noise in a higher frequency (~1–5 kHz) VLF band (not shown here). The ULF and VLF spectral enhancements finally terminated with an interval of broad band noise during hour 2000 UT.

Filtered (period band ~25–45 s) VLF and ULF data for the 1 hour interval 1400–1500 UT are shown in Figures 3*a* and 3*b*. The filtered data clearly show a periodicity with frequency ~30 mHz in both VLF traces as well as in the ULF signals. However, the modulations of the oscillatory signals are different in the ULF and VLF bands, and are also different at times among the three magnetic field components.

Shown in Figure 4 is a schematic representation of the polarizations of the hydromagnetic wave-induced magnetic field changes as observed on the ground at South Pole station and at Siple station throughout the interval 1300–1800 UT, the universal time spanning local noon at the two stations (Siple LT = UT-5 hours). Open and closed circles represent right

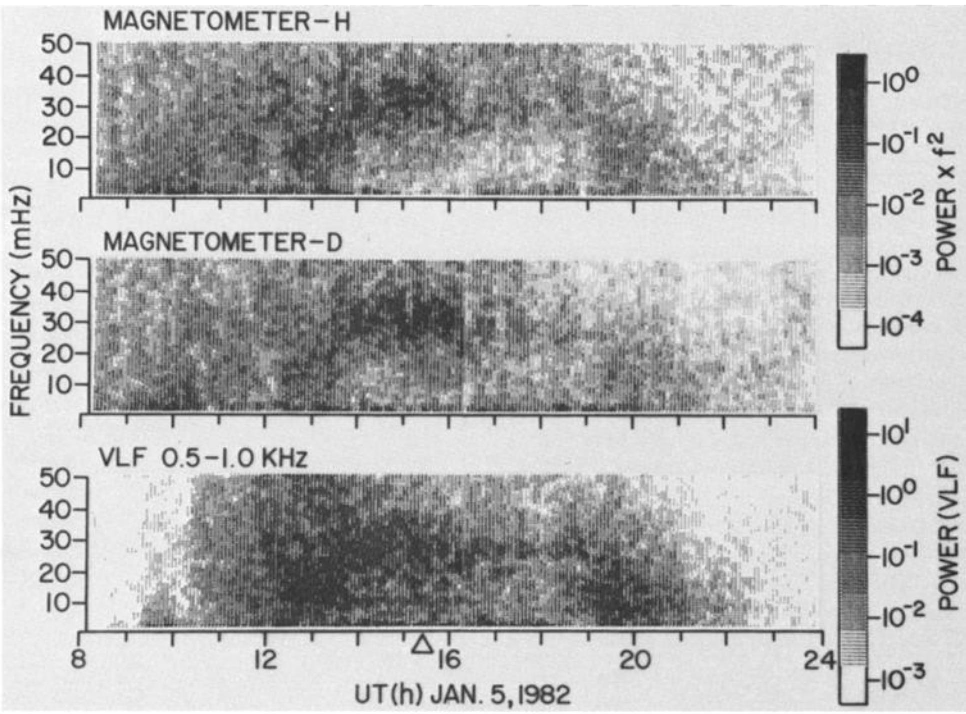

Fig. 2. Dynamic spectra of magnetometer and VLF data from South Pole on January 5, 1982, showing the QP/GP event.

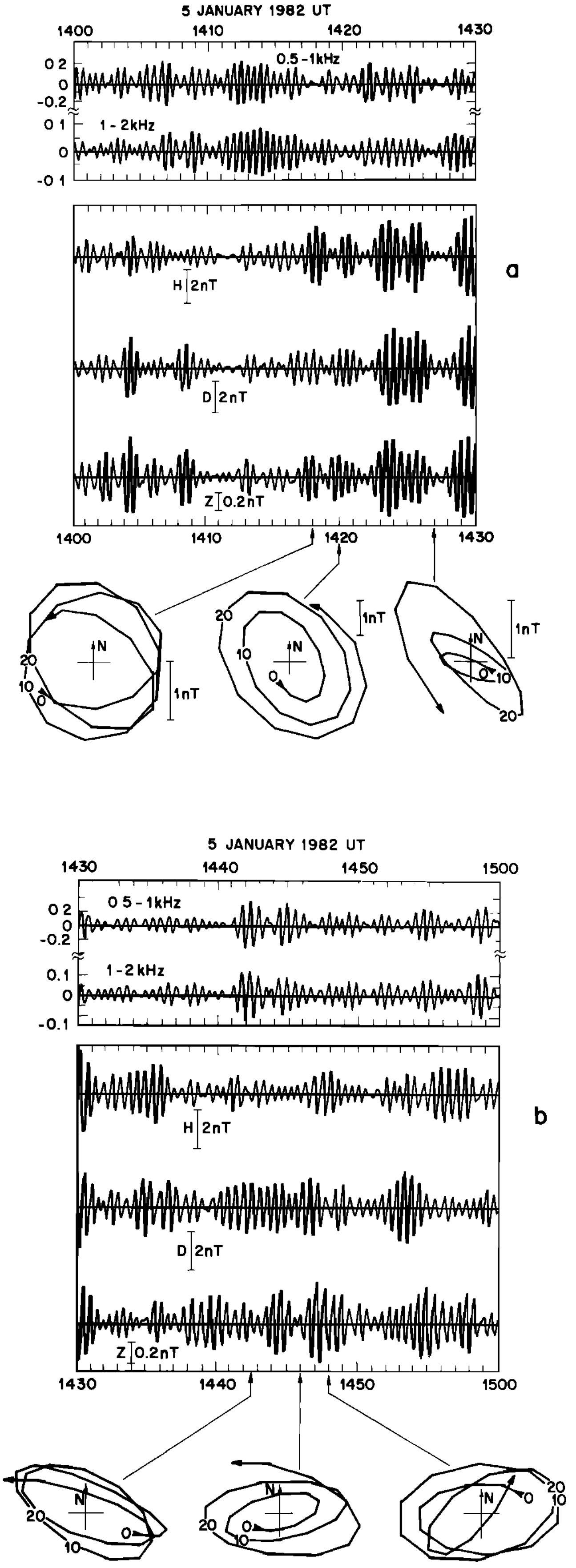

Fig. 3. (*a*) Filtered (25–45 s band) magnetic field and VLF data for 1400–1430 UT on January 5, 1982. Magnetic field hodograms in the *H-D* plane for these time periods are shown at the bottom of the figure. (*b*) Filtered data for 1430–1500 UT on January 5, 1982.

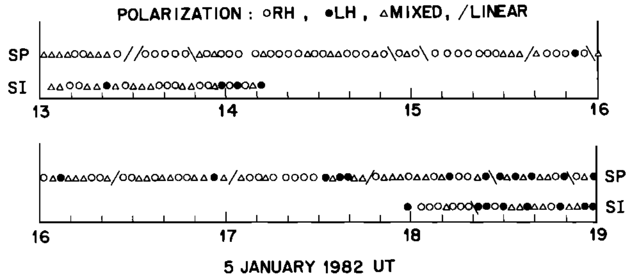

Fig. 4. Schematic representation of the magnetic field polarizations in the *H-D* plane from Siple and South Pole, 1300–1900 UT, January 5, 1982.

hand (RH; clockwise rotation of the disturbance vector in the horizontal plane looking along the magnetic field) and left hand (LH; counterclockwise rotation of the magnetic disturbance vector in the horizontal plane looking along the magnetic field), respectively. Open triangles represent intervals of mixed polarization while a vertical line represents approximately linear (ellipticity $< \sim 0.2$) polarization. Unfortunately, because of instrument adjustments being made at this time, a considerable amount of Siple data were not acquired during this time interval. Nevertheless, it is clear that at the South Pole station as well as at Siple station, RH polarization predominated during the time interval prior to local noon whereas after ~ 1730 UT at South Pole (about 2 hours after South Pole local noon) there was a mixture of RH and LH polarization, with LH polarization beginning to predominate.

These observed polarization characteristics are opposite those expected if the Pc 3 frequency variations are generated by the Kelvin-Helmholtz (KH) instability on the magnetopause [e.g., *Atkinson and Watanabe*, 1969] for waves observed on the equatorward side of a magnetosphere field line resonance [*Samson et al.*, 1971; *Chen and Hasegawa*, 1974; *Southwood*, 1974; *Lanzerotti et al.*, 1974]. It is likely that since the event was seen at Siple with the same polarization as at South Pole, as well as at Syowa station with a more linear polarization [*Tonegawa et al.*, 1985], the KH instability was not the primary hydromagnetic energy source for this event. This is discussed further below.

If we assume that the South Pole field lines were close to, albeit at a latitude higher than, a magnetospheric resonance location, we can make a rough estimate of the equatorial plasma density distribution along the magnetic flux tube. Assuming a magnetospheric field line length of order 35 R_E, we find from a simple transit time calculation than n_{eq} is order 1 cm^{-3} for a first harmonic transverse wave. For a high latitude station such as South Pole, large errors are likely to enter into any such calculation. Nevertheless, assuming an ordinary dipole and a constant plasma density $= 6.5 \times 10^{-22}$ g/cm^3 ($\approx 4 \times 10^{22}$ protons/cm^3), *Westphal and Jacobs* [1962] determined that $\tau \sim 10^4$ s at $\theta_0 \sim 75°$. Thus, for an observed $\tau \sim 30$ s, $\rho \sim 0.3$/cm^3. This is not an unreasonable density distribution for the outermost regions of the earth's magnetosphere on the dayside under reasonably quiet geomagnetic conditions.

Discussion

The likelihood that the magnetic field lines which connect South Pole station into the earth's magnetosphere were closed during the time interval around local noon during the Pc 3 event was investigated by using an Olson-Pfitzer model of the magnetosphere [*Olson and Pfitzer*, 1974; *Olson et al.*, 1979] which incorporated total interconnection between the interplanetary field and the geomagnetic field. The procedure was similar to that used in the work of *Akasofu et al.* [1981] and of

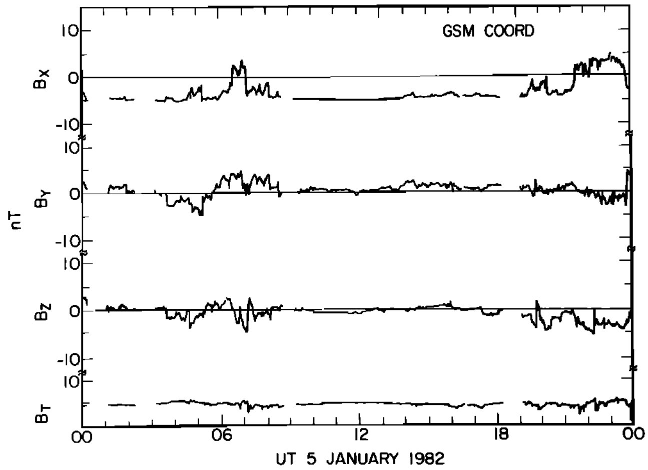

Fig. 5. Interplanetary magnetic field data from the ISEE 3 spacecraft on January 5, 1982.

Akasofu and Roederer [1984]. Shown in Figure 5 is the interplanetary magnetic field measured at 0.01 AU upstream from the earth by the ISEE spacecraft during January 5, 1982. The transit time of the solar wind (and thus the magnetic field) from the spacecraft to the front of the magnetosphere is of the order of an hour or so [*Russell et al.*, 1980]. The interplanetary conditions were rather stable during the interval of most interest here, with a B_Z component of ~ 0 nT, a B_Y component of ~ 0 to 3 nT, and a strong B_X component of ~ -5 nT.

Calculations of the expected boundary between open (polar cap) and closed magnetic field lines were carried out for us by J. Bamber (private communication, 1985). This boundary is shown in Figure 6 by the solid circles. Field lines originating at latitudes higher than the solid points are expected to be open into the magnetotail. Also indicated in that figure are the values of the interplanetary field components used for the calculation. The "jaggedness" of the "boundary" is an indication of the coarseness of the grid used for delineating the polar cap. It is clear that South Pole station, at a magnetic latitude of $\sim 74°$–$78°$ S would be expected to be equatorward of the polar cap boundary throughout the local noon time when the QP/GP event was observed. Nevertheless, the field lines through South Pole station were close to the magnetopause boundary throughout the local daytime time interval. Indeed, the burst of higher frequency VLF noise, and the accompanying disappearance of the QP/GP event at ~ 1700 UT (Figure 2) may be indicative of a crossing of the dayside magnetopause field lines, into the polar cap. This would not be unexpected from the nearness of the station location to the boundary between and closed field lines (Figure 6).

One of the important motivations for studying hydromagnetic waves at high latitudes on the dayside, near the boundary of open and closed field lines, is to attempt to better delineate the generation and transmission of hydromagnetic waves into the magnetosphere. When observation locations are close to, or on, magnetic field lines through the boundary, it should ultimately be possible to differentiate the modes of hydromagnetic energy transmission into the magnetosphere.

A considerable amount of work has been carried out by a number of authors on wave transmission through the magnetopause and its propagation throughout the magnetospheric cavity on the dayside. The most often discussed mode of wave generation and transmission is via the Kelvin-Helmholtz instability, or a modification of the concept to a velocity shear instability [e.g., *Yumoto and Saito*, 1980; *Yumoto*, 1984], both produced by the flow of the solar wind past the magnetosphere. An obvious physical prediction of the Kelvin-Helmholtz model is a change in polarity of the waves across the approximately local noon meridian. Hydromagnetic wave transmission can also occur directly across the magnetopause. Such waves, generated in the bowshock and magnetosheath, can impinge on the magnetopause boundary and be transmitted through the boundary as both fast and slow modes. *Wolfe and Kaufman* [1975] have studied the transmission of hydromagnetic waves through a tangential discontinuity at the nose of the magnetosphere and found that there is not appreciable wave energy transmitted in this mode. Quite recently, some important work by Lee and his collaborators [*Lee*, 1982; *Kwok and Lee*, 1984] has shown that hydromagnetic waves can be efficiently transmitted into the magnetosphere across rotational discontinuities. Such discontinuities are likely to occur at high geomagnetic latitudes, off of the nose of the magnetosphere. *Kwok and Lee* [1984] also show that wave amplification can occur during such a transmission across a rotational discontinuity, with the energy for the amplification being ultimately provided by the solar wind.

The interplanetary magnetic field had a strong B_X component (Figure 5) during much of the time interval of the event discussed herein. Indeed, the field was nearly perpendicular to the nose of the magnetosphere at this time. Such interplanetary conditions are reported to be considerably more favorable for wave generation in the solar wind by bow shock-reflected ions [e.g., *Fairfield*, 1969; *Barnes*, 1970; *Kovner et al.*, 1976; *Russell and Hoppe*, 1983]. Some detailed discussions of these matters are contained in the recent paper by *Wolfe et al.* [1985], particularly regarding the propagation of compressional waves deep into the magnetosphere. Indeed, primarily because of the radial orientation of the interplanetary field at the time it seems quite likely that the magnetic variations in the Pc 3 frequency range detected on this day were the result of waves in the solar wind and not the Kelvin-Helmholtz or velocity shear instabilities. This is also suggested by the polarizations seen at both South Pole and Siple (right-handed

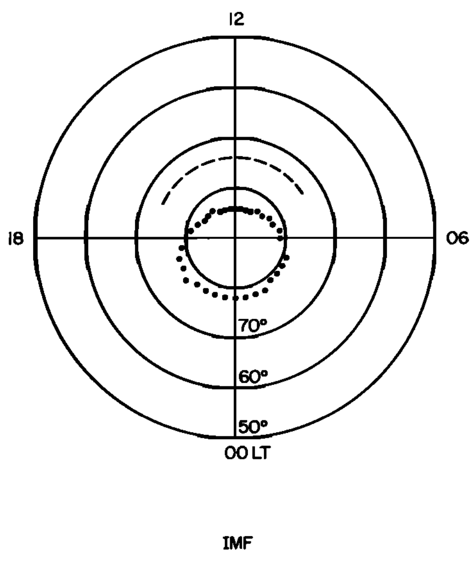

Fig. 6. Boundary between open and closed magnetic field lines (solid points) in the southern polar cusp under the interplanetary magnetic field conditions shown. The approximate local time path of South Pole is indicated by the dashed line.

throughout most of the interval) and from the lack of change in the polarization across local noon. The change in polarization after hour 1700 could well be related to changes in the solar wind beginning during this hour, particularly the onset of a small B_Z component and subsequent larger IMF fluctuations. The circular polarization at high latitude (i.e., South Pole) could reasonably be a result of circular polarization of Alfvén waves in the magnetosheath ($k \parallel B$). Such a polarization would be present after transmission through a rotational discontinuity [*Kwok and Lee*, 1984; *Yumoto*, 1985; L. C. Lee, private communication, 1985].

With respect to the VLF aspects of the event, quasi-periodic VLF emissions in the ~100–600 Hz range were also seen at Siple station (Figure 1) during the interval ~1400–1600 UT. The field strengths were comparable at both Siple and South Pole, being in the range 10–20 μV/m. Thus, it is entirely possible that the VLF emissions could have originated at a location between Siple and South Pole and propagated to those two locations. The VLF emissions would not have to have originated at the high latitude South Pole location. The large-scale (in terms of latitudinal extent) ULF waves could modulate the VLF source. The difference in the occurrence intervals of the periodic VLF emissions at Siple and at South Pole could be a result of propagation differences between the source and Siple and the source and South Pole. For example, if the source region was close to or near the latitude of the auroral zone station Syowa, some precipitation equatorward of Syowa could inhibit the propagation to lower latitudes. The QP-GP event was found to persist longer at Syowa than at South Pole, an observation which suggests that the hydromagnetic waves propagated azimuthally from their magnetopause source [*Tonegawa et al.*, 1985].

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