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Magnetospheric sources of Pc1-2 ULF waves observed in the polar ionospheric waveguide

D.A. NEUDEGG[1]*, B.J. FRASER[2], F.W. MENK[2], G.B. BURNS[3], R.J. MORRIS[3] and M.J. UNDERWOOD[4]

[1]*Department of Physics and Astronomy, University of Leicester, Leicester LE1 7RH, UK*
[2]*Co-operative Research Centre for Satellite Systems, Department of Physics, University of Newcastle, NSW 2308, Australia*
[3]*Australian Antarctic Division, Kingston, TAS 7050, Australia*
[4]*CSIRO Division of Marine Science, Hobart, TAS 7000, Australia*
**current address: Rutherford-Appleton Laboratory, Oxfordshire, OX11 0QX, UK*
D.A.Neudegg@rl.ac.uk

Abstract: Energy from the outer regions of the magnetosphere may be transferred to the polar ionosphere by plasma waves. A magnetometer array operated during the Antarctic winter observed Ultra-Low-Frequency (ULF) plasma waves in the Pc1-2 (0.1–10.0 Hz) frequency range, propagating parallel to the surface of the Earth in a waveguide or duct centred at ~300 km altitude in the ionosphere. These compressional fast mode plasma waves most likely originated in the outer magnetosphere as shear mode plasma waves guided along the geomagnetic field. The region of origin in the magnetosphere for the waves is not certain as several widely spaced volumes map along geomagnetic field lines to a relatively close ensemble in the polar ionosphere. This paper compares the direction of propagation for the waves with signatures of magnetospheric regions geomagnetically projecting onto the ionosphere. Regions such as the polar cusp, low latitude boundary layer and mantle were observed by DMSP spacecraft and a SuperDARN high-frequency radar. The most likely region in the polar ionosphere for the fast mode waves to have originated from is equatorwards of the polar cusp, suggesting the field guided waves originated just inside the magnetopause. A case is made for association of the observed Pc1-2 ULF waves with post-noon, field-aligned-current systems driven by reconnection of the solar Interplanetary Magnetic Field (IMF) and the geomagnetic field near the magnetopause.

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Introduction

The coupling between the magnetosphere, the magnetic cavity in the solar wind caused by the geomagnetic field, and the ionosphere, the partially ionized upper atmosphere from *c.* 100 km to *c.* 500 km altitude, is strongest in the polar regions (e.g. Rodger & Smith 1989). Some of the energy from the outer magnetosphere near 60 000 km from Earth is transferred to the polar ionosphere via plasma waves guided along geomagnetic field lines. The existence of plasma waves was predicted by Alfvén (1942) and their observation on the ground in the polar regions and characterization is an ongoing mature research field. Where the waves originate from in the magnetosphere and where they dissipate to in the ionosphere is still not fully determined. Observations of plasma waves in ground magnetometer records in the Pc1-2 (pulsation continuous) 0.1–10.0 Hz frequency range have been classified into many 'spectral' types, depending on their power distribution as a function of time and frequency (Fukunishi *et al.* 1981) and on the different types associated with various regions of the magnetosphere that geomagnetically map onto the polar ionosphere (e.g. Menk *et al.* 1993).

With several closely spaced regions such as the cusp, low latitude boundary layer (LLBL) and mantle as candidates for wave sources and the present spacing between polar magnetometer stations being larger than the size of these regions, it is difficult to decide between candidate sources. The closely spaced regions in the polar ionosphere geomagnetically map out to a large volume of the outer magnetosphere so the possible range of magnetospheric sources for the waves is large. It is expected that the Pc1-2 waves observed on the ground may originate in the outer magnetosphere (e.g. Anderson *et al.* 1992) and propagate along geomagnetic field lines as transverse shear mode waves to the upper atmosphere. In the ionospheric F region (150–500 km altitude) the field guided shear mode waves may convert (Altman & Fijalkow 1968) into compressional mode waves that propagate across geomagnetic field lines, parallel to the surface of the Earth in a waveguide or duct (Greifinger & Greifinger 1968) centred on the electron concentration peak near 300–350 km altitude. Mid-latitude observations have been made of these ducted compressional Pc1-2 waves from sources near the projection onto the upper atmosphere of the inner magnetosphere plasmapause boundary (e.g. Fraser 1975, 1976). Any single magnetometer observing the Pc1-2 signature may be observing the original field guided mode from the magnetospheric region above the station, the compressional

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Table I. Array magnetometer locations.

Station	Geomagnetic (PGM-88) Latitude	Longitude	Geographic Latitude	Longitude
Davis	74.60°S	102.27°E	68.58°S	77.97°E
Law base	74.70°S	98.63°E	69.39°S	76.38°E
Plateau site	75.64°S	101.81°E	69.42°S	80.19°E
Mawson	70.52°S	92.06°E	67.60°S	62.87°E

mode wave in the ionosphere from some distance away or some combination of the two. Thus the 'source' for the waves observed on the ground is actually the field-guided to compressional mode wave conversion region lying within the projection of a magnetospheric region onto the upper atmosphere.

A year-long study at Davis in Antarctica (Table I) which is usually located near the projection of the southern polar cusp, (the geomagnetic funnel for solar wind entry onto the ionosphere), showed a clear winter occurrence and amplitude maxima for Pc1-2 pulsations and associated them with the proximity of the cusp (Morris & Cole 1991). Widely spaced polar observatories very rarely observe the same waves and thus cannot determine if they are field guided mode waves incident from the magnetosphere or compressional mode waves in the ionosphere. A closely spaced array (*c.* 130 km) of three magnetometers was deployed from Davis station during the Antarctic winter to examine the source location and propagation mechanism of Pc1-2 waves observed at high latitudes. The array was used as an interferometer to determine the angle-of-arrival, speed and attenuation of the Pc1-2 waves in the waveguide/duct. Source regions of the ducted fast mode waves in the ionosphere move in the same way as the ensemble of magnetospheric projections (cusp/LLBL/mantle) onto the polar atmosphere (Neudegg *et al.* 1995, 1996b), poleward/equatorwards of the array for low/high geomagnetic activity, and east to west at the Earth's rotational speed. Wave angle-of-arrival often cannot resolve between the various magnetospheric regions due to their close proximity to each other. This paper is an attempt to reference wave source directions against magnetospheric signatures from spacecraft and radar.

Method

Triangulation of Pc1-2 ULF waves in the ionospheric waveguide

A three station magnetometer array was deployed and operated during an extensive series of vehicle traverses onto the Antarctic Plateau from Davis station during June–August 1992 (Neudegg 1992). A minimum spacing of 100 km was required to allow for magnetometers which integrate signals from approximately a 100 km radius from the altitude of the bottom of the ionized atmosphere. An average spacing of *c.* 130 km was achieved. A four station array would have theoretically allowed for point source location of waves but the requirements for minimum spacing and the difficult nature of winter logistics operations on the Antarctic plateau only permitted a three-station array. A supplementary fourth site was operated at Mawson station but few Pc1-2 wave events were seen in common with the triangular array because of its remoteness from the other sites. The location of the sites in geomagnetic and geographic coordinates are summarized in Table I. The site spacings were Davis–Law = 112 km, Davis–Plateau = 127 km and Law–Plateau = 148 km. The array was operated from 27 July (day 209) to 8 August (day 221) 1992. Each site had two mutually-orthogonal induction magnetometer sensors which were digitally sampled at 10 Hz. The experiment and magnetometer calibrations are detailed in Neudegg *et al.* (1994a) and show that the relative phase responses of the magnetometers do not cause apparent signal delays between the stations. Cross-correlation of the waveforms allowed the time lag between pairs of stations to be calculated (Neudegg *et al.* 1994b). Methods of 'wavefront reconstruction' were developed which calculated the direction-of-propagation/angle-of-arrival of the waves and also their speed (Neudegg *et al.* 1996a).

Magnetospheric particle precipitation signatures - DMSP Spacecraft

The DMSP (Defense Meteorological Satellite Program) is a series of low altitude polar orbiting spacecraft with upward-looking charged particle flux and energy detectors in its complement of instruments. The particle spectra from these instruments have been used to determine the statistical location and time variation of high latitude plasma regions of the magnetosphere near 830 km altitude, above the topside ionosphere (Newell & Meng 1988, 1992). Magnetospheric projections are dynamic in time and space and a spacecraft pass provides snapshots but lacks the ability to sample regions with temporal resolution less than successive passes (~100 min). The DMSP spacecraft used in this study were F8, F10 and F11. The particle detectors point towards the local zenith, directly away from the Earth and have a field of view of 8°. Electrostatic analysers measure electron and ion energies and fluxes from 32 eV to 30 keV in 20 logarithmically based steps (Hardy *et al.* 1985).

The basic definition of the polar cusp is the area of most direct access for magnetosheath particles to the ionosphere. The magnetosheath comprises shocked solar wind plasma between the geomagnetic field boundary at the magnetopause and the bow shock upstream of it in the solar wind. The low latitude boundary layer (LLBL) is the outermost region of the dayside magnetosphere, adjacent to the magnetopause, which geomagnetically maps onto the ionosphere directly equatorward of the cusp. The following criteria were established by Newell & Meng (1988) from observation of numerous particle spectra and are statistical in nature:

E_i, j_i and E_e, j_e are the average ion and electron energies and fluxes respectively,

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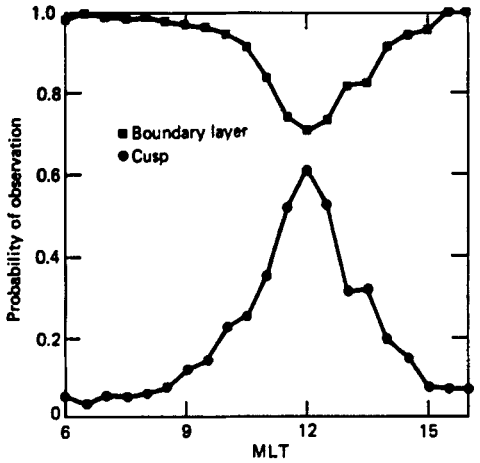


Fig. 1. Normalized probabilities of detecting the cusp (lower) or LLBL (upper) as a function of magnetic local time (MLT) in half hour bins. Probabilities sum to greater than one as both regions may be observed. After Newell & Meng (1988).

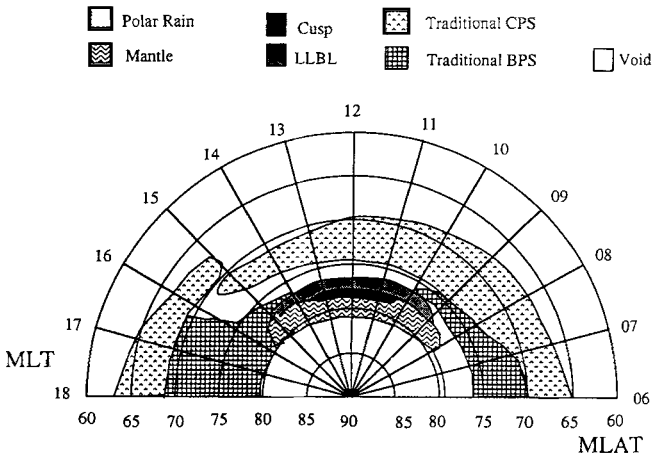


Fig. 2. The average location (in MLT and MLAT) and shape of magnetospheric projections onto the ionosphere determined from DMSP particle signatures. The regions are described in Table II. After Newell & Meng (1992).

i) The region was *cusp* if

$j_i > 10^{10}$ eV/cm^2.sec.sr
$j_e > 6 \times 10^{10}$ eV/cm^2.sec.sr
300 eV < E_i < 3000 eV AND E_e < 220 eV

ii) The region was *boundary layer (LLBL)* if

$j_i > 10^{10}$ eV/cm^2.sec.sr
$j_e > 6 \times 10^{10}$ eV/cm^2.sec.sr AND 3 keV < E_i < 6 keV
OR 220 eV < E_e < 600 eV

The probability of observing the cusp peaks strongly at local magnetic noon (LMN) where the boundary layer has a minimum probability of observation, shown in Fig. 1. The cusp has been observed away from local noon due to solar wind and interplanetary magnetic field (IMF) B_y conditions (e.g. Eather 1985). The statistical cusp was found to have a 0.8°–1.1° geomagnetic latitude (MLAT) extent, independent of magnetic local time (MLT) and a location between 74° and 78° MLAT. The LLBL is narrowest (1.3°) at noon, widening out 3° at 1030 MLT and 1315 MLT. The equatorward boundary varies between 73.5° and 75.5° and the poleward 75.5° to 78°. Newell *et al.* (1991) developed an algorithm for identifying the magnetospheric signatures of high latitude particle precipitation and the region classifications shown in Table II.

Newell & Meng (1992) used the region identification in the previous section to compute probability maps for the various magnetospheric particle precipitation regions onto the ionosphere as a function of geomagnetic latitude (MLAT) and magnetic local time (MLT). A total map of the ionosphere to the magnetosphere was created (Fig. 2) based on plasma precipitation, an average over several thousand DMSP passes. The statistical cusp is 2.5 hours wide from 1045–1315 MLT at 77° MLAT and LLBL from 0900–1500 MLT equatorward of the cusp. An important possible magnetospheric wave source from the spacecraft observations of Anderson *et al.* (1992) is the outer plasmatrough or sub-solar magnetosphere which would project to the atmosphere just equatorward of the LLBL. The open/closed field line boundary, marking the transition from 'open' geomagnetic field lines connected to the IMF inside the polar cap poleward of the cusp and 'closed' field lines with both ends in conjugate hemispheres, runs through the vicinity of the cusp/LLBL. The map does not imply the projections are static features as magnetospheric convection carries field lines poleward across the polar cap and the regions are dynamic with geomagnetic and IMF conditions (Eather 1985).

Table II. Magnetospheric regions from DMSP particle observations (adapted from Newell *et al.* (1991)).

Low Latitude Boundary Layer (LLBL)	Higher temperatures and lower bulk flow velocities than magnetosheath plasma
Cusp proper (CU)	Magnetosheathlike plasma has direct entry to the ionosphere
Near cusp (NC)	Thought to be cusp but marginal spectra between cusp and LLBL.
Mantle (MA)	Immediately poleward of the dayside auroral oval and soft energy spectra
Central Plasma Sheet (CP)	Probably maps to the near Earth region of quasi-dipolar field lines
Boundary Plasma Sheet (BP)	Maps to the distant plasma sheet and Plasma Sheet Boundary Layer (PSBL). Most discrete dayside aurora lie in this region.
Polar Rain (PR)	Precipitation within the polar cap solely of electrons. Polar cap precipitation having a significant ion flux or electron spectral structure classified as BPS or mantle.
Void (VO)	No significant precipitation was observed.

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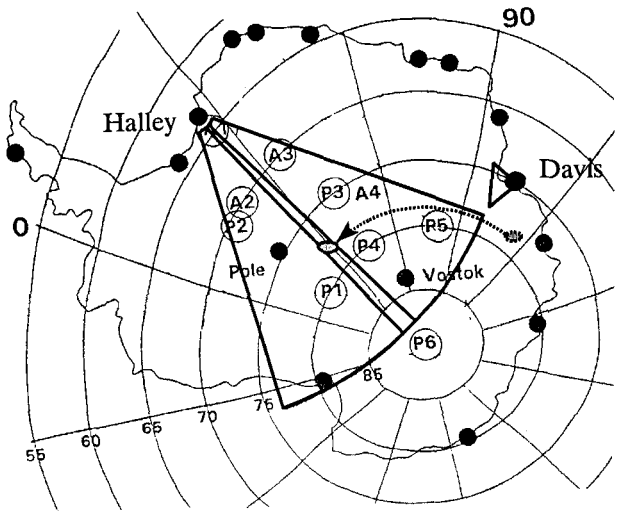


Fig. 3. The Halley radar field of view compared with the location of the triangular magnetometer array near Davis. The twin lines along the meridian toward the invariant pole are the central beam 8. The cusp moves anticlockwise about the invariant pole. A cusp observation in beam 8 shown by the stylised signature may be interpolated back in time to its location near the array at the time of the ducted wave observations. After Neudegg *et al.* (1996b).

Ionospheric cusp signatures in HF radar

The original PACE (Polar Anglo-American Conjugacy Experiment) (Baker *et al.* 1989) consisted of an HF coherent backscatter radar in each hemisphere and has since been incorporated into the larger Super Dual Auroral Radar Network (SuperDARN) (Greenwald *et al.* 1995) of radars across both hemispheres for imaging polar ionospheric convection. The radar used for this study was at Halley, Antarctica operated by British Antarctic Survey (BAS). Baker *et al.* (1995) have determined radar signatures for the cusp and LLBL by case study comparisons with DMSP particle signatures. The radar 'cusp' is characterized by significant backscattered power (>3 dB above the background noise) and wide complex power spectra with a distribution of 'spectral widths' (Hanuise *et al.* 1993), of a Gaussian nature above 220 m s^{-1}. André *et al.* (1999) has shown the distinctive 'cusp-like' spectral widths can be caused by plasma velocity fluctuations in the Pc1-2 (0.1–5.0 Hz) range, perhaps caused by broad scale ULF wave noise from the exterior cusp. The cusp ionospheric plasma typically displays a significant mean Doppler velocity away from the radar, of up to 1000 m s^{-1} in the dayside throat of the polar ionospheric convection pattern. The high velocities in the ionospheric cusp region are often in 'flow channels' (Pinnock *et al.* 1993), shown to be related to bursty magnetic 'reconnection' or 'merging' between the geomagnetic field and the IMF (Neudegg *et al.* 1999, 2000b). Scans on the central beam 8 of the Halley radar, when 'cusp-like' signatures could be recognized, were examined for the days of the magnetometer array campaign.

The Halley radar field-of-view (Fig. 3) encompasses the high latitude projections of the magnetosphere onto the ionosphere including the LLBL and cusp. The coordinate system used is invariant geomagnetic, centred on the geomagnetic South Pole labelled 'P6' in Fig. 3. Beam 8, shown by the double lines, is the central beam aligned almost along the 30° east magnetic meridian to the east of the geographic South Pole and directly toward the south invariant magnetic pole. The location of the triangulation magnetometer array near Davis is shown and the fields of view for the two instruments do not overlap. Attempts to find cusp signatures in beam 16 near the Davis magnetometer array were unsuccessful due to low power returns. The cusp signature position was extrapolated back in time from its observation by the radar to when wave events were observed by the magnetometer array. A hypothetical dotted cusp signature is shown south-east of the magnetometer array where it might be observed at the time of the Pc1-2 wave events, and a dashed line moves it forward in time to where the cusp would be observed in beam 8 of the radar. The cusp is a reasonable approximation as a central reference point for average LLBL and mantle positions (Fig. 2).

The extrapolation relied on three reasonable assumptions:

a) A similar K_p value between the time of wave observations and the radar cusp observation so the cusp remains at approximately the same magnetic latitude.

b) The cusp projection moves east to west at *c.* 15° per hour about the invariant magnetic pole due to the rotation of the Earth and does not significantly alter its longitudinal extent over the 4–5 hours MLT between the radar and magnetometer observations. The longitude of the cusp at the wave observation was determined by rotating the radar cusp west to east, back in time, over the time difference between the magnetometer array wave and radar cusp observations.

c) Any east–west shift in cusp location due to IMF B_y is ignored. Case studies will show only one event with significant IMF B_y and the shifted cusp location does not alter the general conclusions.

Comparison of ULF wave directions with measurements of magnetospheric projections

Interpolation of DMSP signatures involved fitting a set of average projections of the dimensions shown in Fig. 2 to the observations along the ground track relative to the magnetometer array. Fittings of the average projections to the observations are non-unique but the following constraints apply:

a) The MLT of the satellite pass at the array assists in determining the longitudinal location of high latitude features relative to the array magnetic meridian. The average cusp location is centred on 12 MLT and extends

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from 1030 to 1330 MLT, the LLBL from 9 MLT to 15 MLT. So the longitudinal width and centre meridian of the projection fittings may be estimated.

b) Boundaries between magnetospheric projection regions should lie close to lines of constant geomagnetic latitude as the regions are oriented about the geomagnetic pole (as per Fig. 2).

c) Topological constraints, such as the cusp, always lying between the mantle and LLBL as per Newell & Meng (1992) (Fig. 2).

d) Magnitude of K_p may give indications of the latitudinal shift for the projections relative to their average location. For example, a K_p of 5 would be expected to place the cusp, LLBL and mantle equatorward of their average location (e.g. Newell *et al.* 1991) and Davis is an average cusp location station.

Only DMSP passes less than two hours from a Pc1-2 wave event were used. Projections could be rotated about the invariant pole by the appropriate amount, similar to the radar cusp, once they had been fitted to the pass. The observed and predicted high attenuation of high latitude ducted fast mode waves (Neudegg *et al.* 2000a, Greifinger & Greifinger 1973) sets a maximum radius for the Pc1-2 fast mode wave source distance in the ionosphere (where the field guided wave from the magnetosphere converts (Altman & Fijalkow 1968) to a compressional mode wave) from the magnetometer array. The average 1/e attenuation distance for the waves is ~300 ± 220 km. From the rate of change for angle-of-arrival during low K_p it has been calculated that source regions may lie ~500 km from the array. Therefore the radius has been set at a generous 700 km, just beyond the distance from Davis to Mawson station as a very few common events have been observed at both stations by Hansen *et al.* (1992) and in this study. Propagation over this range by fast-mode waves in the ionosphere occurs in the order of one second. The wavefront reconstruction method is not amenable to wave sources inside the array or within the probable 100 km effective field-of-view of the magnetometers so regions directly overhead the array are possibly less likely to be sources for the observed, ducted waves.

Pc1-2 wave event database

The 43 Pc1-2 wave events used to examine dependence of angle-of-arrival on MLT and K_p contained only five events that occurred near useful DMSP passes. Dynamic spectra (wave power versus frequency and time from the Fourier transform of the magnetometer amplitude-time series) were produced by the University of Newcastle Space Plasma Waves Group on days 212, 217, 219 and 221 containing events with band-limited power in the Pc1-2 (0.1–5.0 Hz) frequency range. Fifty-nine new events were selected but only 22 occurred within two hours of DMSP passes. Six more were lost due to indeterminate values of lag between triangle sites (see Neudegg *et al.* (1994b) for method) including all from day 217. Two events were lost on day 221 when the DMSP pass was too far from the array and six events due to time lags not suitable for wave-front reconstruction, with unacceptably large uncertainties in angle-of-arrival and velocity (see Neudegg *et al.* (1996a) for method). Thus 8 events remained from the 59 new events to make 13 from a total 102 events (*c.* 13%) that could be compared with DMSP passes. The spectral types of the events (Fukunishi *et al.* 1981) were generally either HM (hydro-magnetic) emission bursts (Troitskaya 1980) or dispersive structured emissions such as IPDP (Intervals of Pulsations with Decreasing Period) or IPRP (Intervals of Pulsations with Rising Period) (Matveyeva *et al.* 1976, Morris *et al.* 1982). Both spectral types have been associated with the various high latitude magnetospheric projections (Menk *et al.* 1993), particularly the cusp.

Results

Six case studies illustrate comparisons between angle-of-arrival for selected ducted Pc1-2 wave events and the projections of magnetospheric regions from DMSP passes with interpolated radar cusp positions where available. Wave events are coded by the day of year and Pc1-2 event number, e.g. 216_8.

All wave events are in the frequency range 0.2–1.0 Hz. Wave event angles-of-arrival are referenced to the axis of maximum decrease in L-value. L-value at a latitude is the distance in Earth radii (R_E) that a geomagnetic field line from that location reaches at the equatorial magnetosphere. Thus, the axis of maximum decrease in L-value is a measure of global magnetic north in the Southern Hemisphere (Neudegg *et al.* 1996a). DMSP observations of magnetospheric regions along the spacecraft track are coded with the abbreviations from Table II and labelled with the observation time. The 700 km radius around the array for possible wave sources due to waveguide attenuation is indicated by a dashed line. The IMF B_y and B_z components measured by the IMP-8 spacecraft are shown when they were available to assess the likelihood of B_y effects on cusp location. A positive B_y indicates a likely pre-noon shift in cusp location in the southern hemisphere (e.g. Cowley *et al.* 1991). The IMF measurements were taken from the time of the wave events and time-lagged at an average solar wind velocity from the spacecraft location to the magnetopause to assess the actual IMF that would have been applied at the magnetopause when the Pc1-2 events occurred. The clock angle of the IMF, the angle from IMF northwards in the Y–Z plane, is also shown as an indicator of the possibility that reconnection is occurring. It has been shown that low latitude reconnection is likely to occur if the clock angle exceeds ± 45° (Neudegg *et al.* 2000b).

Case 1. Figure 4 shows 3 August 1992 (Day 216) with wave events 216_8, 216_9 and 216_10. Angles-of-arrival are with

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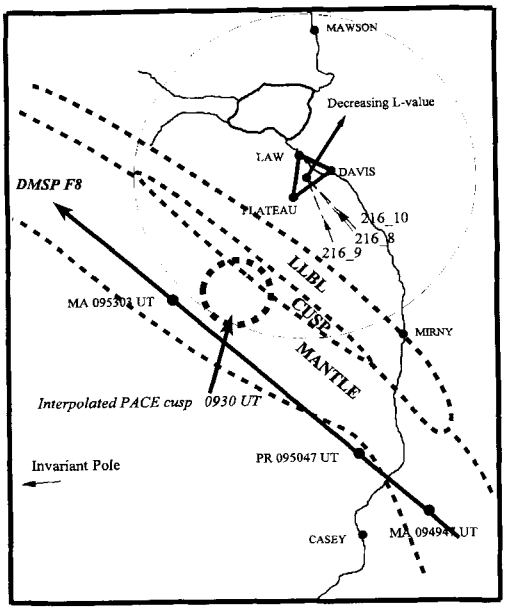


Fig. 4. Case 1. Day 216, 3 August 1992. Pc1-2 wave events:
216_8, 0907–0927UT, angle-of-arrival = 109° ± 8°
216_9, 0907–0923UT, angle-of-arrival = 126° ± 16°
216_10, 0907–0927UT, angle-of-arrival = 106° ± 5°
For scale the Davis–Mawson distance is *c.* 630 km.

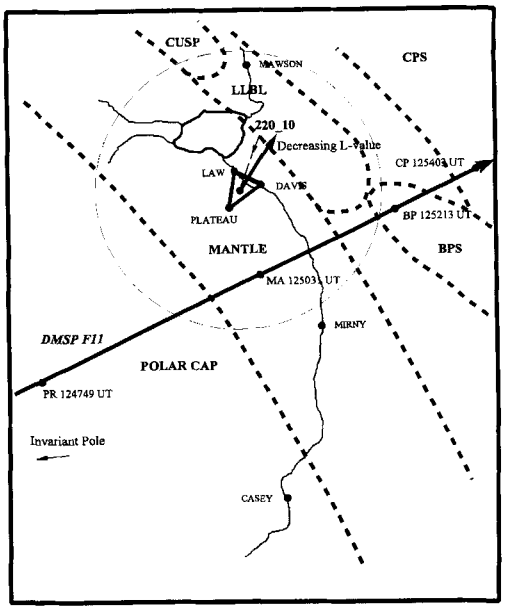


Fig. 5. Case 2: Day 220, 7 August 1992. Pc1-2 wave event:
220_10, 1143–1155UT, angle-of-arrival = 350° ± 6°
For scale the Davis–Mawson distance is *c.* 630 km.

respect to decreasing L-value. A DMSP F8 pass near the array occurred between 0949 and 0954 UT (~1200 MLT at Davis). Two mantle (MA) observations were available and a mantle projection has been fitted around the polar rain observation inside the polar cap. The cusp and LLBL have been placed equatorward of the mantle with average longitudinal and latitudinal extent shown in Fig. 2. The cusp/LLBL central position relative to the array magnetic meridian was determined by the MLT with the centre of the cusp at noon. As geomagnetic indices were low (K_p = 1$^-$ and local K index at Mawson K_{Maw} = 1) the cusp probably lies poleward of the array. The radar cusp was observed in beam 8 (1300–1400 UT, 75°–77° geomagnetic latitude) poleward of the array latitude when K_p was 1$^+$. The signature was rotated eastward (backward in time) by 4 hours or 60° longitude about the invariant pole. As K_p values were low for the time of the radar and wave observations, the cusp was assumed to have moved little in latitude. The shape and size (latitudinal and longitudinal) of the extrapolated cusp is from the original observation of scatter in beam 8, of less longitudinal extent than the particle cusp although their centre longitudes agree. The cusp, LLBL and part of the mantle fall within the 700 km fast mode waveguide attenuation source radius denoted by the dashed circle. The projection of the outer subsolar magnetosphere or plasmatrough is assumed to lie equatorward of the boundary layer, also within the circle. Event 216_9 has an angle-of-arrival in the direction of the LLBL and 216_8 and 216_10 from slightly equatorward of this. Given uncertainties in angle-of-arrival (<± 20° (Neudegg *et al.* 1996a)) and projection location, 216_8 and 216_10 could have sources associated with the LLBL or outer plasmatrough. 216_9 could be associated with the DMSP cusp and the LLBL that is presumed equatorward of the radar cusp. All three wave events have sources on the post-noon side of the cusp/LLBL. The IMP-8 spacecraft measured IMF B_y was 0.6 ± 0.3 nanoTesla (nT) during the events so no significant effect on cusp position would be expected. The IMF B_z was 2.8 ± 0.2 nT giving a range of clock angles of 4° to 19°, not immediately suggestive of low latitude reconnection which agrees with the cusp poleward of the array for a contracted polar cap boundary.

Case 2. Figure 5 shows 7 August 1992 (Day 220) with a DMSP F11 pass at 1247–1255 UT (~1500 MLT). No cusp scatter was observed by the radar. K_p was 5$^+$ before 1200 UT and 5 after. Event 220_10 was one hour prior to the satellite pass. The interpolated magnetospheric regions from DMSP F11 lie 15° east (right in the figure) about the invariant pole at the time of the wave event observation. There were no direct cusp or LLBL observations and their position has been inferred from average projections around Mantle (MA), Boundary Plasma Sheet (BPS) and Central Plasma Sheet (CPS) observations (Newell & Meng 1992). The K_p and post-noon observations constrain the cusp and LLBL projections to within a few degrees of the latitude and longitude of those shown. The LLBL would not lie poleward of the array or west (left in the figure) of the edge of the radius of possible source locations. The equatorward edge of the mantle, LLBL and poleward edge of the outer plasmatrough projection are in the direction of the angle-of-arrival and within the possible source radius. The wave source is on the post-noon side of the cusp/

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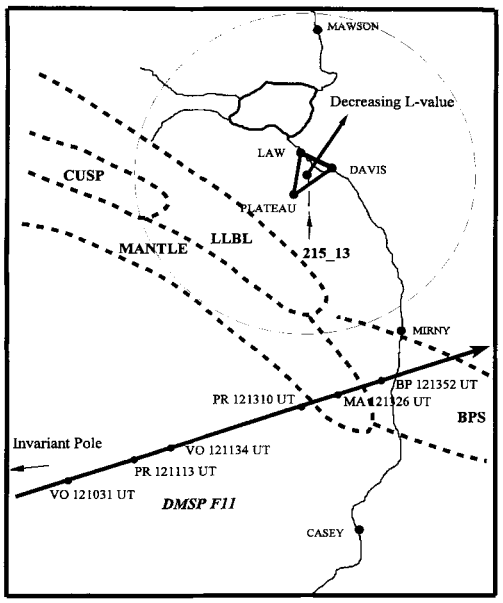


Fig. 6. Case 3: Day 215, 2 August 1992. Pc1-2 wave event:
215_13, 1148–1205UT, angle-of-arrival = 150° ± 5°
For scale the Davis–Mawson distance is *c.* 630 km.

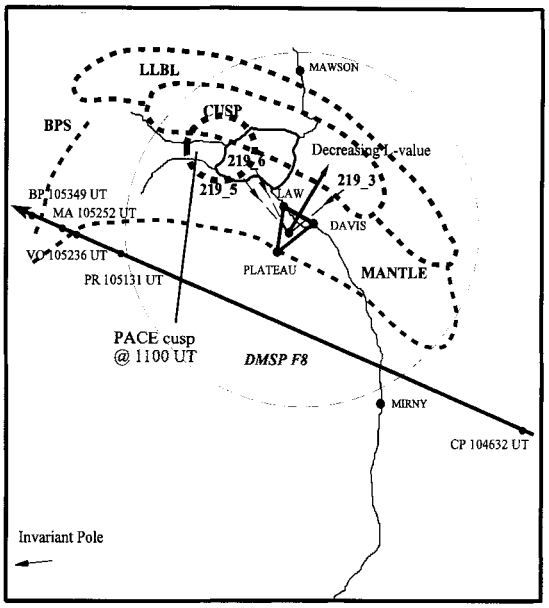


Fig. 7. Case 4: Day 219, 6 August 1992. Pc1-2 wave events:
219_3, 1036–1045UT, angle-of-arrival = 20°±18°
219_5, 1059–1107UT, angle-of-arrival = 286°±6°
219_8, 1116–1124UT, angle-of-arrival = 298°±15°
For scale the Davis–Mawson distance is *c.* 630 km.

LLBL. The IMP-8 spacecraft was in the dusk-side magnetosheath near 16 MLT just behind the dawn-dusk line and so the magnetic field was representative of the IMF near the magnetopause. B_y was 7.0 ± 6.4 nT during the events so a slight pre-noon cusp shift would be expected, taking the cusp slightly further westward from the array. The IMF B_z was -7.3 ± 3.9 nT giving a range of clock angles of 104° to 177°, suggestive of low latitude reconnection and agreeing with the cusp location equatorwards of the array for an expanded polar cap boundary.

Case 3: Figure 6 shows 2 August 1992 (Day 215) with a DMSP F11 pass at 1210–1214 UT (*c.* 1430 MLT). No cusp scatter was observed by the radar. K_p was 1 before 1200 UT and 1⁻ afterwards. Event 215_13 occurred a half-hour prior to the satellite pass. The interpolated magnetospheric regions would lie 7° east (right in the figure) magnetic longitude of their positions shown at the time of the wave observation. Polar rain (PR) and void (VO) observations lie inside the polar cap. Cusp and LLBL projections were constructed from the average Newell & Meng (1992) projections around the mantle (MA) and BPS observations using the very low K index for latitude and time of observation for longitude. The equatorward edge of the LLBL is most likely still poleward of the plateau site. The source region could lie within the LLBL or outer subsolar magnetosphere just equatorward of the LLBL and the wave event source is on the post-noon side of the cusp/LLBL. The IMF B_y was –3.0 ± 0.4 nT suggesting a minor post noon (eastwards) shift of the cusp position from that displayed. The IMF B_z was 1.0 ± 0.6 nT giving a range of clock angles of 60° to 83° which are suggestive of low latitude reconnection.

Case 4. Figure 7 shows 6 August 1992 (Day 219) with a DMSP F8 pass at 1046–1054 UT (*c.* 1300 MLT). K_p = 4⁻. Wave events were 219_3, 219_5, 219_6. The interpolated projections would lie 7° west (left in the figure) in magnetic longitude of their positions shown at the time of the 219_6 observation. There is an unusual configuration of the western edge from the very close void (VO), mantle (MA) and BPS observations causing problems fitting the BPS and mantle boundary to the observations. The cusp and LLBL have been interpolated from average size and location relative to the observed mantle. The longitudinal positions of the cusp and LLBL could be determined to a few degrees from the MLT of the observations. Relatively high K_p suggests the cusp, and LLBL lie equatorward of the array. The Halley radar observed cusp scatter in beam 8, 1300–1330 UT, 72°–75° geomagnetic latitude (< 1 hour duration). K_p was 4⁻ at the time of the radar cusp observation suggesting the latitude of the cusp was < 72°–75° at the time of the wave observations. This places the interpolated radar cusp at Davis slightly poleward and wider in latitude than the inferred DMSP cusp. Projections associated with the wave sources include cusp, LLBL, mantle and outer subsolar magnetosphere (plasmatrough). If the open/closed field line boundary is in the vicinity of the cusp/LLBL boundary then all three event angle-of-arrival vectors point to it. The IMF B_y was 16.4 ± 4.4 nT during the events so a significant pre-noon (westward) shift of the cusp position from that displayed would be expected, implying the wave sources are post-noon of the cusp/LLBL. The IMF B_z was 2.84 ± 0.21 nT giving a range of clock angles of 4° to 19°

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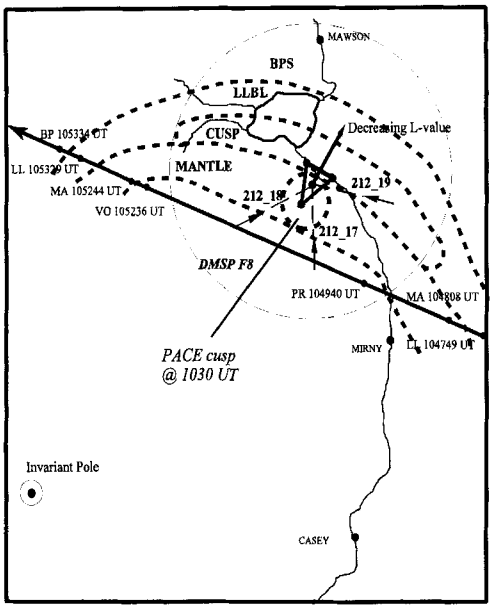


Fig 8. Case 5: Day 221, 8 August 1992. Pc1-2 wave events:
221_18, 1030–1037UT, angle-of-arrival = 314° ± 18°
221_19, 1047–1055UT, angle-of-arrival = 332° ± 14°
For scale the Davis–Mawson distance is *c.* 630 km.

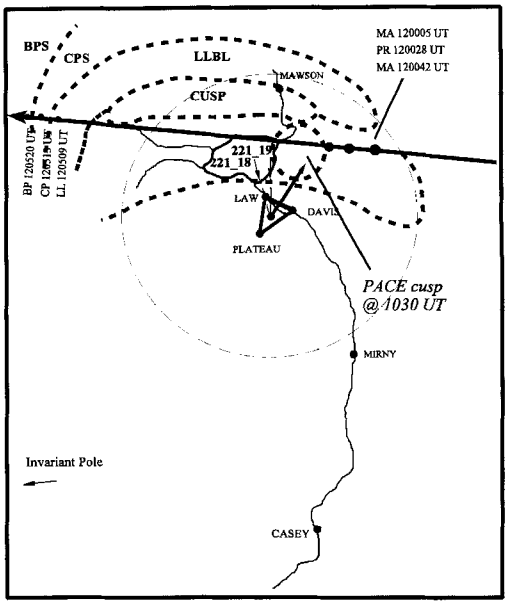


Fig 9. Case 6: Day 212, 30 July 1992. Pc1-2 wave events:
212_17, 1009–1015UT, angle-of-arrival = 146° ± 9°
212_18, 1021–1028UT, angle-of-arrival = 212° ± 1°
212_19, 1049–1055UT, angle-of-arrival = 70° ± 18°
For scale the Davis–Mawson distance is *c.* 630 km.

which are not suggestive of low latitude reconnection.

Case 5. Figure 8 shows 8 August 1992 (Day 221) with a DMSP F8 pass, 1200–1206 UT (*c.* 1415 MLT). $K_p = 4^-$ prior to 1200 UT and decreased to 3 after. Wave events were 221_18 and 221_19. The DMSP inferred magnetospheric regions would lie 15° and 22° east (right in the figure) of their positions shown at the times of the 221_19 and 221_18 observations. Three closely spaced observations of LLBL, CPS and BPS by DMSP bend the projection boundary fitting at the western edge of the satellite pass. There are 90 minutes between wave observations and DMSP where geomagnetic activity decreases, so the cusp will be further equatorward at the time of the wave observations than the DMSP indicates. The LLBL would lie at the edge of the radius of the possible source location with the outer magnetosphere projection outside. A radar cusp observation occurred in beam 8, 74°–77° geomagnetic latitude, 1445–1530 UT and 75°–79°, 1615–1730 UT with $K_p = 3$, less than $K_p = 4$ at the time of the DMSP and wave observations. The radar cusp at the time of the wave events would thus be slightly more equatorward than the radar observation, placing the interpolated radar cusp poleward of the DMSP inferred cusp and pulling the LLBL within the radius of available source locations. The wave event sources are slightly post-noon of the DMSP cusp/LLBL central locations. The IMP-8 spacecraft was in the southern magnetospheric lobe at this time so no IMF information was available.

Case 6. Figure 9 shows 30 July 1992 (Day 212) with a DMSP F8 pass, 1047–1054 UT (*c.* 1300 MLT) when $K_p = 2$. Wave events were 212_17, 1009–1015 UT. The magnetospheric regions would lie 7° east (right in the figure) of their positions shown at the times of the 212_17 observation. The two LLBL and mantle observations anchor the ends of those regions and the cusp has been fitted between them, close to the array latitude as expected for $K_p = 2$. Weak cusp scatter was observed by the Halley radar, 1430–1630 UT, 74°–77° geomagnetic latitude when K_p was 2^+ so the cusp latitude may be slightly poleward of 74°–77°, overhead the array. 212_19 has a source associated with the cusp, LLBL or post noon outer magnetosphere projection if the radar cusp projection is used. The other two events arrived from sources poleward. The mantle is not one of the favoured wave sources although the polar cap has been considered as a source for dispersive structured emissions (Matveyeva *et al.* 1976). The cusp was nearly overhead of the array and wave observations take place over one hour as K_p was slowly increasing, suggesting an equatorward moving cusp consistent with the change in angle-of-arrival from 212_17 & 18 to 19. The IMP-8 spacecraft was in the dawn-side magnetosheath near 9 MLT just behind the dawn-dusk line and so the magnetic field was representative of the IMF near the magnetopause. B_y was -2.0 ± 4.0 nT during the events with a large negative to positive swing at *c.* 1030 UT. The cusp may be expected to be close to the position displayed with slight post-noon (eastward) shift for events 212_17 and 212_18 and pre-noon (westward) for event 212_19. Events 212_19 and 212_17 sources are from the post-noon side of the cusp although only 212_19 is from the direction of the magnetopause. The IMF B_z was -7.3 ± 3.9 nT giving a range

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Table III. Possible source locations for ducted wave events.

Event	Possible source (order of proximity)	Spectral type
216_8	plasmatrough, LLBL	b/d
216_9	plasmatrough, LLBL, cusp	b/d
216_10	plasmatrough, LLBL	b
220_10	LLBL, mantle, plasmatrough	spectra not available
215_13	plasmatrough, LLBL, mantle	b/d
219_3	mantle, cusp, LLBL, plasmatrough	b
219_5	mantle, cusp, LLBL	b
219_6	"	b
221_18	mantle, cusp, LLBL, plasmatrough	b
221_19	"	b
212_17	cusp, mantle, polar cap	b
212_18	"	b
212_19	cusp, LLBL, plasmatrough	b

Spectral type; b = HM emission burst, d = Dispersive structured emission (e.g. IPRP, IPDP).

of clock angles of 104° to 177°, suggestive of low latitude reconnection and agreeing with the cusp location equatorwards of the array for an expanded polar cap boundary.

Discussion

The possible source regions associated with each ducted Pc1-2 ULF wave event are summarized from the case studies in Table III. The regions are ordered by proximity to the array along the wave direction. Waves from the potential source closest to the array will be the least attenuated so that source is perhaps the most likely of candidates along the direction of propagation. Note that 'plasmatrough' indicates the outer subsolar magnetosphere projecting onto the ionosphere equatorward of the LLBL. The individual case studies have difficulty in resolving whether one particular projection is preferred as a source region. This is due to the cusp, LLBL and mantle being narrow enough in latitude that several projections may lie along the direction of arrival for wave events within the radius of possible source regions (allowing for wave attenuation). Table IV summarizes the number of wave events that had a particular region as their closest potential source along the direction of propagation and how many events had a particular region as a potential source within the ducting range of the array. As the wave attenuation range is large compared with the potential source regions there are many events associated with each region except the polar cap. The mantle, plasmatrough and cusp have the greatest number of events for which they are the closest source but no single unique candidate. It is entirely possible that more than one region is the magnetospheric source of the field guided Pc1-2 waves. Anderson *et al.* (1996) presented a space-ground case study of Pc1-2 bursts from one day and concluded that their magnetospheric source was the subsolar outer magnetosphere, earthward of the LLBL with 1–2 hour MLT azimuthal and 1–2 R_E (*c.* 10 000 km) radial extent in the magnetosphere. The results from this study also support a similar source region, although not uniquely. A three station array cannot measure

Table IV. Ducted Pc1-2 sources - likely magnetospheric projections.

Projection	Closest source (number of events out of 13)	Possible source (number of events out of 13)
LLBL	1	11
plasmatrough	4	9
cusp	3	9
mantle	5	9
polar cap	0	2

range to the source region for individual events. Using the cusp distance from the magnetic pole at low K_p (*c.* 1500 km), cusp angular speed relative to the pole (15° hr^{-1}) and the angular speed of the Pc1-2 events from east to west (*c.* 22° hr^{-1}) during low K_p (Neudegg *et al.* 1995), the average wave source location was calculated to be *c.* 500 km from the array. Re-examining the case studies with this fact in mind seems to bias the possible source regions towards the LLBL/outer subsolar magnetosphere, agreeing with the Anderson *et al.* (1996) case study. However, there are still events such as 212_18 and 212_19 that may not come from these regions.

Three of the four cases for which interplanetary magnetic field can be determined suggest from the IMF B_z and clock angle that dayside magnetic reconnection between the geomagnetic and interplanetary magnetic fields was occurring. The odd case (case 1) occurs near the end of a period of low IMF values less than 2nT with clock angle near zero degrees, not suggestive of reconnection. However, either side are long periods of IMF clock angle conducive to reconnection and the three Pc1-2 wave events occurred only 30 min before clock angle returned to below 45°. Using the Equator-S spacecraft near the magnetopause Neudegg *et al.* (2000) showed that flux-transfer-events, indicators of dayside reconnection, could occur with clock angles as low as 30°. Hence, it is plausible that a low level of low latitude reconnection may have occurred during the case 1 wave events, as the IMF value is small and lies between times of probable reconnection. Dayside magnetic reconnection-merging causes enhanced field-aligned-currents (Iijima & Potemra 1976) from the magnetopause to the ionosphere in the vicinity of the cusp, either side of the 'merging gap' in the polar cap boundary. Open magnetic flux passes into the cap through the merging gap to expand the cap during dayside magnetic reconnection, taking the cusp and auroral oval equatorwards. The optical auroral signature of the downwards electrons from the upwards field-aligned current, enhanced by dayside reconnection on the post-noon side of the cusp and merging gap near 14–15 MLT, has been identified using the POLAR spacecraft (Neudegg *et al.* 2001). Dominant production regions of Pc1-2 ion-cyclotron waves are in the early afternoon outer magnetosphere also near 12–15 MLT (Anderson *et al.* 1992) and this region geomagnetically maps to the ionosphere in the vicinity of the post-noon field-aligned-currents. Pc1-2 wave activity observed on the ground has been previously associated with field-aligned-currents. Unstructured Pc1-2 observed at the Arctic

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Bar I station occurred when the LLBL was just poleward, so the station was near the open/closed field line boundary, and a suggested association was with field-aligned-currents (Heacock 1974). Pc1-2 bursts near the cusp were associated with magnetic impulses related to field-aligned-current systems possibly caused by dayside reconnection (Arnoldy *et al.* 1988). Band-limited (0.2–0.4 Hz) unstructured Pc1 activity was observed at auroral zone latitude, Antarctic station Syowa (67°S) by Hansen *et al.* (1991) only when associated with LLBL/cleft-type ions from DMSP satellite observations. The LLBL was equatorward of its average latitude suggesting an expanded polar cap, probably as a result of dayside reconnection and open flux transfer into the cap. Pre- and post-noon activity was explained by auroral oval associated field-aligned-current systems. All the thirteen Pc1-2 wave events presented in this paper, with perhaps the exception of case 6 212_18 and 212_17, have origins post-noon of the cusp location. The probable sources for the waves near the magnetopause are certainly not incompatible with post-noon reconnection driven field-aligned-current systems.

In summary, comparison of Pc1-2 waves of an HM burst or dispersive structured emission spectral type observed propagating in the polar ionospheric waveguide are most likely to have originated in the sub-solar region near noon, either close to the magnetopause or only a few Earth radii inside it in the outer magnetosphere. Hence geomagnetic field guided Pc1-2 ion-cyclotron waves, possibly linked to field-aligned-currents initiated by dayside reconnection or merging of the interplanetary magnetic and geomagnetic fields, will most probably dissipate their energy as compressional waves in the polar ionosphere near 300 km altitude in the region equatorward of the polar cusp. Direct confirmation of the association between Pc1-2 waves in the polar ionosphere and reconnection driven field-aligned-currents requires coordinated observations between an interferometry capable magnetometer array and a direct field-aligned-current measurement such as spacecraft UV auroral measurements. Opportunities now exist for the first time for observations in three dimensions of shear mode ion-cyclotron waves in the magnetosphere by the European Space Agency Cluster fleet of spacecraft (possibly until the end of 2004) and propagation observations of the resultant compressional mode waves in the polar ionosphere by a permanent closely-spaced magnetometer array.

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