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Monitoring cusp/cleft topology using Pc5 ULF waves

S.T. Ables, B.J. Fraser, C.L. Waters, and D.A. Neudegg
Physics Department, University of Newcastle, NSW, Australia

R.J. Morris
Australian Antarctic Division, Tasmania, Australia

Abstract. Induction magnetometer data recorded at three closely spaced sites (~120 Km) in Antarctica (mlat ~ -75°) have been examined for ionospheric signatures of the cusp/cleft region of the magnetosphere. Crossphase analysis of the 1-10 mHz band, using pure--state filtering techniques reveal diurnally varying field line resonances embedded in the spectra, while interstation phase lag measurements indicate azimuthal propagation of waves away from local magnetic noon. Using the T89 external field model crossphase measurements are put in the context of diurnally changing field line topology due to compression at the subsolar region and stretching along the dawn and dusk flanks. On six of the eight days of this study we have identify a consistent two dimensional phase pattern projected in the dayside ionosphere, indicating closed field lines thread these sites during periods of low to moderate geomagnetic activity (Kp<3).

Introduction

Over the past thirty years ground based studies of long period geomagnetic pulsations at high latitudes have fallen into two main categories (1) statistical surveys in which wave properties such as amplitude and frequency are organised by time, location, season etc. [eg Rostoker et al., 1972], and (2) detailed analysis of significant 'events' which are usually of large amplitude and transient in nature. In both cases the intention is to elucidate the coupling mechanism(s) of solar wind energy to the magnetosphere - either directly via boundary interactions, or indirectly through storage and release of energy in the geotail. Boundary processes that have been identified include magnetic reconnection, solar wind pressure pulses, and the Kelvin-Helmholtz instability (KHI) [eg *Samson*, 1991 and references therein].

Statistical results which identify diurnal tendencies in high latitude data suggest associations with morphologically different magnetospheric regions whose ionospheric footprints rotate daily over the ground stations. Enhancements in broadband pulsations 2-4 hours before and after local magnetic noon may be evidence of KHI in the low latitude boundary layer (LLBL) with its ionospheric projection corresponding to the cleft. Modelling of this instability has produced wavelengths and frequencies which are in good agreement with observed boundary fluctuations at the magnetopause [*Muira*, 1987]. Cusp specific pulsations have been eagerly sought but with varying success [eg *Olson*, 1989]. Recently, a feature known as the 'arch' [*McHarg et al.*, 1994], found in high latitude spectrograms, held promise as a 'cusp signature'. *Waters et al.* [1995] analysed data from the CANOPUS array in Canada and concluded that these Pc5 pulsations are mainly due to field line resonances which vary in frequency with latitude and the diurnal variation of mapped field line lengths.

The intention of this paper is to demonstrate that the characteristics of Pc5 waves at cusp/cleft latitudes are not only affected by the plasma properties of the mapped magnetospheric regions but also by magnetosphere topology (ie field line lengths). Using crossphase techniques to distinguish between broadband noise and periodic components in magnetometer time series, we show how Pc5 waves can be used to 'magneto-sound' the outer-regions of the dayside magnetosphere.

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Field Line Resonances

In detecting and analysing field line resonances we adopt a simplification of FLR theories which have been developed to varying degrees of sophistication, starting with the treatment by *Dungey* [1954] in which poloidal and toroidal wave modes were first derived. Two theoretical approaches are typified by *Chen and Hasegawa* [1974a,b]. *Southwood* [1974], and *Chen and Hasegawa* [1974a], assumed a monochromatic source at the magnetopause consistent with the KHI, and found for small source azimuthal wave number, m, shear Alfvén standing waves occur where fast mode compressional waves match the resonant frequency of standing field lines. Furthermore, they predicted that a reversal in wave polarisation occurs across the resonance as well as across a meridian at which m reverses sign (local magnetic noon in the case of KHI-like perturbations). In a different approach *Chen and Hasegawa* [1974b] considered an impulsive (broadband) source which excited surface eigenmodes which couple to discrete resonant field line oscillations. Refinements made by *Kivelson and Southwood* [1986] demonstrated how energy is transferred away from global modes into FLRs [also see *Allan et al.*, 1986]. Later, *Inhester* [1987] performed numerical simulations of this coupling process and found it is most efficient for m values between 1 and 3.

To identify FLRs in our data we first assume there is an ionospheric source within the common field of view of two magnetometers. The crosspower of horizontal magnetic variations detected from each magnetometer should then show a spectral peak at the resonant frequency. Further, if the resonance is sufficiently broad (ie slow spatial variation compared to station spacing) then the interstation crossphase should likewise peak at the resonant frequency. We now show how the crossphase can be used to measure field topology, starting from the WKB approximation for the resonant frequency

$$f = n/2 \int V_A/ds \qquad (1)$$

where n is the harmonic number and V_A the Alfvén velocity. Usually magnetic field and plasma density models are applied to obtain f as a function of magnetic latitude or L-shell [eg *Warner and Orr*, 1979]. At high latitudes (in the outer plasmatrough) variations in f are due predominantly to changes in field line lengths. So, for two closely spaced stations we can estimate a fractional frequency difference

$$(f_1 - f_2) / f_1 \sim 1 - l_1 / l_2 \qquad (2)$$

where l_1 and l_2 are the lengths of the field lines which thread each station. Assuming a constant radial Alfvén velocity profile over the magnetospheric region mapped to the stations, the radial structure of the electric field near resonance ($x=x_r$) is of the form [*Chen and Hasegawa*, 1974a]

$$E_x = K.i / (x - x_r + i\gamma) \qquad (3)$$

where K is a function of azimuthal and field aligned wave numbers, and γ is a loss term which controls the Q of the resonance and therefore the spatial (and spectral) width of the resonant peak. Close to resonance the phase is approximately a linear function of frequency [see for instance *Waters et al.*, 1995] and therefore crossphase between closely spaced stations will be proportional to the fractional frequency offset given in (2) ie.

$$\Phi_1 - \Phi_2 \sim \eta\,(1 - l_1 / l_2) \qquad (4)$$

where η is a function of the resonance Q. Later we use this equation together with an external field model to quantify the contribution of FLRs to interstation crossphase measurements.

Data

This study was conducted during the austral winter of 1992 (30 July - 7 August). Solar daytime at these latitudes occurred between 0400 and 1000 UT which corresponds to pre-noon - noon in local magnetic time. The co-ordinates of the triangular array of stations used in this study are, Davis: 74.6°S, 102.37°E ; Law: 74.7°S, 98.63° E; Plateau: 75.64°S, 101.81°E (PGM-88) [*Burns and Beggs*, 1992].

Magnetic variations were recorded at each station using two orthogonal (X,Y) induction coils. The sensitivity of the combined detection and logging system was 0.2 nT V^{-1} at 10 mHz, with the frequency response falling 6dB per octave down to 1 mHz [*Fraser et al.*, 1991]. This had the effect of spectrally flattening the background $f^{-2.6}$ power law spectrum [*Olson*,1986] of the geomagnetic pulsations. The phase response over this band was essentially flat and timing at each station was provided by a combination of GPS and ultra-stable clocks with interstation errors maintained at less than 50 ms.

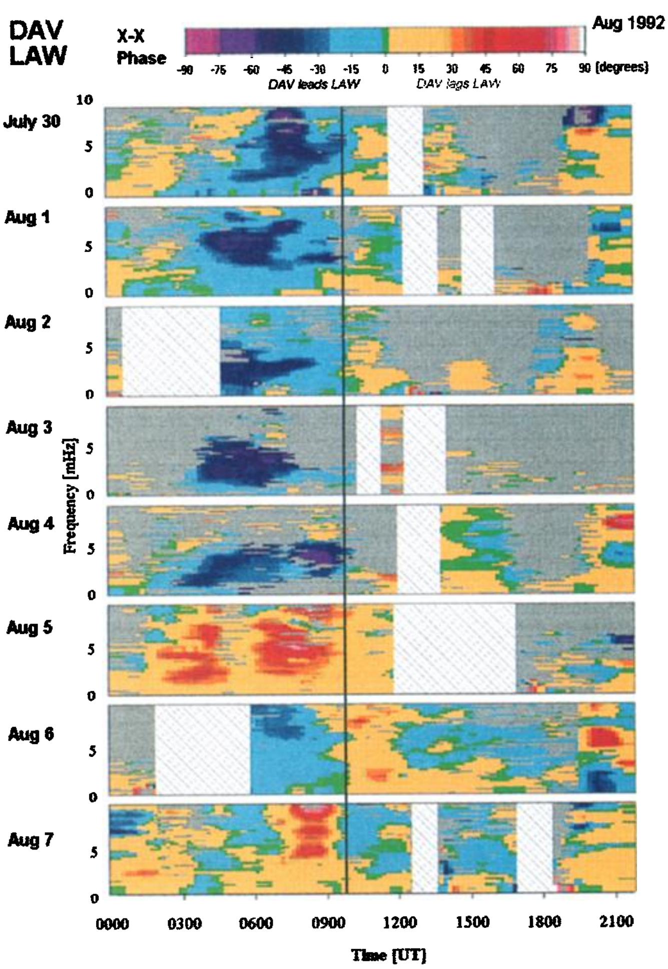

Figure 1. Dynamic phase-lag spectrograms (interstation crossphase) between Davis and Law, for the X (geomagnetic N-S) component. Uncorrelated data, determined from polarized power estimates, have been masked (grey squares). Occasional data gaps are shown cross-hatched. The vertical line indicates local magnetic noon at Davis.

Analysis

Data were sampled at a rate of 1/20 s^{-1}, providing a Nyquist frequency of 25 mHz, suitable for analysis of Pc5 band (1-10 mHz) pulsations. Dynamic spectrograms were generated using 256 point FFTs stepped at 10 minute intervals. Pure state filtering techniques [*Samson*, 1983] were used to detect polarised components in the pulsations.

As a test of our crossphase analysis we first determined the horizontal polarization of Pc5 waves recorded at Davis. We confirm the observations made by *Samson* [1972], and more recently by *Olson and Fraser*, [1994], of a diurnal variation in ellipticity from right-hand before magnetic noon, to left-hand/linear after magnetic noon.

We next sought evidence of azimuthal propagation in interstation crossphase measurements. For eight days of our campaign period, dynamic phase spectrograms (Figure 1) were generated for the X channel of the Davis-Law (E-W) pair. Pure state detection algorithms were used to estimate phases and mask out unpolarised (noise-like) components in the spectra. Immediately obvious is a daily phase reversal around local magnetic noon (eg. July 30, August 1-4 in Figure 1). Since these stations have approximately the same magnetic latitude, we follow *Olson and Rostoker* [1978] and interpret this as evidence of waves propagating away from the sub-solar point and toward the dawn and dusk meridians.

Examining phase as a function of frequency for intervals during the daytime, we note the absence of the linear relationship given in equation (1) of *Olson and Rostoker* [1978]. For instance, between 0600 and 0900 UT, the dynamic crossphase spectrogram for August 1 (in Figure 1) shows a phase minimum (dark band) at 3 mHz, and a second minimum around 7 mHz. Similar patterns with phase minima at slightly different frequencies can be discerned in spectrograms for July 30, August 2-4, when the geomagnetic activity was low (Kp ~1-2). Distinct maxima in phase are also evident in the post-noon sector on most days, although data gaps which start around 1200 UT mask this effect. On August 5 and 7 the diurnal trend in phase is generally reversed and we note this coincides with significantly higher geomagnetic activity (Kp ~ 4).

We propose that these spectral characteristics are due to the superposition of both FLR and propagating wave signatures. The crossphase minima (pre-noon) or maxima (post-noon) around 3 mHz indicate the presence of the fundamental, and above 5 mHz, possibly the second harmonic of the resonance, and we find FLRs occur most favourably during the pre-noon sector.

The reversal of propagation and lack of distinct FLR signatures on August 5 and 7 may be an indication that the stations lie under field lines which are open and/or tailward mapped during periods of high activity. Later we discuss how IMF control of the cusp location can explain this phenomenon.

Extending this model, crossphase measurements for the Davis-Plateau (N-S) pair should contain FLR signatures which dominate over propagation signatures, as these stations lie roughly on the same geomagnetic meridian. To help unravel these coupled processes we have adopted a technique similar to phase hodograms, which usually show the time evolution of phase between orthogonal components at a single site. In a similar fashion Figure 2 displays phase-scatter diagrams in which significant (highly polarised) crossphase measurements for the Davis-Law (E-W) pair have been plotted against concurrent crossphase measurements for the Davis-Plateau pair for frequencies between 1 and 6 mHz. This technique allows relationships in the data to be more readily identified. The criterion used to define significant measurements was the combination of a polarised power threshold (~70 % of the maximum power in an FFT interval), and closure of phase around the triangular array to within 1 degree (ie $\Phi_{DAV\text{-}LAW} - \Phi_{DAV\text{-}PLA} - \Phi_{PLA\text{-}LAW} < 1°$). We avoid describing these data points as 'events' since, depending on the frequency, they may contain several cycles or as

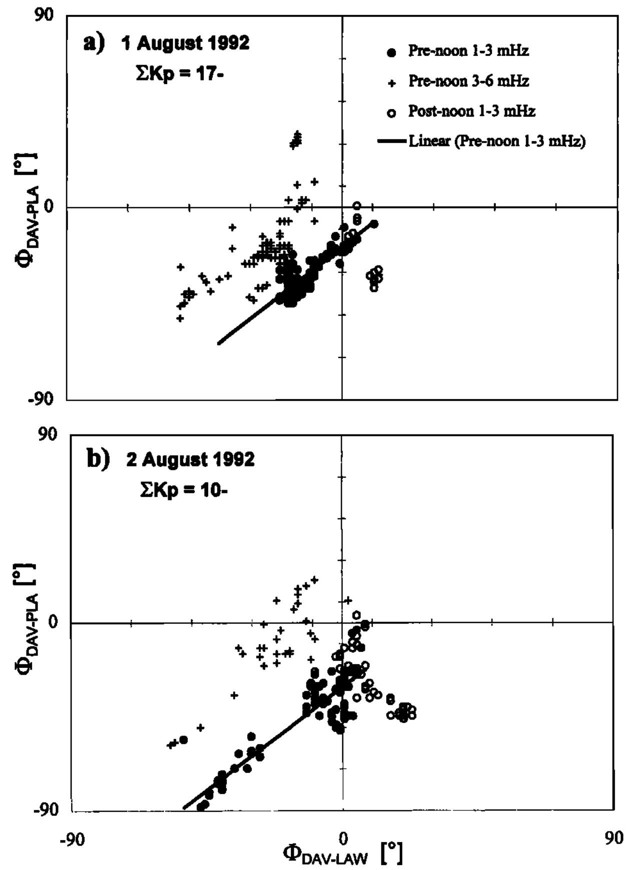

Figure 2. Phase lag scatterplots. Significant interstation crossphase measurements for Davis-Law are plotted against concurrent crossphase measurements for Davis-Plateau. The data is binned into two frequency ranges and two time intervals - pre-noon=0500-0930, post-noon=0930-1400 UT. The regression co-efficient for the trend lines are 0.7 and 0.8 for August 1 and 2, 1992 respectively.

few as one, and there is considerable overlap between consecutive measurements.

Examining both Figure 1 and 2 we find $\Phi_{DAV-LAW}$ (E-W) is generally negative pre-noon and positive post-noon, This is consistent with the expected sense of azimuthal propagation, as well as FLR signatures due to progressively longer field lines dawnward (pre-noon) and duskward (post-noon) of the stations. In contrast, $\Phi_{DAV-PLA}$ (N-S) remains negative throughout the daytime suggesting that field lines threading Plateau are always longer than those threading Davis. This seems reasonable, although poleward propagating forms [*Olson*, 1989] may also contribute to this effect, particularly around noon when there is larger scatter along this axis (eg. Figure 2 (b))

Examining the pre-noon phases for the 1-3 mHz band (filled circles in Figure 2.) we find a roughly linear relationship between $\Phi_{DAV-LAW}$ and $\Phi_{DAV-PLA}$ on days with low to moderate geomagnetic activity (Kp~<2). Using linear regression we estimate slopes of ~1 and intercepts of -20° and -30° for August 1 and 2 respectively. Post-noon phases follow a similar relationship but with slopes of -1. We interpret this as a diurnal change in the gradient of field line lengths for the observed FLRs due to progressively greater stretching on the dawn and dusk flanks and compression at the nose of the magnetosphere. A very interesting feature of the data identified by this scatterplot technique is the presence of harmonically related phase measurements. We expect the second harmonic of FLRs at these latitudes to occur in the frequency range 3-6 mHz . Phase measurements in this band are represented by the crosses in Figure 2 (a,b), and in the pre-noon sector we find the same interstation phase relationship as seen in the 1-3 mHz range, but offset by ~25 degrees along the x-axis. Interpreting this offset as due to azimuthal propagation, we use equation (1) from *Olson and Rostoker* [1978] and calculate projected velocities in the ionosphere of 5.7 Km/s and 4.6 Km/s for August 1 and 2 respectively.

Around local magnetic noon the contribution to phase measurements due to azimuthal propagation should be negligible, therefore the y-intercept of the 1-4 mHz data in Figure 2 (a,b) provides a measure of the change of field line lengths with magnetic latitude (dl/dmlat). Using the T89 external magnetic field model [*Tysganenko*, 1989] and equation (4) we have estimated the effect of diurnal variations of dl/dmlat and dl/dmlong on interstation phase measurements, and the results for low geomagnetic activity (Kp=2) are shown in Figure 3. We have used the y-intercept of -20 degrees from figure 2 (a) to set the resonance 'efficiency factor' η. Although this modelling does not include propagation effects there are many similarities between Figure 3 and Figure 2 (a,b). The main difference is greater slope in pre-noon $\Phi_{DAV-LAW}$ versus $\Phi_{DAV-PLA}$ relationships. Also, modelled post-noon phases for the DAV-LAW pair are considerably smaller compared with our data, suggesting our measured phases in this sector are predominantly the result of azimuthal propagation.

Gradients in plasma density which occur for instance in the LLBL have not been included in this modelling. We expect that increases in density in the radial direction will result in greater measured phase differences, particularly for N-S spaced stations compared with the model. This effect is not evident in our data.

The phase scatterplot for August 7 (not shown) does not show any of these relationships, and the high geomagnetic activity on this day (Kp~4) may be confusing our phase estimation algorithm. Alternatively, the triangular array may have mapped to field-lines which did not close in the dayside magnetosphere, indicating that the cusp passed equatorward of the stations on this day. We examine the likelihood of this in more detail in the following section.

Discussion

It is important to note there is considerable spatial and temporal 'blurring' inherent in our recording and analysis of Pc5 waves. Due to the large field of view of the magnetometers we may be recording the superposition of many FLR signatures. *Hughes and Southwood* [1976] analytically derived the modification of ULF waves by the ionosphere and found dissipation effects such as Joule heating result in spatial low pass filtering of variations. At high latitudes, particle

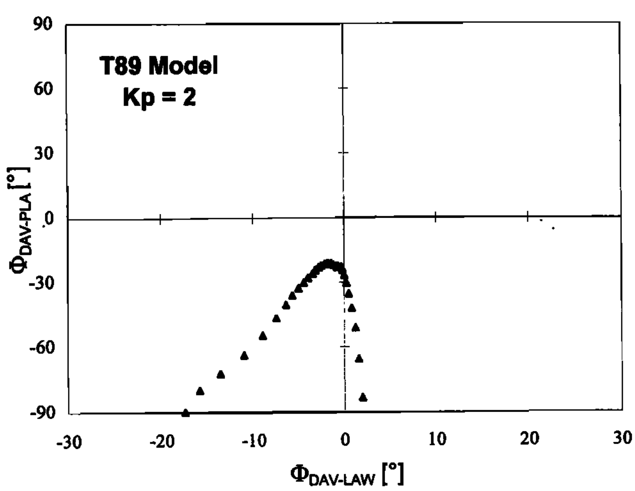

Figure 3. Model equivalent of Figure 2. The T89 external field model was used to determine field line lengths threading Davis, Law and Plateau as a function of time. The phase offsets represented in this figure have been computed assuming a constant of proportionality with resonant frequency offsets, which is related to the Q of the resonance. Each point represents a 15 minute interval starting at 0530 UT (bottom left) and ending at 1400 UT. Note the different scales on the abscissa compared to Figure 2.

precipitation complicates diurnal patterns, possibly explaining the often noted asymmetry in pre- and post-noon pulsation amplitudes [*Sibeck et al.*, 1996]. This may also explain the reduced spatial and temporal coherence of post-noon pulsations, as described for instance by *Samson* [1972].

Regardless of these difficulties, we believe the topology inferred from our measurements can be used as a diagnostic of the 'wave cusp' location. As a test of this diagnostic we have examined IMP-8 satellite data for evidence of IMF and/or solar wind control. Statistical studies of the 'particle cusp' performed by *Newell et al.* [1989] using the low altitude, polar orbiting DMSP F7 satellite, have established a roughly linear relationship between magnitude of the IMF Bz component and the latitude of the cusp. For the winter/equinox cusp $\lambda_0 \sim 76$ degrees, and therefore poleward of Davis for Bz > -2 nT during the period of our study.

Examining IMP-8 magnetic field data (not shown) we find the IMF Bz component had small variation (< 5 nT p-p) from August 1-4 and was generally positive. On August 4 at around 1600 UT rapid N-S turnings in the IMF occurred, resulting in a dramatic increase in geomagnetic activity (Kp~5). The Bz component then remained large and negative until 0500 UT on August 6 and we therefore expect that the cusp passed equatorward of our array on August 5. The crossphase measurements for the Davis-Law pair on this day (in Figure 1) show a distinct reversal in the diurnal trend seen in previous days and peaks in phase versus frequency are less evident. Further, when the Bz component became positive during the first half of August 6 the previous diurnal trend was re-established. A trend similar to the August 5 crossphases is seen on August 7, when the IMF Bz was again large and negative. Although the mechanism which produces these apparent reversals in azimuthal propagation is unclear, we conclude that the field lines which map to our array during these periods were no longer closed in the dayside magnetosphere, explaining the absence of clear FLR signatures.

In conjunction with IMF Bz, the solar wind dynamic pressure (SWDP) can modify cusp topology (eg. *Yamauchi et al.*, 1996). IMP-8 solar wind plasma data shows SWDP dropping from ~3nP to ~1nP over 1-2 August. This resulted in less compression at the nose of the magnetosphere, leading to longer field line lengths and a corresponding increase in dl/dmlat in the magnetic noon meridian. This may explain the different y-intercepts in figure 2 (a) and (b).

Finally, we find some correlation between solar wind velocity and the azimuthal propagation speeds inferred from harmonically related crossphase measurements. Mapping velocities of 5.7 and 4.6 Km/s from the ionosphere to the LLBL at the equator gives speeds of ~270 and 210 Km/s for August 1 and 2 respectively, and we note this ratio of 6:5 closely matches the ratio of solar wind velocities (not shown) for these days.

We conclude that field line resonances provide a recognisable and repeatable two dimensional phase pattern on the ground, at low geomagnetic activity. At cusp/cleft latitudes this pattern collapses with increased geomagnetic activity suggesting mapping to open field lines. Using this technique we believe we can differentiate between open and closed field line regions leading to the identification of a 'wave cusp' around local magnetic noon.

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S.T. Ables, B.J. Fraser, C.L. Waters, D.A. Neudegg, Department of Physics, University of Newcastle, Callaghan, NSW 2308, Australia. (e-mail: phsta@cc.newcastle.edu.au)

R.J. Morris, Australian Antarctic Division, Channel Hwy, Kingston, Tasmania 7050, Australia.(e-mail: ray_mor@marvin.antdiv.gov.au)

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