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# A statistical study of the local time asymmetry of Pc 5 ULF wave characteristics observed at midlatitudes by SAMNET

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**Abstract.** A total of 129 Pc 5 events were identified in more than a year of midlatitude magnetometer data from the United Kingdom Sub-Auroral Magnetometer Network (SAMNET). The horizontal polarization and azimuthal wavenumbers associated with these events were estimated, and their variations with magnetic local time were studied. A marked local time asymmetry was apparent in the Pc 5 wave characteristics with distinctly different polarization and azimuthal wave characteristics occurring on either side of noon. The morning sector observations of predominantly clockwise polarization and westward phase propagation suggest that the majority of the morning sector Pc 5 waves are the midlatitude signature of solar wind driven field line resonances occurring at higher latitudes. It is suggested that the most likely energy sources for these waves are the Kelvin-Helmholtz instability at the magnetopause boundary or cavity/waveguide modes prompted by impulsive variations in the solar wind. The large variation in the polarization azimuths (ellipse orientations) observed in the morning sector was interpreted as a result of the large ionospheric conductivity gradients that occur around and after dawn, which alter the ionospheric rotation of Alfvén waves from 90°. It is suggested that the afternoon sector Pc 5 waves are the ground signature of compressional waves in the magnetosphere, mainly cavity/waveguide modes. There is little evidence of field line resonances in the afternoon sector. The possibly dominant role of cavity/waveguide modes in the magnetosphere is heightened by the observation of preferential frequencies in both the morning and afternoon sectors.

## 1. Introduction

It is more than 30 years since quasi-sinusoidal oscillations of the Earth's magnetic field, observed by ground-based magnetometers, were attributed to hydromagnetic waves in the magnetosphere. Since then, a large number of theoretical and observational works have described the nature of ULF waves (periods of >10 s), which are suspected to be a mixture of transverse standing wave oscillations of the Earth's magnetic field lines and global compressional oscillations of the magnetospheric cavity. Remote sensing of ULF waves using ground-based instrumentation is an important tool for studying these waves. The horizontal polarization of ULF waves observed on the ground can be used to predict the wave structure and characteristics in the magnetosphere. Multipoint ground observations can unravel the spatial variations of the wave properties that cannot be achieved with a single-spacecraft observation. These multipoint ground observations combined with conjugate satellite observations can be used to investigate the effect of the ionosphere on the wave polarization and attenuation.

The lower-frequency ULF waves, termed Pc 5 waves (150-600 s), have been extensively studied with the use of ground-based magnetometers, auroral radar, and satellites. These studies have focused on many features, including wave polarization, occurrence distributions, and the relationship with solar wind variations. Early observations of Pc 5 polarization variations on the ground [e.g., *Samson et al.*, 1971; *Samson and Rostoker*, 1972] highlighted the dependence of Pc 5 polarization on both the local time and the latitude of the observation. These observations led to the development of the field line resonance theory [*Southwood*, 1974; *Chen and Hasegawa*, 1974], which described the expected latitudinal and local time variations of the amplitude and polarization of solar wind driven waves that were resonant on

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a particular geomagnetic field line. Field line resonance theory predicts that waves with a westward (eastward) phase propagation have clockwise (anticlockwise) polarization poleward of the resonant field line, where maximum amplitude occurs, and anticlockwise (clockwise) polarization equatorward of it. *Samson et al.* [1971] observed a switch in polarization at midday consistent with waves propagating eastward in the afternoon and westward in the morning. This was suggestive of waves driven by the solar wind (for example, by the Kelvin-Helmholtz instability at the magnetopause [e.g., *Pu and Kivelson*, 1983]).

The global cavity mode theory was developed to explain features of ULF observations not convincingly explained by the field line resonance theory. On the basis of the observations of *Kivelson et al.* [1984], *Kivelson and Southwood* [1985, 1986] developed the global mode theory. They suggested that an impulse at the magnetopause could set up a series of quantized "global" or "cavity" modes oscillating at the natural eigenfrequencies of the magnetospheric cavity. These global modes could then couple to field line resonances at points where the cavity eigenfrequencies matched the field line eigenfrequencies. The damping of the cavity modes would then arise from an irreversible coupling of energy into the localized field line resonances. The global mode therefore has features of both compressional and Alfvén mode waves. Near the resonant field line it has the character of an Alfvén mode wave; away from the resonant field line it is similar to a compressional mode wave. However, the fact that the magnetospheric cavity is open in the tailward direction led to the extension of the cavity wave model into a waveguide model [*Samson et al.*, 1992]. Instead of being azimuthally standing structures, as with the cavity wave model, these waveguide modes propagate azimuthally downtail in a cavity formed by turning points on dipolar field lines and the magnetopause. The waveguide theory predicts frequencies in the Pc 5 range and also the occurrence of multiple discrete frequencies, which are often observed [*Ruohoniemi et al.*, 1991; *Samson et al.*, 1991].

Ground-based observations of wave polarization combined with those of azimuthal wavenumber provide important pointers to the source mechanisms of Pc 5 waves. The azimuthal wavenumber ($m$ value) of a ULF wave is easily measured on the ground by using longitudinally spaced magnetometer stations. The azimuthal wavenumber provides information about the azimuthal scale of the wave and about its phase propogation; a negative (positive) $m$ represents westward (eastward) phase propogation. As a result of a lack of longitudinally spaced magnetometer chains there have been relatively few statistical studies of the variations in the azimuthal wavenumber of ULF waves. *Olson and Rostoker* [1978], using high-latitude observations of Pc 4-5 waves, suggested that the magnitude and sign of the azimuthal wavenumbers they observed were consistent with a solar wind source for the waves (for example, the Kelvin-Helmholtz instability at the magnetopause boundary). *Mier-Jedrzejowicz and Southwood* [1979], using midlatitude observations of Pc 4 wave $m$ values, suggested that the main source for these waves was the nightside, as the signals propagated preferentially away from this region. *Yeoman et al.* [1990b] used Pc 5 observations by the Sweden and Britain Radar Experiment (SABRE) radar to study the variation in the coupling between compressional modes and Alfvénic field line resonances for varying azimuthal wavenumbers ($m \sim$ 0-10). Using a database of mainly afternoon and eastward propagating morning sector events and a method of determining the "compressiveness" of a wave from its ionospheric boundary conditions, they concluded (1) that maximum coupling occurred between the Alfvénic and compressional modes for $m \sim$ 1-3 and (2) that for larger $m$ values ($m \gtrsim 5$) the wave was purely compressional.

The full effect of the ionosphere on the characteristics of ULF waves observed on the ground can be considerable, and so it is important to distinguish between features in ground-based data that are a consequence of the ionosphere and those that relate to magnetospheric oscillations. It is well known that the polarization of an incident Alfvén wave is rotated by 90° on transmission through a horizontally uniform ionosphere and that small-scale magnetospheric variations are shielded from the ground [e.g., *Hughes*, 1974; *Hughes and Southwood*, 1976a, b]. Ground observations are also the result of integrations over large regions of the ionosphere and are hence smeared representations of the magnetospheric waves [e.g., *Poulter and Allan*, 1985]. In regions of the ionosphere where large conductivity gradients occur, the 90° rotation of incident Alfvén waves does not always hold, and the rotation angle depends on the ionospheric conductivity distribution [*Glassmeier*, 1984]. This feature is important, particularly in the auroral zone and at the dawn and dusk terminators. For compressional waves, such as some cavity/waveguide oscillations that may show little or no coupling to transverse field line oscillations and hence possess very little field-aligned current, the ionosphere behaves like a thin film and has little effect on the signal transmission [*Kivelson and Southwood*, 1988].

Both ground-based and satellite observations of Pc 5 ULF waves have noted a local time asymmetry in the wave characteristics on either side of noon. Satellite studies have shown that transverse, azimuthally polarized waves, which are well correlated with ground-based observations, predominate in the morning sector of the magnetosphere, whereas compressional and radially polarized waves, which are poorly correlated with ground observations, predominate in the afternoon sector of the magnetosphere [e.g., *Kokubun*, 1980; *Yumoto et al.*, 1983; *Kokubun et al.*, 1989; *Anderson et al.*, 1990]. Afternoon sector Pc 5 events observed on the ground appear to be rarer than those observed in the morning sector [e.g., *Gupta*, 1975], and it has been suggested that they occur preferably during periods of northward interplanetary magnetic field (IMF) [*Rostoker and Sullivan*, 1987]. An asymmetry between the characteristics of morning and afternoon sector Pc 5 waves has also been observed by ground magnetometers at high latitudes [e.g., *Ziesolleck and McDiarmid*, 1995], midlatitudes [e.g., *Chisham et al.*, 1995], and low latitudes [e.g., *Ziesolleck and Chamalaun*, 1993]. The asymmetries observed both in space and on the ground suggest that different wave excitation mechanisms dominate on either side of the noon meridian.

Another explanation for some of the local time differences in wave characteristics observed on the ground is the effect of the ionosphere. *Chisham et al.* [1995], using data from 129 Pc 5 events observed by the United Kingdom Sub-Auroral Magnetometer Network (SAMNET), observed a local time asymmetry in the orientation of the horizontal polarization ellipse (or polarization azimuth). In the morning the orientations appeared to be approximately evenly spread across all possible orientations, whereas in the afternoon the orientations were clustered about 0° (geomagnetic north-south). They suggested that the spread in azimuths in the morning sector was a consequence of the ionospheric conductivity gradients that occur around dawn, which can change the ionospheric rotation of Alfvén waves from 90°. A similar suggestion was made to explain the differences in polarization azimuths observed on either side of noon at low latitudes by *Ziesolleck and Chamalaun* [1993].

This paper presents the first major statistical study of the polarization and azimuthal wavenumber variations of Pc 5 ULF waves at midlatitudes using observations by SAMNET. The observed local time differences in the Pc 5 wave features are interpreted in terms of possible wave generation mechanisms and ionospheric modifications.

## 2. Data Analysis

SAMNET [*Yeoman et al.*, 1990a] comprises seven three-component fluxgate magnetometers with a sampling period of 5 s. The data are recorded in the $H$ (geomagnetic north-south), $D$ (geomagnetic east-west), $Z$ (vertical) coordinate system. The magnetometers can measure magnetic field variations over a range of ±512 nT with a resolution of 0.25 nT. SAMNET is a two-dimensional magnetometer array consisting of two longitudinal chains (at $L\sim4.4$ and $L\sim3.3$) and a latitudinal chain (on the United Kingdom meridian). The geographic and corrected geomagnetic coordinates of the seven SAMNET stations are presented in Table 1 along with their dipole field $L$ shell position.

More than a year of SAMNET data were searched for Pc 5 events, and 129 events were identified, employing the following selection criteria: (1) The wave consisted of at least three wave cycles with a stable period in the Pc 5 period range (150-600 s); (2) the wave amplitude was at least 3 nT peak to peak; and (3) the wave was visible at all available stations on the SAMNET array. The large number of events observed provided an excellent basis for a statistical study of ground-based midlatitude Pc 5 characteristics.

The horizontal polarizations and azimuthal wavenumbers of the Pc 5 waves observed by SAMNET were calculated by using the method of complex demodulation [e.g., *Beamish et al.*, 1979]. This method of analysis is ideal for studying nonstationary time series and allows the estimation of instantaneous values of ULF wave amplitude, phase, and polarization for particular frequency bands. The polarization of a wave can be described by two parameters, the ellipticity and the azimuth (or ellipse orientation). The ellipticity is given by the ratio of the minor axis to the major axis of the polarization ellipse; a negative ellipticity represents a clockwise polarization, and a positive ellipticity represents an anticlockwise polarization (viewed in the direction of the geomagnetic field line). The polarization azimuth is 0° for a north-south orientation and increases positively as the polarization orientation rotates clockwise, being 90° for an east-west orientation. The polarization characteristics are averaged across the center of each event to obtain a complete polarization estimate, which characterizes the event at each station. The ellipticity estimates are usually quite stable over the center of an event, the standard deviation of the averaged values usually being ~0.05. This acts as a good error estimate for the ellipticity measurement made at each station. The azimuth estimates are generally not so reliable, the

**Table 1.** Coordinates and $L$ Shell Values of the SAMNET Stations

| Station | Code | Geographic Latitude | Geographic Longitude | Geomagnetic Latitude | Geomagnetic Longitude | $L$ Shell |
|---|---|---|---|---|---|---|
| Faroes | FAR | 62.05 | 352.98 | 60.77 | 78.12 | 4.26 |
| Nordli | NOR | 64.37 | 13.36 | 61.28 | 95.28 | 4.40 |
| Oulu | OUL | 65.10 | 25.85 | 61.30 | 105.56 | 4.41 |
| Glenmore | GML | 57.16 | 356.32 | 54.94 | 77.99 | 3.08 |
| Kvistaberg | KVI | 59.50 | 17.63 | 55.83 | 95.95 | 3.22 |
| Nurmijarvi | NUR | 60.51 | 24.66 | 56.59 | 102.17 | 3.35 |
| York | YOR | 53.95 | 358.95 | 50.99 | 78.57 | 2.57 |

All values were calculated by using the IGRF for 1988 at an altitude of 120 km.

standard deviation of the averaged values usually being ~10°. These averaged polarization characteristics can be presented in the form of two-dimensional polarization maps illustrating the horizontal polarization of each event across the SAMNET array.

Azimuthal wavenumbers ($m$ values) for an event are estimated by calculating phase differences between stations on the longitudinal chains. Four estimates of $m$ are usually calculated for each Pc 5 event (for the station pairs FAR-NOR, NOR-OUL, GML-KVI, and KVI-NUR). As the stations in each chain occur at slightly different geomagnetic latitudes, the $m$ values are calculated by using only the $D$ component of the wave. This method avoids the possibility of incorrectly interpreting latitudinal phase variations, which can often be large in the $H$ component, as longitudinal phase differences. Comparisons of wave trains from three stations in a longitudinal chain allow a good estimate of the direction of phase propagation. With this knowledge the maximum $m$ value that can be estimated without ambiguity is $360°/\Delta\phi$, where $\Delta\phi$ is the station separation in geomagnetic longitude. Therefore, for the SAMNET array, $m$ values with $|m| < 20$ can be considered reliable. For larger $m$ values an ambiguity occurs, as one or more complete wavelengths may occur between stations. If this ambiguity occurred regularly, it would result in a random spread in phase differences between stations from 0° to 360° and hence a random spread in $m$ values. This is not the case, and combined with the fact that waves with large $m$ are generally shielded from the ground, this reinforces the reliability of our measurements. The error in each $m$ value generally depends on the variability of the phase differences across the center of the event, which varies from event to event, but the standard error of an estimate of $m$ is typically ~1-2.

Field line eigenperiods (outside the plasmasphere) at midlatitudes have generally been estimated to be $\lesssim 200$ s (near the lower bound for Pc 5 waves). Field line resonances in the Pc 5 band generally occur at higher latitudes than those of the SAMNET array, and so field line resonance associated Pc 5 waves seen at these midlatitudes would usually be a measurement of the wave signal equatorward of the resonance position. Field line resonance theory predicts that equatorward of resonance westward (eastward) propagating waves should have anticlockwise (clockwise) polarization.

Knowledge of the plasmapause location is important in interpreting midlatitude wave observations, as it may have affected the observed wave signal. In the morning the plasmapause lies most often between the two SAMNET longitudinal magnetometer chains (at $L \sim 3$-5, depending on the geomagnetic activity level). In the afternoon, as a result of the plasmaspheric bulge [e.g., *Chappell et al.*, 1970b], the whole SAMNET array is quite often located within the plasmasphere (plasmapause at $L \sim 5+$). This fact is important in comparing the results of midlatitude observations on either side of noon. We have attempted to estimate the plasmapause position for all the Pc 5 events observed by SAMNET, using the method of *Yeoman* [1988]. This method is based on that used by *Orr and Webb* [1975], which uses an empirical measure of the plasmapause shape in local time [*Chappell et al.*, 1971], which is scaled by the observed dependence of the plasmapause position in the early morning sector on variations in the $Kp$ index [*Chappell et al.*, 1970a, b]. This method gives a good agreement with a study of 41 crossings of the plasmapause observed by GEOS 2. However, the method can be used only when the relevant average $Kp \leq 4$o, which restricts the number of events for which a plasmapause position can be estimated.

A plasmapause position could be estimated for 61% of the morning sector events. For 9% of these events the plasmapause was poleward of the higher-latitude SAMNET chain, for 28% the plasmapause was colatitudinal with the higher-latitude SAMNET chain, and for 63% the plasmapause was between the two SAMNET chains. For the afternoon sector events a plasmapause position could be estimated in 73% of the cases. For 71% of these events the plasmapause was poleward of the higher-latitude SAMNET chain, for 29% the plasmapause was colatitudinal with the higher-latitude SAMNET chain, and there were no instances of its falling equatorward of this position. Therefore, in the afternoon, SAMNET is observing predominantly within the plasmasphere. As a result of the increased plasma density and hence the decreased Alfvén velocity, the field line eigenperiods found just inside the plasmasphere are greater than those found just outside. The possibility arises therefore that field line resonances within the outer plasmasphere may have periods in the Pc 5 range. The SAMNET observations would then be close to or poleward of the resonant field line. Field line resonance theory predicts that poleward of resonance westward (eastward) propagating waves should have clockwise (anticlockwise) polarization.

## 3. Statistics

SAMNET polarization maps were compiled for all of the 129 Pc 5 events observed. These maps display the spatial variation of the wave polarization on the ground. In the morning sector, anticlockwise polarization was predominant, but two distinct types of polarization maps were regularly observed: (1) The polarization was invariant across SAMNET (i.e., there was little variation in the ellipticity and azimuth between stations), and (2) the polarization azimuth rotated with longitude, changing by ~90° across the SAMNET longitudinal extent. *Chisham et al.* [1995] studied 31 events of this second type (henceforth termed "rotating azimuth events") suggesting that the variations in the polarization orientation were a result of the large ionospheric conductivity gradients that occur around dawn. An example of a polarization map for a rotating azimuth event is presented in Figure 1. In this figure the polarization azimuth changes from being ~-45° in the west of the SAMNET array, to ~90° in the middle of the array, and to ~30° in the east of the array. In the afternoon sector, only one type of polarization map was regularly observed. In this case the polarization was invariant across the SAMNET array with the polarization ellipses having a clockwise/linear sense of polarization and an alignment approximately in the geomagnetic north-south direction (i.e., polarization azimuths of ~0°). An example of one of these afternoon sector polarization maps is presented in Figure 2. These general features of the Pc 5 polarization distribution are clearly seen in Figures 3-5. These figures are all presented without error bars to avoid unneccessary cluttering. Details of the errors in the measurements are detailed above.

Figure 3 presents the distribution of the measured polarization ellipticities for all of the Pc 5 events against the magnetic local time of the associated SAMNET stations. For 129 events and ~5-6 stations operational per event, this results in ~700 points. In Figure 3 the solid symbols represent the ellipticity measurements that display the characteristics expected equatorward of a field line resonance, that is, anticlockwise (clockwise) polarization for westward (eastward) propagating waves. The open symbols represent the ellipticity measurements that do not display the characteristics expected equatorward of a field line resonance. Probably the most outstanding feature of Figure 3 is that the polarization in the morning is almost exclusively anticlockwise (positive ellipticity). There are a few instances of clockwise polarization, most of which occur closer to noon. In the afternoon the dominant polarization sense is clockwise (negative ellipticity). However, there are also a large number of estimates close to linear polarization (zero ellipticity) and also some of anticlockwise polarization. The dominance of the solid symbols (especially in the morning sector) in Figure 3 supports the idea that the midlatitude Pc 5 observations made by SAMNET are measurements of the wave signal equatorward of a field line resonance.

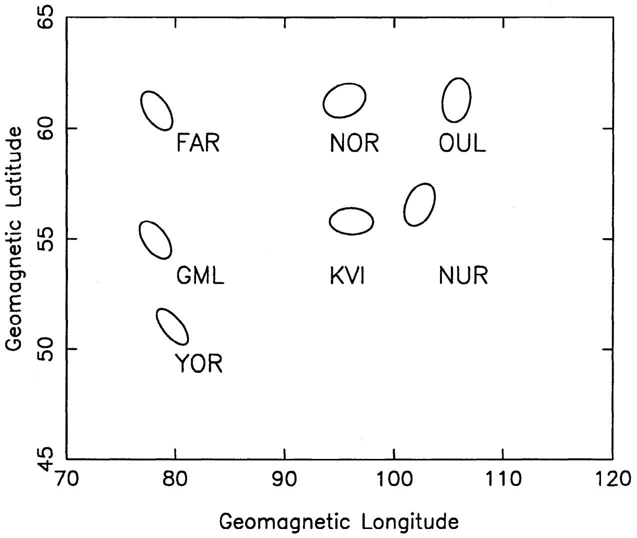

**Figure 1.** SAMNET polarization map for a typical morning sector Pc 5 event. This map shows the features of a rotating azimuth event. The open ellipses represent anticlockwise polarization. The centers of the ellipses represent the station locations.

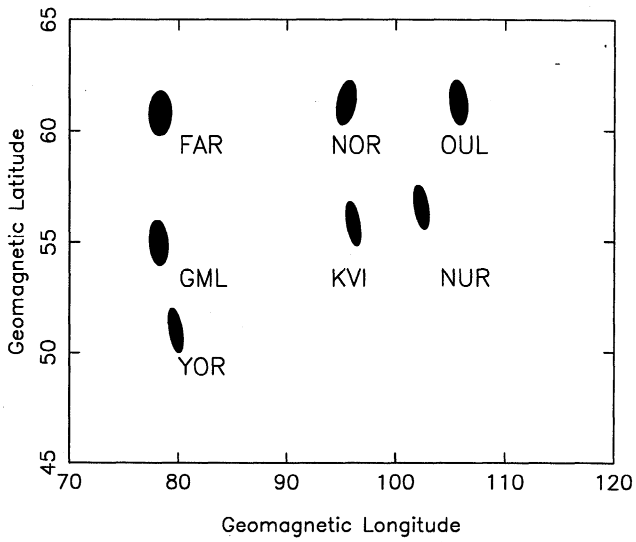

**Figure 2.** SAMNET polarization map for a typical afternoon sector Pc 5 event. The polarization ellipses are all aligned approximately north-south. The solid ellipses represent clockwise polarization. The centers of the ellipses represent the station locations.

Figure 4 presents the distribution of the measured polarization azimuths against magnetic local time. A clear local time asymmetry exists in the azimuth distributions on either side of noon. In the morning the azimuths are well spread across all the possible orientations. In the afternoon the polarization azimuths appear to be more clustered around 0° to -30° (i.e., approximately north-south orientation). To study the spread of the polarization orientation per event, Figure 5 displays the standard deviation of the polarization azimuth across SAMNET for each Pc 5 event against the magnetic local time of the center of the event (taking account of the wraparound in the polarization azimuth at +90°/-90° if appropriate). In this figure the solid symbols represent the 31 rotating azimuth events studied by *Chisham et al.* [1995], and the open symbols represent the rest of the 129 Pc 5 events observed by SAMNET. It is clear from the figure that the typical variation in azimuth in the morning is quite large and the rotating azimuth events in particular show a large variation. By stark contrast, in the afternoon it is very clear that there is very little variation in azimuth for the majority of the events, because the majority of the SAMNET polarization maps in the afternoon are similar to the one presented in Figure 2.

To study the relationship between the polarization azimuth distribution and the location of sunrise and to assess whether or not a connection exists, Figure

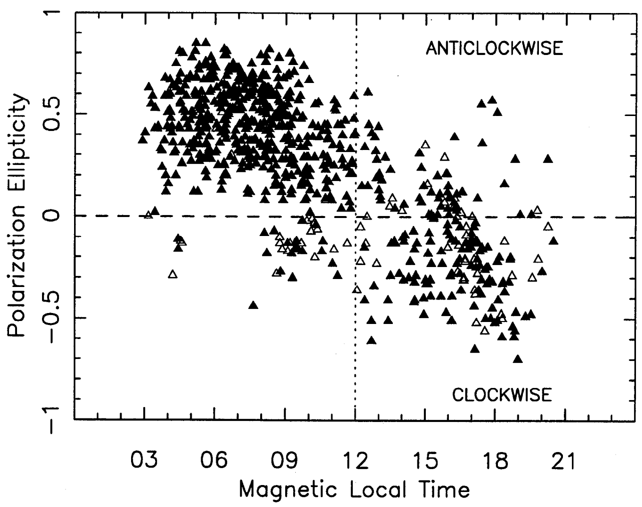

**Figure 3.** Distribution of polarization ellipticity against magnetic local time measured at all the available SAMNET stations for the 129 Pc 5 events observed. Positive ellipticity represents clockwise polarization, whereas negative ellipticity represents anticlockwise polarization. The solid symbols represent ellipticity measurements that display the characteristics expected equatorward of a field line resonance, and the open symbols represent all the other ellipticity measurements.

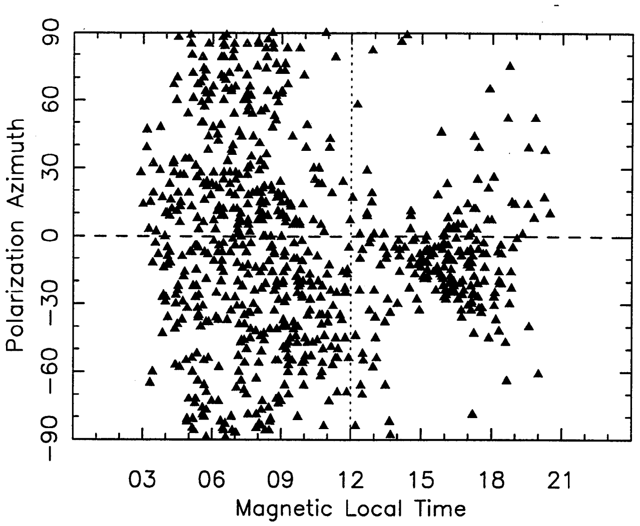

**Figure 4.** Distribution of polarization azimuth (ellipse orientation) against magnetic local time measured at all the available SAMNET stations for the 129 Pc 5 events observed. Here, 0° represents an ellipse with a north-south orientation; 90° represents an ellipse with an east-west orientation.

6 presents the polarization azimuth estimates against their local time distance from the ground sunrise position. Three block contour plots are presented in Figure 6: the distribution for all events (Figure 6a), the distribution for rotating azimuth events (Figure 6b), and the distribution for all other events (i.e., excluding rotating azimuth events) (Figure 6c). In general, for all events, before sunrise the distributions are clearly centered around 0° (north-south orientation) with the estimated azimuths peaking between -30° and 30°. At sunrise the peak positions of the distributions change dramatically. The rotating azimuth events (Figure 6b) appear to be more widely spread from 0° to -90° and 60° to 90°. For the other events (Figure 6c) the peak shifts to approximately -30° with the bulk of the estimated azimuths being between 0° and -60°. A clear drop in both distributions occurs in the 0° to 60° range directly after sunrise. A few hours after sunrise the estimated azimuths become progressively more centered in the 0° to -30° range. This trend continues into the early afternoon, where there should be no effects on wave polarization due to sunrise-related ionospheric conductivity gradients. These observations appear to confirm that the changes in azimuth occurring in the morning sector are a result of the ionospheric conductivity gradients occurring around sunrise, as suggested by *Chisham et al.* [1995]. These results are also a mirror image (around 0°) of the measured azimuths of low-latitude Pc 5 events observed by *Ziesolleck and Chamalaun* [1993], which were clustered in a band from 30° to 60° around and after the sunrise region. The measurements of *Ziesolleck and Chamalaun* [1993] were made in the southern hemisphere, and so we would expect (for fundamental field line oscillations) their azimuth measurements to be a mirror image of our northern hemisphere results. Not enough events were observed around and after the sunset region to study the same phenomenon in the late afternoon/evening sector of the magnetosphere. However, Figure 5 shows that there are a few events near dusk that show a large variation in azimuth across SAMNET. These variations may be associated with the conductivity gradients that occur near the dusk terminator.

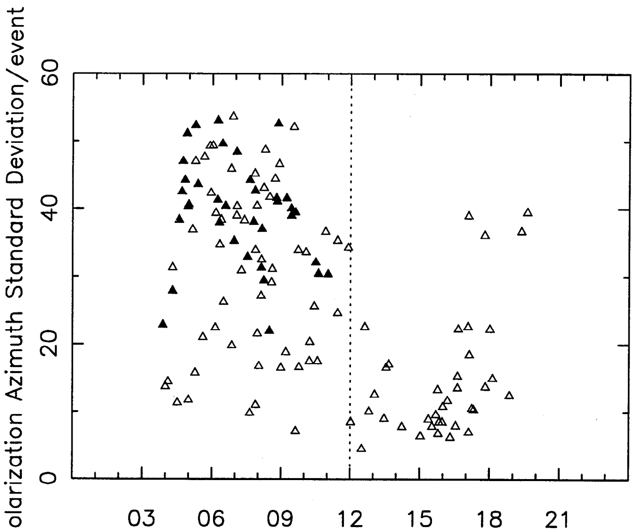

**Figure 5.** Distribution of the standard deviation of the polarization azimuth per event against the magnetic local time of the center of the corresponding event for all 129 Pc 5 events observed by SAMNET. The solid symbols represent the rotating azimuth events studied by *Chisham et al.* [1995].

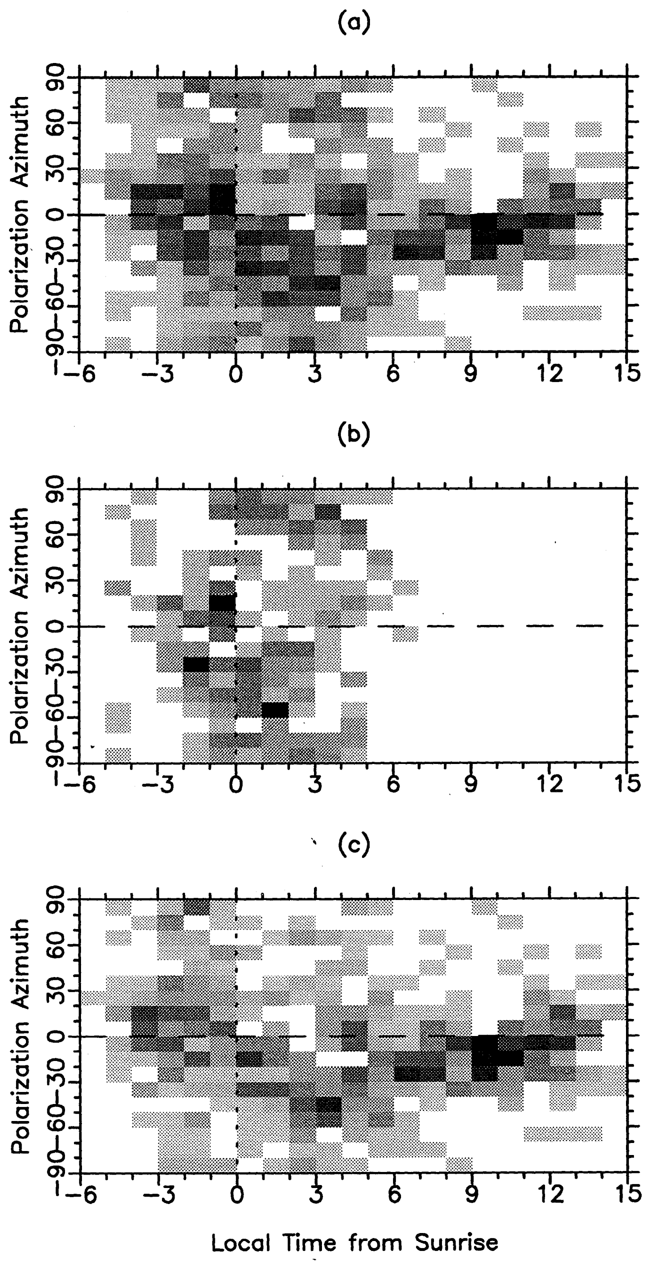

**Figure 6.** Block contour plots of the distributions of polarization azimuth (ellipse orientation) against the local time difference from the appropriate ground sunrise times measured at all the SAMNET stations for (a) all of the 129 Pc 5 events observed, (b) the rotating azimuth events [*Chisham et al.*, 1995], and (c) all the other events (i.e., Figure 6a minus 6b). The darker blocks represent the higher occurrence rates.

Figure 7 presents the distribution of the measured azimuthal wavenumbers ($m$ values) against magnetic local time. This figure contains all four of the $m$ value measurements made for each event (if available). The solid symbols in Figure 7 represent measurements made by using the station pairs on the higher-latitude chains (FAR-NOR, NOR-OUL), whereas the open symbols represent measurements made by using the station pairs on the lower-latitude chains (GML-KVI, KVI-NUR). The figure illustrates that in the morning sector the propagation direction is almost exclusively westward (negative $m$) and the magnitude is almost exclusively low (-8 $< m <$ 0) with a peak around $m \sim$ -3. The almost exclusive westward phase propagation in the morning matches the solar wind propagation direction and suggests that the solar wind is the major source of energy for these waves. In general, these results are similar to the observations of *Olson and Rostoker* [1978], who interpreted their results as being consistent with a solar wind source (for example, the Kelvin-Helmholtz instability at the magnetopause). In the local afternoon there exists a much larger spread in the value of $m$, encompassing waves with both eastward and westward phase propagation, although eastward phase propagation is predominant. Once again the magnitude of $m$ is almost exclusively low (-4 $< m <$ 10). Comparing the distribution of the open and solid symbols in Figure 7 suggests that there is little difference between the spread of $m$ values measured on the two longitudinal chains.

It is possible to compare the polarization and azimuthal wavenumber estimates for an event by plotting the ellipticity for the event averaged across all the SAMNET stations against the average azimuthal wavenumber for that event, as Figure 8 shows for all the 129 Pc 5 events (this method was also used by *Mier-Jedrzejowicz and Southwood* [1979]). In this figure the solid symbols represent events observed in the morning sector, the open symbols represent events observed in the after-

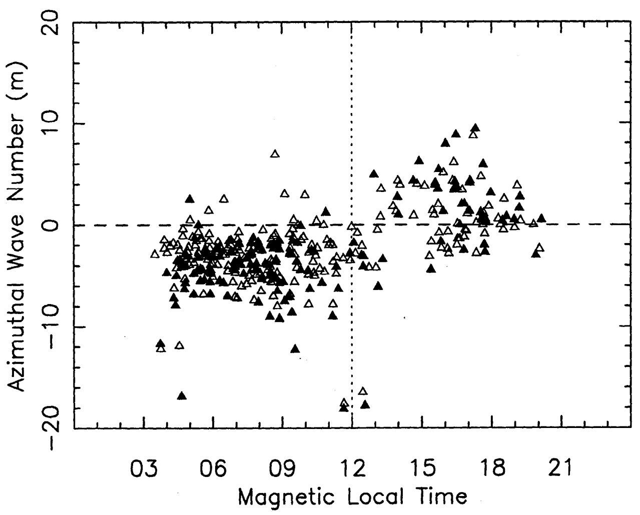

**Figure 7.** Distribution of azimuthal wavenumber against magnetic local time measured between the available SAMNET stations for the 129 Pc 5 events observed. Negative azimuthal wavenumber represents westward phase propagation, whereas positive azimuthal wavenumber represents eastward phase propagation. Solid symbols represent measurements made by using the station pairs on the higher-latitude chains (FAR-NOR, NOR-OUL), whereas open symbols represent measurements made by using the station pairs on the lower-latitude chains (GML-KVI, KVI-NUR).

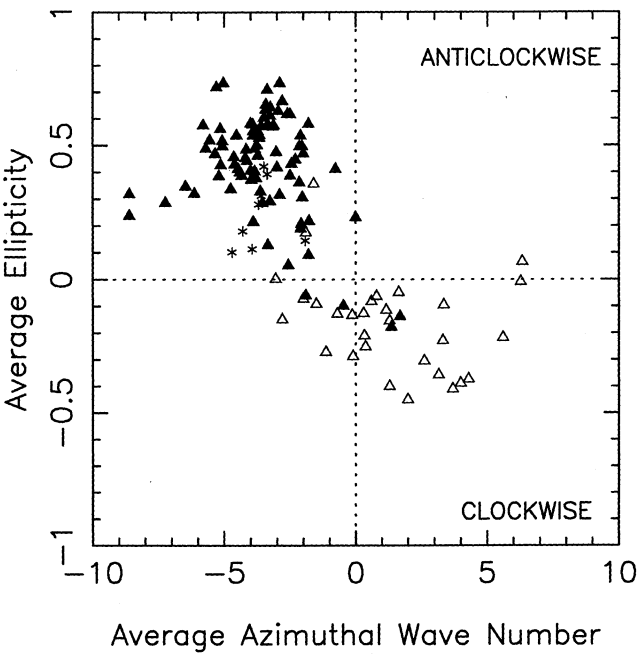

**Figure 8.** Plot of the average azimuthal wavenumber for each event against the average ellipticity for the event, averaging across all the available SAMNET stations for the 129 Pc 5 events observed. Solid symbols represent morning sector events, open symbols represent afternoon sector events, and asterisks represent events that straddle the noon boundary.

noon sector, and the asterisks represent events observed across noon. There are a few clear trends in the data shown in Figure 8. The morning events and those observed around noon predominantly have anticlockwise polarization and westward phase propagation (this has been shown in Figures 3 and 7). There are also a few morning sector events that show clockwise polarization but with a mixture of westward and eastward phase propagation. The afternoon events predominantly have clockwise polarization and eastward phase propagation. However, there are a few afternoon sector events that have westward phase propagation but with a mixture of clockwise and anticlockwise polarization.

## 4. Discussion

It is clear from this study that the features of Pc 5 waves observed at midlatitudes on the ground differ greatly on either side of noon. Large differences in ULF wave characteristics (such as occurrence statistics, polarization, and propagation direction) on either side of noon have been observed before both in space and at high and low latitudes on the ground [e.g., *Gupta*, 1975; *Kokubun*, 1980; *Yumoto et al.*, 1983; *Kokubun et al.*, 1989; *Anderson et al.*, 1990; *Ziesolleck and McDiarmid*, 1994]. The large statistical study of the midlatitude signature of Pc 5 events presented here complements these previous works.

Spacecraft observations of morning sector Pc 5 waves [e.g., *Kokubun*, 1980; *Yumoto et al.*, 1983; *Kokubun et al.*, 1989; *Anderson et al.*, 1990] show that they are predominantly fundamental mode transverse waves with azimuthal polarization and a good ground correlation. These observations, combined with recent ground-based statistical studies [*Ziesolleck and Chamalaun*, 1993; *Ziesolleck and McDiarmid*, 1994, 1995], support the theory that morning sector Pc 5 events are predominantly solar wind driven field line resonances. Predominantly westward phase propagation is observed ($1 < |m| < 10$) with anticlockwise (clockwise) polarization equatorward (poleward) of the expected field line resonance position. The results presented in this study also support this hypothesis with the bulk of the events displaying westward phase propagation and anticlockwise polarization, suggesting that for the majority of the events the observations represent the Pc 5 wave signal equatorward of the field line resonance position. However, Figures 3 and 8 illustrate that a few morning sector events do show clockwise polarization. A possi-

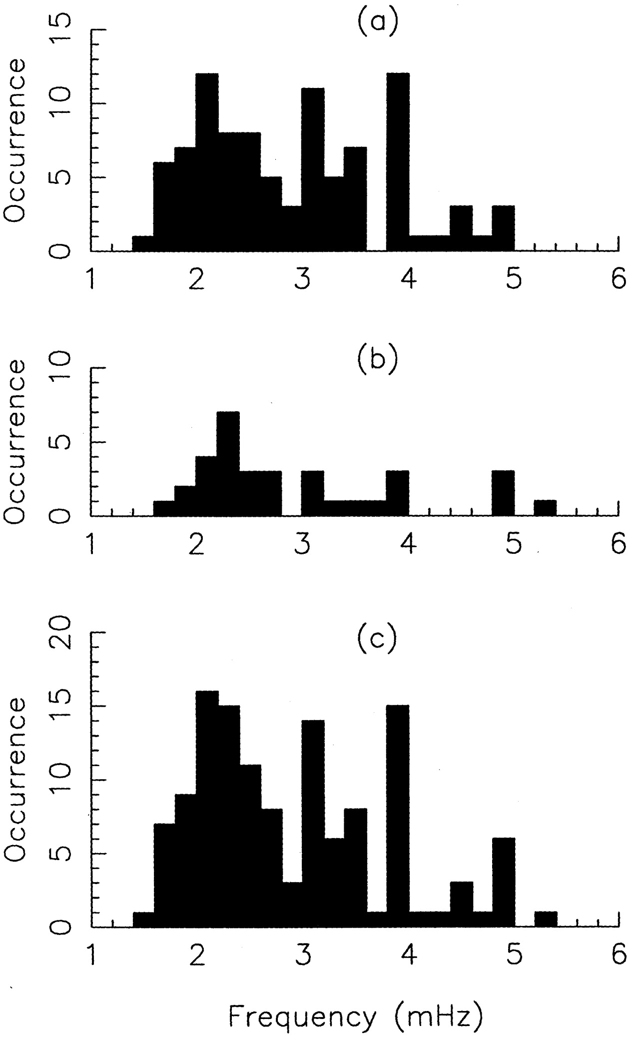

**Figure 9.** Histogram showing the distribution of the measured frequencies of the 129 Pc 5 events observed by SAMNET. The three histograms represent (a) morning sector events, (b) afternoon sector events, and (c) all events.

ble explanation for these clockwise events is that those with westward phase propagation are the poleward signature of solar wind driven field line resonances occurring equatorward of the SAMNET array in the plasmasphere (open symbols in the clockwise morning sector in Figure 3) and that those with eastward phase propagation are the signature of high-latitude field line resonances driven by nightside sources (solid symbols in the clockwise morning sector in Figure 3).

The big question concerning morning sector Pc 5 events is which (if either) of the following mechanisms is the dominant energy source for the bulk of the observations: (1) the Kelvin-Helmholtz instability at the magnetopause or (2) compressional cavity/waveguide modes driven by solar wind impulses. In the cavity/waveguide scenario, pressure pulses in the solar wind set up azimuthally propagating compressional wave modes in a waveguide cavity formed by turning points on dipolar field lines and the magnetopause [*Samson et al.*, 1992]. The waveguide mode consists of a number of compressional eigenmodes, each of which can couple to a different field line resonance. The observation of a set of discrete frequencies is a characteristic of cavity/waveguide modes [*Samson et al.*, 1991]. *Ziesolleck and McDiarmid* [1995] have presented evidence that these discrete frequencies are not a unique set, as was suggested by *Samson et al.* [1992]. However, they do show evidence that preferential frequencies do occur, most likely as a result of the discrete frequencies of the cavity/waveguide modes. *Ziesolleck and McDiarmid* [1995] presented evidence that preferential frequencies occur near 2 and 3 mHz at all stations in their study and also near 4 mHz at lower-latitude stations. Figure 9 presents histograms of the frequency distribution of the 129 Pc 5 events observed by SAMNET categorized by morning sector events (Figure 9a), afternoon sector events (Figure 9b), and all events (Figure 9c). These Pc 5 events were chosen by selecting waveforms from magnetograms by eye, and so only one frequency exists for each event. However, Figure 9 shows that a number of preferential frequencies do occur approximately centered around 2.1, 3.1, and 3.9 mHz and also possibly 4.9 mHz. These preferential frequencies are remarkably similar to those observed by *Ziesolleck and McDiarmid* [1995] and suggest that a large number of the morning sector observations are a result of cavity/waveguide modes. Maximum coupling of compressional cavity modes to field line resonances appears to occur for $m \sim$ 1-3 [*Yeoman et al.*, 1990b]. A large number of the morning sector observations have $m$ values in this region.

In the Kelvin-Helmholtz scenario, surface waves are generated on the magnetopause (or within the low-latitude boundary layer) by the Kelvin-Helmholtz instability. These surface waves couple to field line oscillations in the magnetosphere, and the surface wave energy propagates evanescently into the magnetosphere until it reaches a field line whose eigenperiod matches that of the surface wave where a field line resonance can occur. *Pu and Kivelson* [1983] and *Miura* [1992] have shown that the energy flux resulting from the Kelvin-Helmholtz instability on the dayside magnetopause is enough to generate Pc 5 waves observed in the outer magnetosphere. They also show that for conditions of northward IMF the energy input from the Kelvin-Helmholtz instability is potentially very large. For the 129 Pc 5 events observed by SAMNET, IMF $B_z$ data from the IMP 8 spacecraft were available for 43 of the events (34 morning and 9 afternoon events). The IMF directions for these events are detailed in Table 2. Twenty of the morning events for which IMF magnetic field data were available (59%) occurred during times of northward IMF, suggesting that the Kelvin-Helmholtz instability may play some part in generating field line resonances in the morning sector. It has also been suggested [*Miura*, 1992; *Nosé et al.*, 1995] that the Kelvin-Helmholtz instability may be the reason for the dawn-dusk asymmetry in Pc 5 occurrence. For the Kelvin-Helmholtz instability to develop to a finite amplitude a seed perturbation is necessary [*Miura*, 1992]. The turbulence that occurs in the dawnside magnetosheath, downstream of the quasi-parallel bow shock, provides the seed perturbation for the instability to develop. This turbulence is rare in the duskside magnetosheath, and so the occurrence of the Kelvin-Helmholtz instability on the dusk flank magnetopause is likely to be minimal. It is probable that both the wave generation mechanisms described above are active in the morning sector of the magnetosphere and also that the decreased likelihood of the Kelvin-Helmholtz instability on the dusk flank of the magnetosphere can explain the reduced occurrence of Pc 5 events in the afternoon sector.

The characteristics of afternoon sector Pc 5 waves are markedly different from those observed in the morning sector. Spacecraft observations of afternoon sector

**Table 2.** Number of Observations of Particular IMF Orientations From IMP 8 for Morning and Afternoon Sector Pc 5 Events

| | Northward IMF (Positive $B_z$) | Southward IMF (Negative $B_z$) |
|---|---|---|
| Morning sector events | 20 (59%) | 14 (41%) |
| Afternoon sector events | 2 (22%) | 7 (78%) |

Pc 5 events [e.g., *Kokubun*, 1980; *Yumoto et al.*, 1983; *Kokubun et al.*, 1989; *Anderson et al.*, 1990] suggest that they are predominantly a mixture of compressional and radially polarized waves. They also show that the radially polarized waves have a poor ground correlation. These radially polarized waves are likely to be predominantly driven by westward drifting ions from the nightside of the magnetosphere (for example, by drift bounce resonance [*Southwood et al.*, 1969; *Southwood*, 1976]) and will usually have azimuthal wavenumbers $|m| \sim 100$. Waves with these very large azimuthal wavenumbers are shielded from the ground [*Hughes and Southwood*, 1976a] and so will not be observed by ground-based magnetometers. Therefore they are unlikely to form a significant part of the ground-based data set observed in this paper.

The frequent spacecraft observations of compressional waves in the afternoon are confirmed by auroral radar observations. Observations of Pc 5 ULF waves by the SABRE radar were generally dominated by Alfvénic waves in the morning sector and compressional waves in the afternoon sector [*Chisham et al.*, 1995; T.K. Yeoman, personal communication, 1996]. Ground-based observations of afternoon Pc 5 events by *Rostoker and Sullivan* [1987] suggest that these waves are the ground signature of compressional oscillations of the whole magnetospheric cavity; 75% of the events they observed were globally visible all the way to the equator. Other ground-based observations [*Ziesolleck and Chamalaun*, 1993; *Ziesolleck and McDiarmid*, 1994, 1995] show no obvious signs of field line resonances occurring in the afternoon sector. *Ziesolleck and McDiarmid* [1994] do observe an amplitude maximum at $L \sim 7$, but no polarization reversal is observed. The general pattern of ground-based observations is clockwise/linear polarization with a north-south orientation, small $m$ values ($1 < |m| < 3$) with generally eastward propagation, and polarization and frequency appearing independent of latitude. This scenario appears the same at high latitudes [*Ziesolleck and McDiarmid*, 1994], midlatitudes (the present study), and low latitudes [*Ziesolleck and Chamalaun*, 1993]. *Ziesolleck and McDiarmid* [1994] interpret the north-south directed ellipses as relating to azimuthal oscillations in the magnetosphere due to the 90° ionospheric rotation. This seems an unlikely interpretation; very few azimuthal oscillations are observed by spacecraft in the afternoon sector. It is more likely that these waves undergo no ionospheric rotation as a result of their predominantly compressional nature in the magnetosphere. This scenario of no rotation is supported by auroral radar observations of afternoon sector Pc 5 waves with north-south directed linear polarization in the ionosphere [*Villain*, 1982]. Spacecraft observations of compressional waves also generally show a significant radial component [e.g., *Anderson et al.*, 1990]. The afternoon sector ground-based observations appear consistent with the expected ground signature of this type of compressional mode. Whether or not these compressional waves are cavity/waveguide modes is not certain, although the observation of preferential frequencies in the afternoon (Figure 9b) might suggest that this is the case. The reason for the rare occurrence of any coupling to field line resonances in the afternoon sector is unclear. Figures 7 and 8 show that there are also a significant number of afternoon sector Pc 5 waves exhibiting westward phase propagation. A solar wind source for these waves is unlikely, and a particle instability involving ions drifting from a nightside particle injection is a possible source for these oscillations.

The interpretations presented above for the local time asymmetry in midlatitude Pc 5 characteristics have not considered any effect the location of the plasmapause may be having on the wave observations. In the morning sector the plasmapause was predominantly located between the two SAMNET longitudinal chains. However, the similarity of the wave polarization and $m$ values on these two chains suggests that the plasmapause is having no effect on the morning sector wave observations. In the afternoon sector the whole SAMNET array was typically within the plasmasphere. However, the fact that the SAMNET observations of clockwise/linear polarization with a north-south orientation match observations made at higher latitudes [e.g., *Ziesolleck and McDiarmid*, 1994] suggests that the plasmapause is not playing a significant part in altering the morphology of afternoon sector Pc 5 waves either.

Apart from studying the variation of wave polarization and $m$ value with local time, other statistical comparisons have been made with the results of previous Pc 5 studies. *Ziesolleck and Chamalaun* [1993] and *Ziesolleck and McDiarmid* [1995] showed that for events observed at low latitudes and high latitudes, respectively, the Pc 5 frequency appeared to increase with increasing $Kp$. The reason for this correlation is not entirely clear, although *Ziesolleck and Chamalaun* [1993] interpreted it as a consequence of the increase of cavity resonance frequencies due to the compression of the magnetosphere at more disturbed times. However, for the 129 Pc 5 events observed by SAMNET there appears to be no significant correlation between the Pc 5 frequency and $Kp$. It is likely that these waves are the result of a mixture of wave sources, and so any correlation that might exist for one particular energy source (such as cavity/waveguide modes) is not clearly evident.

*Rostoker and Sullivan* [1987] observed a number of Pc 5 events in the afternoon sector, all of which occurred at times of zero or positive IMF $B_z$ (northward IMF). They suggested that although times of northward IMF were more conducive to wave generation through the Kelvin-Helmholtz instability [*Pu and Kivelson*, 1983], their afternoon Pc 5 waves were most likely the consequence of compressional cavity modes. In complete contrast to the results presented by *Rostoker and Sullivan* [1987], Table 2 shows that seven of the nine afternoon events observed by SAMNET for which IMF magnetic field data were available occurred during times of southward IMF. For the other two events, $B_z$, although positive, was very close to zero. It is possible that conditions of southward IMF are more conducive to the excitation of compressional cavity/waveguide modes, although the reasons are not clear. Conditions of southward IMF also stimulate substorm activity, which may provide the particles that are possibly responsible for the westward propagating afternoon sector events.

*Olson and Rostoker* [1978], using high-latitude Pc 5 observations, obtained results similar to those presented here and in other ground-based studies (i.e., predominantly westward (eastward) phase propagation in the morning (afternoon)). They also observed a linear relationship between the azimuthal wavenumbers ($m$) and the wave frequency ($f$), which suggested a constant phase velocity for the waves. Similar relationships have been observed between multiple field line resonance frequencies supposedly generated by cavity/waveguide modes [*Ziesolleck and McDiarmid*, 1994]. *Olson and Rostoker* [1978] suggested that this linear relationship supported the Kelvin-Helmholtz instability as the phase velocity, when mapped to the magnetopause, matched typical magnetosheath velocities. For the 129 Pc 5 events presented here there appears no significant relationship between the Pc 5 frequency and azimuthal wavenumber. The azimuthal wavenumbers observed here are also generally smaller in magnitude than those found by *Olson and Rostoker* [1978]. Whereas it is not obvious which energy source dominates the Pc 5 events observed by SAMNET, it is possible that those observed at high latitudes (close to the magnetopause boundary) by *Olson and Rostoker* [1978] are predominantly Kelvin-Helmholtz generated field line resonances.

## 5. Summary

This paper presents the first major statistical study of the local time asymmetry of Pc 5 waves at midlatitudes combining ground-based observations of the polarization and azimuthal wavenumber of Pc 5 waves observed by SAMNET. These midlatitude Pc 5 observations illustrate clearly the distinct asymmetry that occurs between wave features in the morning and afternoon sectors of the magnetosphere. The change is quite dramatic at noon and shows that different wave generation mechanisms dominate on either side of noon. The wave features support previous suggestions that field line resonances (generated either by the Kelvin-Helmholtz instability or by cavity/waveguide modes) dominate in the morning sector, whereas compressional waves (probably cavity/waveguide modes or waves generated by westward drifting ion populations), which show little evidence of coupling to field line resonances, dominate in the afternoon sector of the magnetosphere. It would be interesting to extend this study by making simultaneous observations of Pc 5 waves at high, middle, and low latitudes. This approach might help to clarify the overall wave picture. This study also presents convincing evidence that large ionospheric conductivity gradients around the sunrise region are responsible for the large variation in polarization orientation that occurs in the morning sector. A similar study of Pc 5 waves around and after the sunset region to ascertain whether the same effect occurs there would be interesting.

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