GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 2, PAGES 231-234, JANUARY 15, 2001

Propagation of 10-50 mHz ULF waves with high spatial coherence at high latitudes

T.A. Howard and F.W. Menk

Physics Department and Cooperative Research Centre for Satellite Systems, University of Newcastle, NSW, Australia.

Abstract. We used the IMAGE high latitude magnetometer array from two weeks in March 1996 to study 10–50 mHz (Pc3–4) pulsations that exhibit high coherence over an extended spatial region. These are a small sub-class of daytime Pc3 activity at high latitudes. Nine of eleven events did not show evidence of field line resonance harmonics. Instead, the observed amplitudes decreased equatorward, and phase relationships indicate poleward propagation. The results suggest that the pulsations are due to incoming fast mode waves driving forced field line oscillations or are propagating direct to the ionosphere. Coherence scale lengths at the ground are of order 1×10^3 km, and the pulsation frequency often appears to be predicted by the ion-cyclotron mechanism in the upstream solar wind.

Introduction

Pc3–4 geomagnetic pulsations ($7 \leq f \leq 100$ mHz) are often attributed to resonant or forced oscillations of field lines [*Orr*, 1984] stimulated by propagating fast-mode ULF waves [e.g. *Matsuoka et al.*, 1997]. The occurrence, amplitude and frequency of the pulsations may be connected with properties of the solar wind [*Greenstadt and Olson*, 1979], suggesting that the waves are generated by the ion-cyclotron mechanism upstream of the bow shock [eg. *Plyasova-Bakounina et al.*, 1978]. The wave frequency f should then depend on the cone angle θ_{xB} and the interplanetary magnetic field strength B_{IMF} according to [*Takahashi et al.*, 1984]

$$f(mHz) \sim 7.6 \cos^2 \theta_{xB} |B_{IMF}|(nT), \qquad (1)$$

whereas *Le and Russell* [1996] found the empirical relationship

$$f(mHz) = (0.72 + 4.67 \cos \theta_{xB}) |B_{IMF}|(nT) \qquad (2)$$

using ISEE spacecraft data.

At high latitudes the Pc3–4 spectrum includes quasi-periodic (burst-like) fluctuations and monochromatic, spatially coherent pulsations. The former may be due to the modulation of precipitating electron beams [*Engebretson et al.*, 1991], with coherence lengths of order 140–180 km in ground magnetometer data [*Szuberla et al.*, 1998] and 30–60 km in the ionosphere [*Baker et al.*, 1998]. The mechanism by which the monochromatic, spatially coherent pulsations reach the ground is not yet clear. Studies at auroral latitudes [*Tonegawa and Fukunishi*,1984; *Ziesolleck et al.*, 1997] linked them with harmonics of field line resonances (FLRs) or propagating compressional waves. Signatures of FLRs include a peak in amplitude and reversal in phase at the resonant latitude [*Waters et al.*, 1995].

This study investigates the origin of coherent Pc3–4 pulsations at high latitudes. We examined magnetometer array data for Pc3–4 pulsation events exhibiting high coherence over an extended region, and their spatial variation in power, coherence and phase. The pulsation frequency was also compared with solar wind properties using equations (1) and (2).

Experimental

Ground magnetometer data were obtained from 19 stations of the IMAGE array, spanning 3.4<L<15 (57°N to 76°N CGM) across Scandinavia and the Arctic [*Lühr*, 1994]. The data were sampled in geographic coordinates at 0.1 Hz with a resolution of ~0.1 nT, and rotated into geomagnetic (H, D) coordinates before analysis. We examined daytime pulsation activity at all stations during two weeks of March 1996 during which there was both quiet and moderate levels of magnetic activity. This was done using filtered time series and dynamic (whole day) power spectra for each station, and individual and dynamic cross-power and cross-phase spectra [*Waters et al.*, 1995] between station pairs. Filtering included a high pass filter at 2 mHz to remove the long period and DC components of the time series and low pass at the Nyquist frequency (50 mHz) to prevent aliasing. Dynamic spectra were computed with a 256-point (43 min long) FFT stepping every 35 points.

Eleven intervals were found when stable, monochromatic oscillations in the 10–50 mHz frequency range were observed across virtually the entire IMAGE array. These occurred mostly in the morning and noon sectors and represent a limited sub-class of Pc3 activity at these latitudes, since the more broadband quasi-periodic signals may persist for some hours each day. For each in-

Paper number 2000GL011993.
0094-8276/01/2000GL011993$05.00

terval we then calculated the interstation coherence and phase with approximately 13 degrees of freedom [*Jenkins and Watts,* 1969]. The phase values were obtained from cross-phase spectra for overlapping combinations of station pairs of increasing separation (phase closure) to resolve 2π ambiguities. The effective meridional (ie. along the same meridian) and azimuthal velocity components were then calculated from the interstation phase trends. Azimuthal and meridional coherence lengths were estimated for each interval relative to a central reference station. Note that Pc5 FLRs were observed virtually daily in the dynamic cross-phase spectra and may be used as a guide to the open/closed field line configuration [*Ables et al.,* 1998]. Finally, θ_{xB} and B_{IMF} were determined from WIND data.

Results

For each interval the amplitude, cross-phase and coherence for the H and D components were plotted against latitude and longitude. Here we present results for one typical interval, on March 23, 1996 (K_p=2–). Figure 1 shows stacked H component time series for meridional IMAGE stations, bandpass filtered over 15–40 mHz. CGM coordinates for 100 km altitude are used throughout, and LT~UT+1. Packets of sinusoidal oscillations occur at all stations, with amplitudes decreasing progressively equatorward of ~74° latitude.

Figure 2 illustrates interstation properties for Sørøya-Kilpisjärvi (SOR–KIL), separated in latitude by 170 km. The upper panel displays the detrended time series, and the second panel the discrete cross-power spectrum (with 0.6 mHz resolution). The remaining two panels show the coherence and cross-phase with a resolution of ~3 mHz. For each plot a half hour interval from 0730 to 0800 UT has been selected. The pulsations of interest are identified by the peak in cross-power and coherence near 26 mHz. The corresponding cross-phase value is ~−30°, ie. KIL leading SOR. The same procedure was conducted for many other combinations of station pairs.

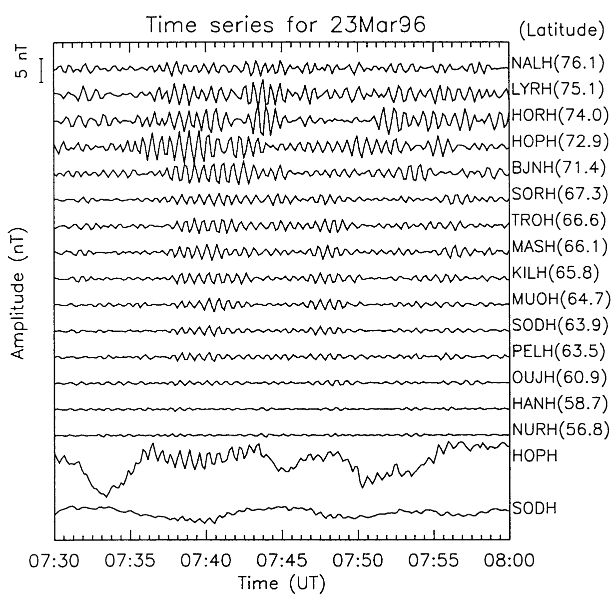

Figure 1. H component stacked time series plots for 0730–0800 UT, March 23, 1996. For comparison, the bottom two traces show time series from HOP and SOD, high-pass filtered at 2 mHz.

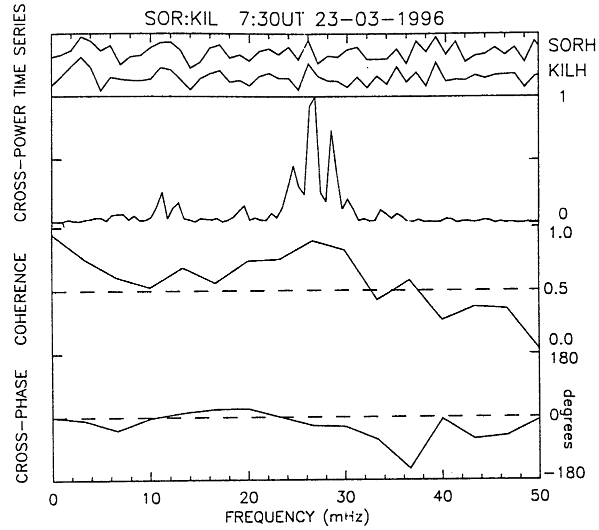

Figure 2. Example of interstation analysis for SOR and KIL, 0730–0800 UT, March 23, 1996. Time series, cross-power, coherence and cross-phase spectra are shown.

Figure 3 summarizes the variation in signal amplitude, coherence and phase with latitude and longitude for this interval. For both H and D components the amplitude (top panels) decreased equatorward of ~75° latitude as represented by the exponential lines of best fit. The D component amplitude was somewhat lower than for the H component; this is typical of other events. The amplitude of these Pc3–4 signals is typically an order of magnitude lower than for the Pc5 FLRs that dominate at these latitudes. The next panels show coherence as a function of latitude, relative to the reference station (SOR, 67.3° N). The error bars represent the 90% confidence interval for upper and lower limits of coherence of 0.65 and 0 and the curves represent a 2nd order polynomial curve of best fit to the plot. Coherence length is estimated relative to a threshold of 0.65 following *Olson and Szuberla* [1997]. With 13 degrees of freedom this threshold marks the lowest limit of coherence for which we could distinguish the signal from noise (coherence=0) with 90% confidence. Uncertainties in coherence length were determined from a polynomial fit of the upper and lower limits of each point. For both H and D components the meridional coherence length for the event shown here is therefore $(1.4 \pm 0.7) \times 10^3$ km. The final panels in this group show the variation in phase with latitude relative to the reference station. Confidence limits for the phase values were calculated from an equation given in *Jenkins and Watts* [1969] but these uncertainties were generally smaller than the timing errors, represented by the error bars. No phase values are shown where the coherence is <0.6.

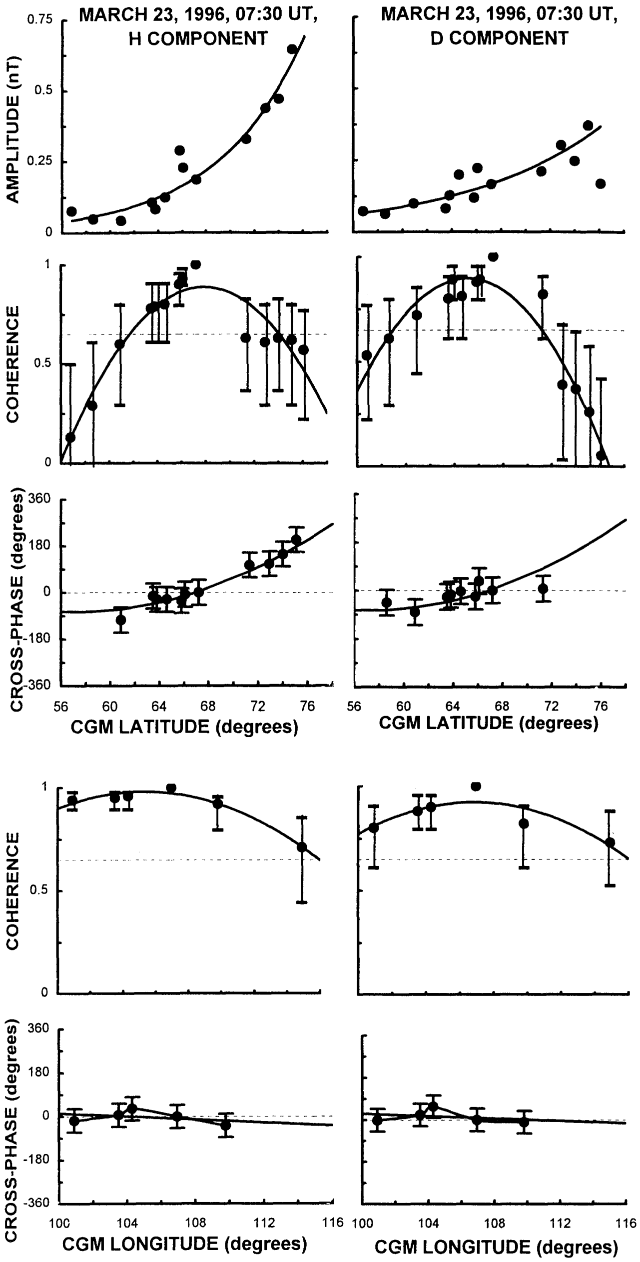

Figure 3. Amplitude, coherence and phase profiles as a function of latitude and longitude for the H and D components (left and right hand panels respectively) for the March 23 event.

The observed phase delays, if mapped to the equatorial plane of the magnetosphere using a dipolar magnetic field model, relate to an equivalent poleward speed of $\sim 0.8\times10^3$ km.s^{-1}. The curve in both of the third panels represents the phase values determined using an approximation of an incoming fast mode wave propagating through a dipole field with speed 2.0×10^3 km.s^{-1}.

Signatures of Pc5 FLRs are clearly seen in the dynamic cross-phase spectra (not shown) $\leq 75°$ magnetic latitude. The open/closed field line boundary is thus $> 75°$ at this time.

The lower pairs of panels in fig.3 show the azimuthal variation in signal coherence and cross-phase relative to MAS (106.9° longitude), with uncertainties estimated as above. Phase contributions due to the (small) latitudinal separation between stations have been taken into account. The coherence is high beyond the extent of the IMAGE array, ie. the azimuthal coherence length >700 km. The phase variation for the H component indicates azimuthal wave number m is -5 ± 4.

Table 1 summarizes results for all 11 events. The conventions adopted here are as follows. Positive ground and magnetospheric velocities denote propagation poleward and toward the Earth respectively. Positive m numbers represent westward propagation. The ground velocity directions are positive west of the north-south line. 'Calculated frequency' and 'empirical frequency' are determined from equations (1) and (2) respectively. The ranges shown for these frequencies are due to the variation in B_{IMF} during the interval, taking into account the propagation time from WIND to the magnetopause. All events were recorded under quiet magnetic activity conditions, with the average $K_p \sim 2-$.

Discussion

For several intervals amplitude decreased exponentially moving equatorward, but two intervals (Mar 6, 26) exhibited a localized peak in amplitude and phase change characteristic of FLRs [*Ziesolleck et al.*, 1997]. We believe these two intervals are possible FLR harmonics. Amplitudes for some of the lower frequency Pc4 events started to increase again at the lowest latitude stations, which we interpret as evidence of FLRs near the equatorward portion of the array. Amplitudes also decreased at the highest latitude stations, which we believe are near or on open field lines. *Odera et al.* [1991] found Pc3–4 amplitude increased linearly with increasing latitude, but had only one data point at > 68° dipole latitude.

All three intervals on March 5 exhibited low coherence (with respect to SOR) and anomalous phase at BJN (71.4° CGM), the only station between SOR at 67° and HOP at 73°. There is insufficient station coverage to explain the behaviour on this day. The average meridional and azimuthal coherence lengths for the remaining 8 intervals are $\sim 1 \times 10^3$ and >700 km respectively. These signals are clearly not of the type discussed by *Szuberla et al.* [1998], which were more impulsive in nature and less coherent over great distance. We observed many such impulsive signals, and several monochromatic Pc3–4 events with shorter coherence lengths, but excluded them from this study.

The frequencies of about half our Pc3 events fell within the range predicted by equations (1) and (2). These results suggest many high coherence Pc3 pulsations at high latitudes are due to upstream waves generated by a quasi-parallel shock structure and ion-cyclotron resonance. The propagation direction results derived from cross-phase profiles for latitude and longitude suggest these waves are propagating poleward. One possibility is that incoming fast mode waves drive forced field line oscillations in the magnetosphere. A

Table 1. Summary of results

Date 1996	Start time, UT	Freq., mHz (± 0.3)	Ground velocity		Wave number m	Coherence length, $\times 10^3$ km	M'Spheric speed, $\times 10^3$ km/s (error)	Calculated frequency mHz	Empirical frequency mHz
			Speed ($\times 10^1$ km/s)	Dir'n (degrees)					
Mar. 2	10:30	16.6	1.8 ± 0.3	20 ± 3	4 ± 2	1.5 ± 0.6	0.2 (3%)	14 – 25	12 – 17
Mar. 2	11:00	16.6	1.7 ± 0.5	19 ± 2	4 ± 2	1.3 ± 0.9	0.4 (7%)	13 – 24	12 – 16
Mar. 4	07:15	41.6	1.3 ± 0.2	-77 ± 6	–	1.1 ± 0.4	0.3 (12%)	40 – 60	36 – 44
Mar. 5	04:30	26.6	2.8 ± 0.6	-16 ± 2	0 ± 3	0.6 ± 1.1	0.2 (5%)	3.1 – 7.5	9.5 – 14
Mar. 5	06:30	25.8	-3.0 ± 0.3	-32 ± 30	-7 ± 3	0.6 ± 1.2	-1.9 (43%)	7.9 – 13	12 – 16
Mar. 5	11:45	22.7	0.5 ± 1.2	-76 ± 3	–	0.6 ± 1.1	0.3 (61%)	11 – 34	13 – 23
Mar. 6	08:00	34.0	4.5 ± 0.5	-74 ± 27	-7 ± 4	0.8 ± 0.9	1.2 (44%)	34 – 53	28 – 36
Mar. 19	08:45	24.1	5.2 ± 1.6	30 ± 7	0 ± 3	1.1 ± 0.6	0.6 (8%)	11 – 26	14 – 20
Mar. 23	07:30	26.6	4.2 ± 1.2	-32 ± 5	-5 ± 4	1.4 ± 0.7	0.8 (9%)	11 – 24	13 – 20
Mar. 23	11:30	20.0	2.9 ± 1.0	-48 ± 1	-8 ± 2	0.5 ± 2.6	0.5 (6%)	28 – 38	23 – 27
Mar. 26	11:15	20.8	2.8 ± 0.1	18 ± 7	3 ± 2	1.8 ± 0.6	0.4 (4%)	–	–

field-guided wave will take longer to travel along an outer field line than it would along an inner field line including the distance in the equatorial plane between the field lines. This would result in an apparent poleward propagation of the waves observed on the ground. Alternatively, the waves may propagate direct to the ionosphere from the stagnation point in the equatorial plane on the magnetopause [eg. *Francis et al.*, 1959]. In this case it is not clear why the amplitude increases moving poleward.

Our study is limited by the 10-s sampling rate of the IMAGE stations and the large gaps between SOR (L=6.8), BJN (L=9.9) and HOP (L=11.8). While Earth induction effects due to the Arctic ocean and inland anomalies may affect the amplitude and phase of larger period (Pc5) pulsations (*Viljanen et al.*, 1995), we do not believe this affects the present results.

The events studied here are a subset of the observed Pc3–4 activity that is dominated by quasi-structured pulsations but also includes localized discrete packets of sinusoidal pulsations. We are presently performing a more extensive study including near-conjugate Antarctic data which will be reported in a future paper.

Acknowledgments. We thank Lasse Hakkinen at FMI for the supply of IMAGE data, and all those who maintain the array. This work was supported by the Australian Research Council, the University of Newcastle and the Cooperative Research Centre for Satellite Systems. FWM thanks the hospitality of the University of York during this project. We thank C.L Waters and P. Ponomarenko for helpful discussions.

References

Ables, S.T., B.J. Fraser, C.L. Waters, and D.A. Neudegg, Monitoring cusp/cleft topology using Pc5 ULF waves, *Geophys. Res. Lett., 25,* 1507, 1998.

Baker, K.B., M.J. Engebretson, A.S. Roger, and R.L. Arnoldy, The coherence length of band-limited Pc3 pulsations in the ionsphere, *Geophys. Res. Lett., 25,* 2357, 1998.

Engebretson, M.J., C.-I. Meng, R.L. Arnoldy, and L.J. Cahill, Jr., The role of the ionosphere in coupling upstream ULF wave power into the dayside magnetosphere, *J. Geophys. Res., 96,* 1527, 1991.

Francis, W.E., M.I. Green, and A.J. Dessler, Hyrdromagnetic propagation of sudden commencements of magnetic storms, *J. Geophys. Res., 64,* 1643, 1959.

Greenstadt, E.W. and J.V. Olson, Geomagnetic pulsation signals and hourly distribution of the IMF orientation, *J. Geophys. Res., 84,* 1493, 1979.

Jenkins, G.M. and D.G. Watts, *Spectral analysis and its applications*, Holden Day, San Fransisco, 1968.

Le, G. and C.T. Russell, Solar wind control of upstream wave frequency, *J. Geophys. Res., 101,* 2571, 1996.

Lühr, H., The IMAGE magnetometer network, *STEP Int., 4,* 4, 1994.

Matsuoka, H., K. Takahashi, S. Kokubun, K. Yumoto, T. Yamamoto, S.I. Solovyev, and E.F. Vershinin, Phase and amplitude structure of Pc3 magnetic pulsations as determined from multipoint observations, *J. Geophys. Res., 102,* 2391, 1997.

Odera, T.J., D. Van Swol, C.T. Russell, and C.A. Green, Pc 3,4 magnetic pulsations observed simultaneously in the magnetosphere and at multiple ground stations, *Geophys. Res. Lett., 18,* 1671, 1991.

Olson, J.V. and C.A.L Szuberla, A study of Pc 3 at cusp latitudes, *J. Geophys. Res., 102,* 11375, 1997.

Orr, D., Magnetospheric hydrodynamic waves: their eigenperiods, amplitudes and phase variations; a tutorial introduction, *J. Geophys., 55,* 76, 1984.

Plyasova-Bakounina, T.A., Y.V. Golikov, V.A. Troitskaya, and P.C. Hedgecock, Pulsations in the solar wind and on the ground, *Planet. Space Sci., 26,* 547, 1978.

Szuberla, C.A.L., J.V. Olson, M.J. Engebretson, B.J. Fraser, and S. Ables, Interstation Pc3 coherence at cusp latitudes, *Geophys. Res. Lett., 25,* 2381, 1998.

Takahashi, K., R.L. McPherron, and T. Terasawa, Dependence of the spectrum of Pc 3–4 pulsations on the interplanetary magnetic field, *J. Geophys. Res., 89,* 2770, 1984.

Tonegawa, Y. and H. Fukunishi, Harmonic structure of Pc 3–5 magnetic pulsations observed at the Syowa-Husafell conjugate pair, *J. Geophys. Res., 89,* 6737, 1984.

Viljanen, A., K. Kauristie, and K. Pajunpää, On induction effects at EISCAT and IMAGE magnetometer stations, *Geophys. J. Int., 121,* 893, 1995.

Waters, C.L., J.C. Samson, and E.F. Donovan, Temporal variation of the frequency of high latitude field line resonances, *J. Geophys. Res., 100,* 7987, 1995.

Ziesolleck, C.W.S., D.R. McDiarmid, and Q. Feng, A comparison between Pc 3–4 pulsations observed by GOES 7 and the CANOPUS magnetometer array, *J. Geophys. Res., 102,* 4893, 1997.

T.A. Howard and F.W. Menk, Physics Department and Cooperative Research Centre for Satellite Systems, University of Newcastle, University Drive, Callaghan, NSW, 2308, Australia.

(Received: July 5, 2000; Revised: September 25, 2000; Accepted: October 12, 2000)