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Review articles

Hydromagnetic waves at low latitudes: a symposium review from the fifth IAGA assembly*

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Abstract. The aim of the symposium was to bring together investigators with interests in low latitude hydromagnetic waves in order to review the present state of knowledge in this area of magnetospheric physics. Of particular importance is the means by which wave energy is transferred to low latitudes to produce geomagnetic pulsations on the ground. The group of contributed papers reviewed shows that definitive experiments are underway and new theories capable of providing resonant wave energy at low latitudes are being developed. Particular topics covered by the review include solar wind control, wave spectra, array studies of wave parameters, storm time waves, and global wave resonance theory involving the coupling of compressional and transverse waves in the magnetosphere.

Key words: Hydromagnetic waves – Geomagnetic pulsations – Magnetospheric physics – Low latitude phenomena

1. Introduction

Our understanding of hydromagnetic wave generation and propagation mechanisms in the magnetosphere and the ionosphere has greatly increased over the last few years (see for example the review by Hughes, 1982). This occurred largely because of the data accumulated during the International Magnetospheric Study (IMS) between 1976–1979, and the stimulation provided by the ULF Pulsation Working Group within Division III of the International Association of Geomagnetism and Aeronomy (IAGA) on Magnetospheric Phenomena. However, until recently research has concentrated on waves observed at high and middle latitudes. This is a natural consequence of the available spacecraft data and the location of ground recording stations and arrays at that time. Theoretical work has also been largely confined to high latitudes through the development of generation theories such as the Kelvin-Helmholtz instability (Southwood, 1974; Chen and Hasegawa, 1974) and the drift mirror and bounce resonance instabilities (Hasegawa, 1969; Southwood, 1973) which relate to the outer magnetospheric region beyond the plasmapause.

Despite this improved understanding of hydromagnetic wave phenomena, we still have not specifically identified the mechanisms which transfer wave energy to low and equatorial latitudes. Spacecraft measurements cannot be undertaken in these low altitude field line regions and we must look at groundbased observations to provide the experimental data required. In order to stimulate both theoretical and experiment research in this area, IAGA organized a half day symposium on hydromagnetic waves at low latitudes which was held at the Fifth General Assembly of IAGA in Prague on August 12, 1985. The symposium was convened by L.J. Lanzerotti and its aim was to assemble and present observational and theoretical results from low latitude wave studies in order to assess the present state of knowledge. This would then provide a basis on which to plan future research. This review attempts to summarize the more important results which came from the contributed papers presented at the symposium. It is written as an overview and it has not been possible to treat all papers equally. What is presented orally or by poster to stimulate discussion may not always be suitable for publication. Papers have been selected to fit an ordered set and those omitted may well be the more important ones. Two invited review papers summarizing previous experimental and theoretical work on low latitude hydromagnetic waves were also presented and they are included elsewhere in this issue (Vero, 1986; Yumoto, 1986).

The symposium, with only a one-half day duration, was short by IAGA standards. However it was well attended and a total of 21 contributed papers were presented. Of these, ten were oral presentations with the remainder displayed as poster papers. In what follows, papers are cited from two reference lists. The first contains references used in the review and are generally key papers in the development of the topic and provide a background to that topic. These references are cited in the normal way by author and year. The papers in the second list are cited by author name only and are those presented as contributed papers to the symposium.

2. Solar wind control

The energy source for hydromagnetic waves observed on the ground as geomagnetic pulsations may be either internal or external to the magnetosphere. Internal sources of energy include instabilities associated with the cyclotron, bounce and drift motion of particles whose distribution functions

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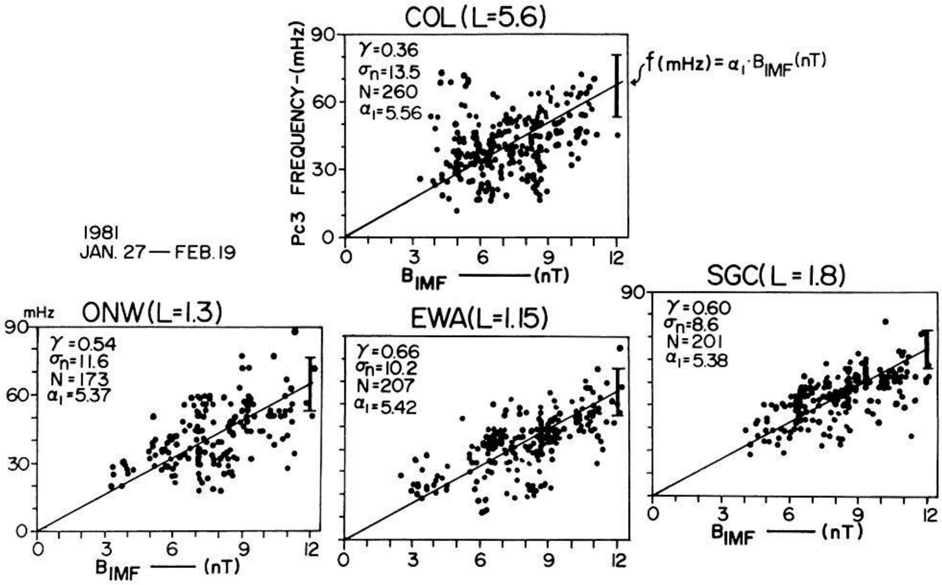

Fig. 1. Scatter plots of the daytime Pc 3-4 wave frequencies observed at four ground stations against the IMF magnitude observed by ISEE-3 for 23 days of data. The solid line indicates the regression line $f(\mathrm{mHz})=\alpha_1 \cdot B_{\mathrm{IMF}}(\mathrm{nT})$. The γ and σ_n are the linear correlation coefficient and the deviation about the regression respectively. [From Yumoto et al., 1985a]

are anisotropic. Free energy internal sources include pressure gradients, velocity shears, and rapid changes in magnetospheric geometry associated with substorms.

It is generally accepted that some of the dayside Pc 3-4 pulsation energy is associated with sources external to the magnetosphere (Odera, 1986). Statistical studies show that the period of these waves is strongly correlated with the magnitude of the interplanetary magnetic field (IMF) while the occurrence rate depends on the orientation of the IMF (see for example, Greenstadt et al., 1980). These effects are often seen most significantly at low latitudes (Russell et al., 1983). This topic is well covered in the accompanying reviews by Vero (1986) and Yumoto (1986).

The basis for the association of Pc 3-4 pulsation wave frequency (f) with the IMF magnitude (B_{sw}) has been the "Borok B-index" originally formulated by Troitskaya et al. (1971) in the form $f(\mathrm{Hz}) \simeq 0.006\ B_{sw}$ (nT). A number of contributed papers readdressed this relationship with respect to the variability of magnetospheric conditions. Using wave frequencies determined by spectral analysis, Best et al. investigated the seasonal and K_p variation in the $f-B_{sw}$ relationship for daytime Pc 4 pulsations recorded over four years at a $L=2.4$ station. A strong correlation was found to exist in summer afternoon data only, and took the empirical form

$$B_{sw}=0.7+1.1\ \mathrm{Kp}+150f$$

over the range $0 \leq \mathrm{Kp} \leq 4$. It is important to note that no dependence on Kp was found for Pc 3 pulsation data. A more extensive study of IMF relationships using three low latitude Pacific stations separated in longitude over $L=1.1-1.8$, and a high latitude station, College at $L=5.6$ was reported by Saito et al. and many of the results have since been published (Yumoto et al., 1985a). The Pc 3-4 wave frequencies were found to be well correlated with B_{sw} with the best correlation at low latitudes. This result is illustrated in Fig. 1. Furthermore, the daytime wave amplitudes at low latitudes correlated well with the IMF cone angle θ_{XB}. Changes in θ_{XB} on a short time scale (20–60 min) were found to be consistent with the microstructure of the daytime Pc 3 activity. This important result has been reported previously by Troitskaya (1984) and was also alluded to in other symposium papers. The conclusion from the Saito et al. results was that high latitude Pc 3-4 pulsations are associated with both the surface waves at the magnetosphere and the upstream waves in the earth's foreshock, while low latitude Pc 3-4 pulsations are associated mainly with the magnetosonic upstream waves propagating into the inner magnetosphere.

In contrast to the results of Saito et al. just described, Playasova-Bakounina et al. found that IMF associated Pc 2-4 wave events with amplitudes up to 20 nT appeared predominantly near cusp latitudes. Using the $f=0.006\ B_{sw}$ formula, these authors separated their data into two categories; waves of external origin and waves of internal origin. With both f and B_{sw} known, waves which satisfied the formula were classified to be of external origin while those which did not were considered to be of internal magnetospheric origin. The former group showed greatest amplitudes near the cusp while the latter group peaked at lower latitudes.

In accepting the results of Saito et al. and Plyasova-Bakounina et al. derived from the $f-B_{sw}$ relationship, it appears that we have two irreconcilable conclusions. However, there are a number of points that must be considered. Firstly, the $f-B_{sw}$ relationship is an empirical non-linear function which also depends on other upstream magnetosonic wave parameters (Russell and Hoppe, 1981). In spite of this it relates f and B_{sw} with remarkably high correlation. Secondly, Pc 3-4 are the dominant daytime pulsations seen at low and middle latitudes. At high latitudes their signature is often contaminated by Pi 1 aurorally associated pulsations, a point noted by Yumoto et al. (1985a), and a lower correlation from the $f-B_{sw}$ relationship may not be unexpected.

Preliminary results from a Pc 3-4 pulsation study at cusp latitudes (Engebretson, private communication) indicates that the wave data satisfies the $f-B_{sw}$ relationship remarkably well and concludes that the source is in the upstream region. From these results we can conclude that there may be two paths for the entry of upstream Pc 3 wave energy into the inner magnetosphere, one directly through the subsolar region of the magnetosheath and another along high latitude field lines and into the cusp region. The importance of these two propagation paths for the transmission of wave energy into the magnetosphere and their relative contribution to low latitude Pc 3 pulsations must await further research.

3. Wave spectra

Dynamic spectral analysis provides a convenient method for studying the wave characteristics of pulsations. This is particularly important nowadays with the availability of digital data and the use of modern digital analysis techniques. If wave results from station arrays are available, then the comparison of dynamic spectra provides a simple but effective means of observing interstation wave properties across ground or satellite networks or between ground stations and satellites.

These techniques were utilized in the studies reported by Miletits and Vero, and Hollo and Vero. In the first study, dynamic spectra from a subauroral station and a low latitude station were compared. An example is shown in Fig. 2 where it can be seen that the predominant wave periods near 20 s and 90 s are common to both latitudes and activity commences and ceases at the same time. This high degree of correlation in time and frequency was not always seen, although the dominant frequencies at the two stations were occasionally harmonically related. The common signals were interpreted as primary waves from the upstream source. In another study, using activity indices and spectra from the same low latitude station in association with ATS-6 synchronous spacecraft magnetometer data, Hollo and Vero found Pc 3-4 wave activity on the ground at low latitudes that was not evident at synchronous orbit. The presence of harmonic structure seen at synchronous orbit (see for example Takahashi and McPherron, 1982) did not appear to have a significant influence on the wave spectra seen on the ground. Simultaneous commencement and cessation of wave events at synchronous orbit and on the ground were significant only during the local morning and in the 20–25 s period range. Conclusions were that wave amplification in the inner magnetosphere below synchronous altitude is strongly modulated by the solar wind and creates sharp resonant spectral lines in the ground wave activity observations.

Boshoff and Sutcliffe reported observations from three stations at $L=1.76$ and spanning 35° in longitude. From comparisons of dynamic spectra they reported one day in which the high frequency Pc 3 spectral components present at two stations were absent at the third, more westerly, station situated on an island below the South Atlantic Magnetic Anomaly. It was speculated that the lower magnetic field intensity and the associated particle precipitation at the anomaly may deplete the plasmasphere thereby eliminating the resonances at the higher frequencies.

Over closer distances and using a network of four low latitude Pc 3 recording stations, Ansari and Fraser considered longitudinal and latitudinal variations in dynamic wave spectra. In general, wave spectra were similar over a longitudinal range of 17° at $L=1.8$ with a dominant frequency band at 40–45 mHz. The higher latitude station at $L=2.8$ also exhibited lower frequency Pc 4 bands ($\sim$10 mHz) on some days and higher frequency bands (60–80 mHz) on others. Sometimes completely different wave spectra were observed on the north-south and east-west components with the longitudinal stations showing similar spectra on corresponding components. This could indicate decoupling between the radial and azimuthal wave components in the magnetosphere. Harmonic structure with $\Delta f \sim 10$ mHz was occasionally seen during local afternoon.

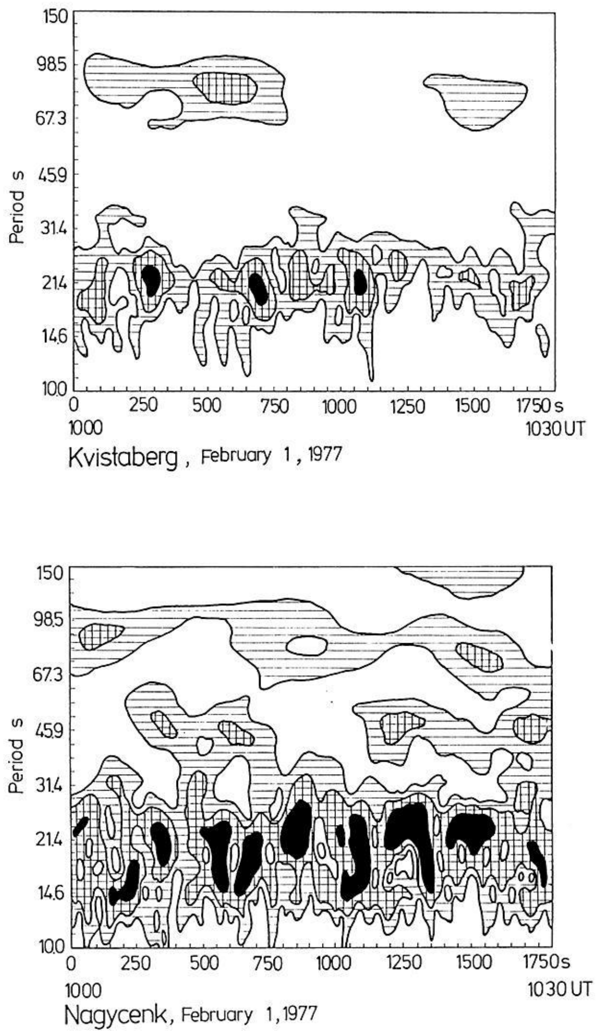

Fig. 2. Dynamic spectra of Pc 3-5 pulsations observed between 1,000–1,030 h LT, February 1, 1977 at Kvistaberg at subauroral latitudes and Nagycenk at low latitudes. (From Miletits and Vero)

4. Array studies

In order to study the properties of resonant field line structures associated with Pc 3-5 pulsations it is necessary to employ latitudinal and/or longitudinal chains of stations. The importance of multipoint observations in pulsation research was established by Samson et al. (1971) who identified phase variations with latitude which were later interpreted in terms of the Kelvin-Helmholtz instability at the magnetopause, coupling to a transverse field line resonance within the magnetosphere (Southwood, 1974; Chen and Hasegawa, 1974). It is only recently that interstation studies have been undertaken at low latitude stations. For example, Saka and Kim (1985) and Ansari and Fraser (1986) often observed Pc 3 propagation azimuthally away from the noon meridian towards dusk and dawn with left-hand (LH) wave

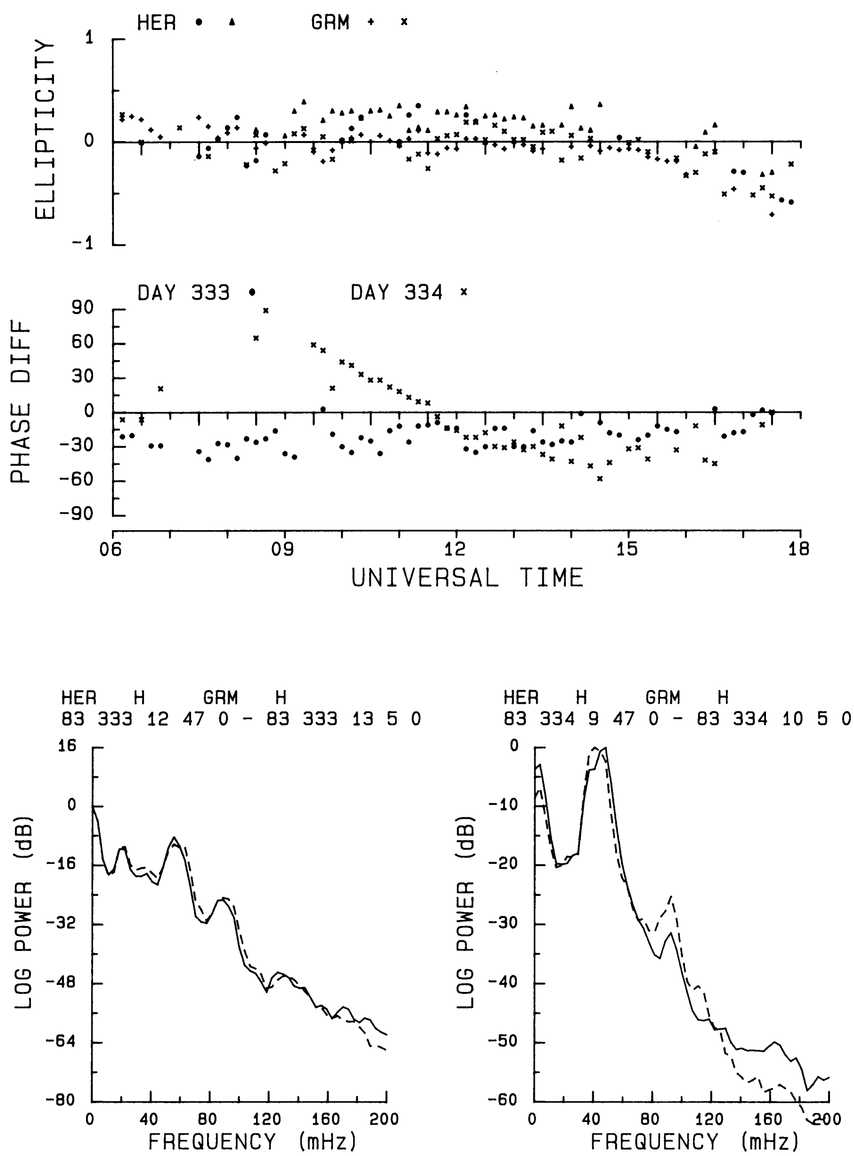

Fig. 3. *Top:* Polarization ellipticity of Pc 3 waves observed at Hermanus and Grahamstown ($L=1.85$) on November 29–30, 1983. LH polarization is positive and RH negative. *Centre:* Phase difference between signals observed at the two stations for the two days. Eastward propagation is positive and westward negative. *Bottom:* Wave spectra from two 63 min segments on November 29 and 30, 1983, respectively. The H components from both stations are plotted. (From Sutcliffe)

polarization before noon and right-hand (RH) after noon. Azimuthal wave numbers were generally low with $m<10$.

The resonant field line model explains the latitudinal variation of wave amplitude and the associated reversal of wave polarization near the resonant field line latitude (Walker, 1980). Assuming this model, the apparent latitudinal propagation away from the equator (Saka and Kim, 1985; Ansari and Fraser, 1986) may be interpreted in terms of the latitudinal phase variation in the field line resonance structure and is consistent with a resonance region situated at a higher latitude. The diurnal azimuthal propagation and polarization patterns predicted by the Kelvin-Helmholtz instability at the magnetopause are also observed at low latitudes. However, these properties are not necessarily unique to the Kelvin-Helmholtz mechanism, a point discussed by Ansari and Fraser (1986).

The spatial and temporal structure of Pc 3 waves at two stations 7° apart in longitude at $L=1.85$ were considered by Sutcliffe. Using two days of data, it was found that wave polarization was LH almost all day with dominant RH appearing only after 15 h. Low wave numbers were observed ($m<10$) and interstation phase differences indicated westward propagation all day on one of the days. Eastward propagation is seen only before noon, which is contrary to earlier studies. These results are illustrated in Fig. 3. However, there is often a significant day to day variability in azimuthal propagation (Mier-Jedrzejowicż and Southwood, 1981) and these results are not unexpected. They may in fact, suggest a field line resonance source moving towards noon. Harmonic structure was also exhibited in the wave spectra (Fig. 3), with odd harmonics being identified on one day and even harmonics on the other.

The complex nature of individual Pc 3-5 wave packet structure was first noted at synchronous orbit by Mier-Jedrzejowicz and Hughes (1980) with observations of a gradual change in the relative phase between two spacecraft signals with time across a wave packet. The gradual phase drift ended with a sudden jump back into phase at the commencement of a new wave packet. Similar phase jumps were also observed in ground data from middle latitude stations. One possible explanation is that the phase drifts are a consequence of a free resonant shell oscillation in the absence of a driving force.

At low latitudes Lanzerotti et al. (1981) reported com-

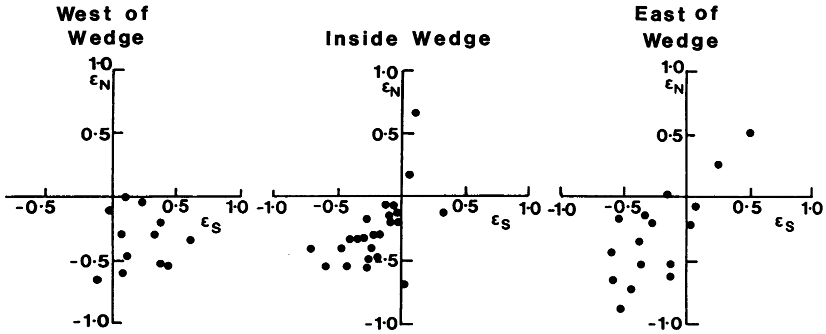

Fig. 4. Pi 2 polarization ellipticities (ε_s) at two low latitude stations ($L \sim 1.7$) plotted in current wedge centred coordinates against polarization ellipticities (ε_n) at higher latitude stations. (From Lester and Singer)

plicated phase jumps and polarization changes over intervals of a few minutes which were variable between signal components and stations. At the symposium Lanzerotti et al. extended their earlier results by noting that significantly different frequencies were often observed simultaneously with the polarization changes. The paper by Sutcliffe previously discussed also noted ellipticity changes over short time intervals, which were attributed to the mixing of LH and RH polarized wave packets.

Pc 3 phase structure observed at three longitudinally spaced stations ($L = 1.8$) by Ansari and Fraser did not show any systematic temporal or spatial patterns. Phase differences between corresponding signal components at different stations often showed a greater similarity than did the two components at a single station. Phase differences between pairs of stations were mostly variable and no consistent frequency changes or phase jumps were observed. None of the phase jump results considered above suggest a consistent phase pattern and are difficult to explain in terms of currently understood hydromagnetic wave theory in the magnetosphere. It may be necessary to look at nighttime impulsive Pi 2 pulsations in association with daytime Pc 3 waves or amplitude and phase variations resulting from low latitude ionospheric currents and irregularities in order to find an answer to the phase jump phenomenon.

A useful method for identifying hydromagnetic wave modes in the magnetosphere is to study conjugate wave characteristics. This was undertaken at $L \sim 1.5$ by Saito et al. using data from Australia and Japan. Comparison of conjugate polarization data indicated predominantly LH waves in the daylight morning hours with mixed and often opposite polarizations in the afternoon. No particular wave mode types were identified, but a primary source outside the magnetosphere was assumed. Following earlier arguments (Saka and Kim, 1985; Ansari and Fraser, 1986) it was speculated that these waves produce westward propagation in the morning and eastward propagation in the afternoon and can couple to various hydromagnetic resonances in the plasmasphere. Further details of this work are included in Yumoto et al. (1985b).

5. Statistical studies

In the past a great deal of knowledge on groundbased pulsations has been obtained using statistical data. At the symposium, two papers were presented using extensive data sets. Ansari and Fraser studied the diurnal seasonal and magnetic activity variations using four low latitude stations. Average frequencies at $L = 1.8$ were higher than those at $L = 2.7$ perhaps illustrating a frequency-latitude relationship. A single noon peak in wave occurrence was seen at all stations, not a new result but a property which has important implications with regard to the identification of wave generation mechanisms. Wave occurrence was evenly distributed over the range of magnetic activity $K_p = 2$-5. In contrast to this, Yang and Chang found Pc 3 occurrence at Beijing peaked for local $K = 3$. Day-time wave frequencies were found to be higher than night-time frequencies, a result which is consistent with the field line resonance theory.

6. Storm associated waves

Three papers were presented on the low latitude observation of waves associated with substorms and magnetic storms. In the only paper presented at the symposium on Pc 1 ion cyclotron waves, Maltseva and Troitskaya studied the variation in IPDP wave frequency with latitude with the emphasis on low latitude signatures. IPDP events are a train of irregular amplitude pulsations normally seen at high latitudes and showing intervals of diminishing wave period with time. It was found that the frequency variation with latitude is such that $f_{O^+} < f_{IPDP} < f_{He^+}$ where f_{O^+} and f_{He^+} are the cyclotron frequencies of oxygen and helium ions in the magnetospheric plasma. Using this frequency variation with latitude it was suggested that IPDP may be capable of penetrating down to latitudes $L < 3$.

Pi 2 pulsations seen at the onset of a substorm are now used extensively to study the dynamics of substorms. Of importance is the relationship between the Pi 2 wave polarization characteristics and the location of a three dimensional current system, called the current wedge (McPherron et al., 1973) which develops at substorm onset. At midlatitudes ($L \sim 3$) Pi 2 polarization is anticlockwise west of the wedge, inside the wedge and also to the east of the wedge (Lester et al., 1984). However, at the symposium Lester and Singer reported that at low latitudes ($L \sim 1.7$) it is clockwise west of the wedge and anticlockwise inside and east of the wedge (Fig. 4). This suggests that a polarization reversal occurs somewhere between $L = 1.3$ and 3 west of the wedge, a result which has yet to be directly observed.

7. Ionosphere effects

Interesting measurements of vertical ionospheric electron drift velocities at the equator by the Jicamarca radar were reported by Patel and Lagos. They found quasiperiodic fluctuations with 90–120 s periods over an altitude range of 200–935 km. These vertical oscillations of the electrons resulted from an east-west electric field component. A number of suggestions were made as to the origin of these waves. They could be drift waves of internal ionospheric origin driven by plasma gradients, or alternatively, hydromagnetic modes of magnetospheric origin. Further details are discussed by Patel and Lagos (1985).

Wide ranging results on the ionospheric and magnetospheric signatures of a ground explosion at $L=1.5$ were the subject of a paper by Alperovich et al. This is an example of coupling between earth, ionospheric and magnetospheric processes resulting in the generation of a nonlinear mixture of RH and LH polarized ion-acoustic impulsive waves. The signatures were observed by the low altitude Aureol 3 satellite in the conjugate hemisphere. Several inter-hemispheric bounces of the wave energy packet were seen and an interpretation was made in terms of large amplitude solitary waves.

8. Hydromagnetic wave theory

In the preceding sections many papers have reported the existence of significant Pc 3-4 wave energy in discrete bands at low latitudes ($L<3$). Furthermore it was shown that these waves may or may not be associated with similar activity at middle and high latitudes. It is generally considered that the probable source of the low latitude pulsations is the field line resonance mechanism. If the wave energy source is external to the magnetosphere, in the upstream waves region, then it is necessary to transfer significant energy to middle and low latitude field lines in order to excite these resonances. The Kelvin-Helmholtz instability is incapable of doing this, and furthermore it will not produce the single noon maximum observed in Pc 3 wave occurrence. Also, the coupling of compressional mode waves from this instability to the field line resonance is limited to waves with large azimuthal wave numbers. However, the coupling of global magnetospheric compressional modes, excited by impulses at the magnetopause, to field line resonances has recently been suggested as a possible source of waves (Kivelson and Southwood, 1985; Allan et al., 1985). The two modes exhibit strong coupling and relate to low azimuthal wave numbers, which are now known to predominate (Sect. 4). Kivelson and Zhu explained that this mechanism can excite waves at any latitude within the bounds of the chosen magnetosphere–plasmasphere system. The global compressional wave has a finite amplitude over a large radial scale and a discrete frequency spectrum will be seen, determined by the radial boundary conditions. The dominant transverse component may be either toroidal or poloidal. The toroidal oscillations are confined to L-shells whose resonant frequency matches the frequency of the global mode. There is a transfer of energy from the global mode to the field line resonance resulting in the damping of the global mode. Further details of this work are included in Kivelson and Southwood (1986) and Allan et al. (1986).

Although we have known for a long time that the field line resonance mechanism is the origin of many discrete wave phenomena seen on the ground it was not until the observations of the STARE radar at high latitudes became available that the spatial amplitude and phase structure of the resonance was seen (Walker, 1980). Because of ionospheric screening and spatial integration it is difficult to identify unambiguously the resonance using ground magnetometer arrays. The application of a novel method developed by Baransky et al. (1985) was described by Feygin et al. using low latitude data. It is assumed that each field line has its own discrete frequency of oscillation as shown in Fig. 5a. Using north-south and east-west magnetometer data from two stations (N and S) spaced 100 km apart, it was shown that the frequency at which the amplitude ratio of the north-south components from the two stations passes through unity indicates the field line resonance frequency for the field line midway between the two stations (Fig. 5b). Feygin et al. described results from pairs of stations spaced 100 km apart at Sogra ($L=3.6$). A resonance was found at 33 mHz which was interpreted as the second harmonic for the $L=3.6$ field line. A "gradient-time analysis" method based on the numerical comparison of digital dynamic spectra was also described. Over 34 min, the resonant frequency varied from 26 to 38 mHz. The phase characteristics of the resonance signatures observed on the ground were also discussed and it was concluded that the plasmasphere may be a more favorable region for the field line resonance than the plasmapause. This is a potentially powerful method for locating the latitude of the field line resonance and may be capable of determining the range of latitude over which the field line resonance mechanism operates and the associated frequency variation with latitude.

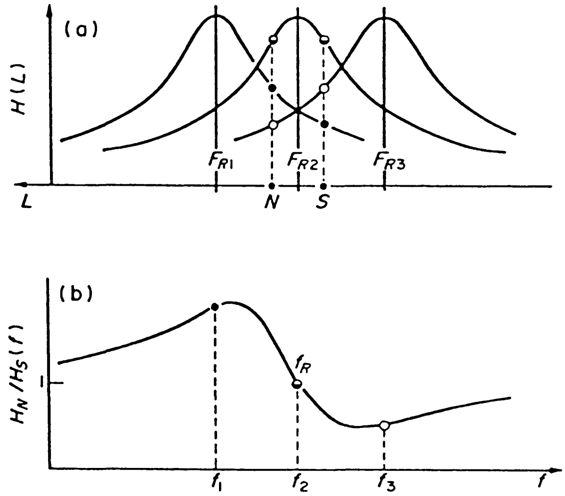

Fig. 5. **a** Schematic of the meridional distributions of wave amplitude H(L) for three spectral components $f_1<f_2<f_3$ of geomagnetic pulsations. Each component experiences the local resonance amplification at the foot of the field line with resonance frequency $F_r=f$. **b** Ratio of spectral amplitudes $H_N/H_S(f)$ of pulsations recorded simultaneously at points N and S. The frequency f_R determined from the conditions $H_N/H_S(f)=1$ and $\partial(H_N/H_S)/\partial f<0$, should be the resonant frequency of the field line intersecting the meridian at the midpoint of NS ($f_R=F_{R2}$) [From Baransky et al., 1985]

9. Conclusions

The symposium on low latitude hydromagnetic waves provided an opportunity for the assessment of present knowledge and a forum to plan for the future. Current understanding of the source and properties of long period hydromagnetic waves at low latitudes are summarized below. The summary is certainly not complete, but concentrates on the results reported at the symposium and reinforced to some extent by recent results reported in the open literature.

The energy sources for waves observed on the ground may be internal or external. Overwhelming evidence presented at the symposium supported upstream waves as an external source of Pc 3-4 waves at low latitudes. This included the solar wind/IMF parameter correlations with pulsation frequency and amplitude and the simultaneous switch-on and switch-off of wave activity over short intervals of time and a wide range of latitude. In contrast to this, Pi 2 and Pc 1/Pi 1 waves result from internal free energy processes directly or indirectly associated with magnetospheric substorms.

At low latitudes, ground magnetometer arrays provide the primary data for spatial and temporal studies of wave properties. Pc 3-4 wave properties of importance for identifying generation and propagation mechanisms that have been determined from array studies include:

1. The relationships between solar wind/IMF and Pc 3 wave parameters;
2. A predominance of LH polarized waves before noon and RH waves after noon on particular days. This pattern is not always seen and must be clarified.
3. Low azimuthal wave numbers ($m < 10$).
4. On many occasions, a propagation pattern is seen in which waves propagate away from noon towards the dawn and dusk terminators. Again, this pattern is not always seen.
5. Harmonic wave structure, known to exist at synchronous orbit and at high latitudes, has been tentatively observed at low latitudes, but further studies are needed.
6. High and low latitude dynamic wave spectra often show similar characteristics.
7. Pc 3 wave amplitudes and occurrences peak near local noon.

Recently suggested wave theories involving the coupling of global compressional wave eigenmodes to the field line resonance appear to be capable of explaining many of the properties listed above. However, these models are still in their infancy and have yet to be applied to a fully realistic magnetosphere.

From the experience of this symposium a number of directions for future research in low latitude hydromagnetic waves are obvious. Firstly, observations should be undertaken to check the predictions of the global compressional wave theory. These include observations of compressional waves and resonance structures in the magnetosphere and plasmasphere using radial satellite paths, and the association of these wave properties with upstream waves and pulsations on the ground. Observations of the latitudinal structure of Pc 3-4 pulsations at low latitudes must be undertaken using ground arrays in order to identify field line resonance regions. The confused results on the spatial structure of Pc 3 phase jumps and associated polarization and frequency changes over short intervals of time must also be explained. For substorm associated waves, particularly the Pi 2 and IPDP pulsations, it is important to understand the low latitude signatures in detail before we can determine the mechanisms by which the waves are propagated to these latitudes.

Hopefully, much of this work can be accomplished within the next year or two. This would seem appropriate since a symposium on hydromagnetic waves in the polar cusp region is scheduled to be held at the next IUGG General Assembly in Vancouver in August 1987. By this time we may understand the sources of low latitude hydromagnetic waves and be capable of relating them to the higher latitude observations.

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Alperovich, L.S., Y.I. Galperin, M.B. Gokhberg, O.A. Pokhotelov, R.Z. Sagdeev: Solitary Alfven wave in the low-latitude magnetosphere.

Ansari, I.A., B.J. Fraser: Spectral characteristics of low-latitude Pc 3 geomagnetic pulsations in South East Australia.

Ansari, I.A., B.J. Fraser: Wave packet structure and phase jumps in low-latitude Pc 3 geomagnetic pulsations.

Ansari, I.A., B.J. Fraser: A statistical study of low latitude Pc 3 geomagnetic pulsations.

Best, A., I. Best, and J.J. Linthe: Spectral characteristics of Pc 3 and Pc 4 pulsations in middle latitudes.

Boshoff, H.F.V., and P.R. Sutcliffe: Local time and longitudinal variations of Pc 3 pulsation frequency.

Feygin, F.Z., Yu. N. Kurchashov, Ya. S. Nikomarov, V.A. Pilipenko, and A. Best: Preliminary results of U.S.S.R.-G.D.R. experiment for the synchronous registration of geomagnetic pulsations at two low-latitude meridional profiles.

Fraser, B.J.: A review of contributed papers.

Hollo, L., and J. Vero: One year comparison of ATS and ground pulsation spectra.

Ivanova, P.K., and N.G. Kleimenova: Long-period pulsations at $L < 3$ during great magnetic disturbances.

Kivelson, M.G., and X.M. Zhu: Pc 3-4 pulsations at low latitudes and generation of parallel currents.

Lanzerotti, L.J., L.V. Medford, and A. Wolfe: Variations in hydromagnetic wave frequencies at low geomagnetic latitudes.

Lester, M., H.J. Singer: Pi 2 pulsations and the substorm current wedge-polarization characteristics at low latitudes ($L < 3$)

Maltseva, N., V. Troitskaya: On movement of IPDP generation sources in the region $L < 3$.

Menk, F.W., C. Ziesolleck, B.J. Fraser, R.L. McPherron, and P.W. McNabb: Propagation of Pc3-4 pulsations across a low-latitude array.

Miletits, J.Cz., and J. Vero: Dynamic spectra of pulsation events at $L = 2$ and 3.

Patel, V.L., and P. Lagos: Low-frequency fluctuations of the electric field in the equatorial ionosphere.

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Saito, T., K. Yumoto, K.D. Cole, J. Ward, J. Soegijo, A.J. Chen, and Y. Tanaka: Wave characteristics of Pc 3-4 pulsations observed at low latitude conjugate stations ($L < 2.1$).

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Sutcliffe, P.R.: The spatial and temporal structure of low-latitude Pc 3 pulsation fields.

Vero, J.: Experimental aspects of low-latitude pulsations – A review.

Yang, S.-F., and J.-X. Chang: The correlation between Pc 3 geomagnetic pulsation and K-index in Beijing.

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