Pi2 pulsations: field line resonances or a driven response?

I. J. Rae, I. R. Mann, D. K. Milling, Z. C. Dent, and A. Kale

Abstract: We present an interval on 7^{th} March 2004 whereby clear quasi-periodic Pi2 pulsations are observed following the onset of an isolated magnetospheric substorm. During this interval, we succesfully employ cross-phase analysis techniques to recreate discrete points along the Alfvén continuum for the first time following the substorm expansion phase onset. Using the complex demodulation analysis technique, we study the latitudinal and longitudinal properties of the Pi2 pulsations in terms of amplitude, phase, ellipticity and polarisation and demonstrate that the Pi2 pulsations have the characteristics of a driven field line resonance. These results allow us to answer a long-standing question in substorm physics; whether the frequency of the high-latitude Pi2 pulsation results from a directly-driven response to a magnetotail driver, or from the properties of the magnetospheric field lines. We find that, at least in this event study, that the Pi2 structure is most likely determined from inherent frequencies of the nightside magnetosphere including the natural frequencies of the standing Alfvén waves, specifically resulting in a monochromatic field line resonance (FLR), rather than any variation in the temporal dynamics of the magnetotail driver.

Key words: ULF waves, Field Line Resonance, Pi2, substorm.

1. Introduction

Ultra Low Frequency (ULF) wave activity has been associated with the auroral substorm for nearly 40 years [1]. More specifically, the time of substorm onset has been shown to be concurrent with the excitation of impulsive pulsations in the Pi2 (40-200s or 6-25 mHz) frequency range [7]. The origin of Pi2s is thought to be disturbances in the near-Earth plasma sheet, resulting in the generation of field aligned currents in the substorm current wedge. The field–aligned currents are carried by the transient, transverse Alfvén wave generated during substorm onset. If there is an impedance mismatch between the incident Alfvén wave and the ionosphere, then the wave may be partially reflected. The Alfvén wave can thus bounce between the Central Plasma Sheet (CPS) and ionosphere, giving rise to the decaying periodic Pi2 waveform [3, 13]. In ground-based magnetograms, this creates the well–known observation of Pi2 pulsations "riding on" the magnetic bays associated with the substorm current wedge (SCW).

In addition to the auroral zone Pi2 pulsations related to establishing the substorm current wedge, Pi2 pulsations may also be observed over a wider range of latitude and longitude away from the onset region. A range of authors have proposed that CPS disturbances at substorm onset may excite compressional fast mode waves. These fast mode waves may impact the plasmasphere, generating compressional plasmaspheric cavity mode Pi2 signatures [15], or propagate towards the flanks where they may excite a field line resonant Pi2 signature. In some cases, substorm onset has been linked to the Earthward propagation of Bursty Bulk Flows (BBFs) [2]. Braking of these BBFs may generate inertial field–aligned currents, which may also be established by Alfvén waves with a Pi2 signature, in addition to possibly directly-driving Pi2 waveforms identical to the flow burst structure within the BBF [8, 9, 10]. An extensive review of Pi2 pulsations is provided in [13] and references therein.

Presumably the frequency content of bursts of Pi2 pulsations is governed by either the natural frequencies within the near-Earth CPS, or by the frequency content of the CPS disturbances at substorm onset, or in fact a combination of the two. It is often suggested that the dominant periodicity in a Pi2 packet is determined by the bounce time of the Alfvén waves as they propagate along the magnetic field and set up the field aligned currents in the substorm current wedge. Indeed, studies of the Pi2 polarisation ellipse [11] have shown that the upward and downward field aligned current elements of the SCW can be determined from the properties of Pi2s. In this model, the Pi2 periodicity should be determined either by the bounce time (there and back) between the ionosphere and the CPS or between conjugate ionospheres.

In this study we identify and analyse clear quasi-periodic frequencies in the Pi2 frequency band associated with substorm onset on 7th March 2004. Through the application of the cross-phase technique [16], we are able, for the first time, to identify a snapshot of part of the structure of the Alfvén continuum in the nightside magnetosphere for a short period of time following expansion phase onset. By comparing the properties of the wave with the structure of the continuum, we examine the hypothesis that the Pi2 pulsations observed on this day were a field line resonant enhancement within the Alfvén continuum.

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2. Instrumentation

In this paper we utilise the Canadian Array for Realtime Investigations of Magnetic Activity (CARISMA) magnetometer network, formerly the Canadian Auroral Network for the OPEN Program Unified Study [14] – CANOPUS. In its present incarnation, the CARISMA magnetometer array is able to re-

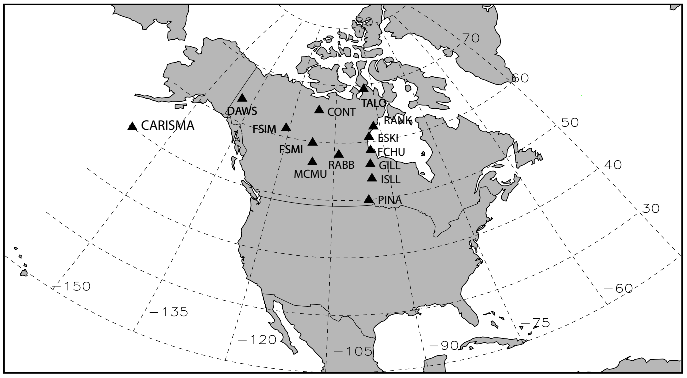

Fig. 1. The locations of the magnetometers comprising the current CARISMA magnetometer array. The overlaid grid shows contours of geographic latitude and longitude.

Site Code	Site	CGM Lat. (°N)	CGM Lon. (°E)	L value
TAL	Taloyoak	78.54	330.01	NA
CON	Contwoyto	72.97	303.87	11.84
RAN	Rankin Inlet	72.47	335.36	11.20
ESK	Eskimo Point	70.78	332.51	9.37
FCH	Fort Churchill	68.57	332.92	7.61
FSM	Fort Smith	67.45	306.16	6.90
FSI	Fort Simpson	67.33	293.50	6.84
RAB	Rabbit Lake	67.05	318.42	6.68
GIL	Gillam	66.28	332.46	6.27
DAW	Dawson	65.92	273.16	6.10
MCM	Fort Mcmurray	64.31	308.52	5.40
ISL	Island Lake	63.86	332.80	5.23
PIN	Pinawa	60.19	331.20	4.11

Table 1. Locations of the CARISMA magentometers used during this study. Dipole-L and CGM latitudes and longitudes are calculated using the NSSDC MODELWeb facility (http://nssdc.gsfc.nasa.gov/space/cgm/cgm.html).

solve both latitudinal and longitudinal current structures associated with a substorm when in the correct local time sector; with the forthcoming upgrade and deployment of 15 further fluxgate magnetometers, CARISMA will be able to measure these current systems in extended regions of latitude, longitude and local times, including to mid-latitude regions.

Figure 1 shows the location of the relevant magnetometer stations used in this study, and Table 1 lists their station ID, CGM (Corrected Geomagnetic) coordinates and dipole L-value. We concentrate on the latitudinal "Churchill line" magnetometers in this paper, though information is required on the azimuthal characteristics on the Pi2 pulsations, obtained from measurements along a line of approximately constant latitude.

3. Observations: 7^{th} March 2004

The CARISMA magnetometer database (http://www.ssdp.ca) was surveyed in order to find an interval which contained an isolated substorm within two hours of local midnight, and which contained quasi-periodic and clear Pi2 signatures in order to test the hypotheses outlined in Section 1. Figure 2 shows one such event and the corresponding (a) H- and (b) D-component magnetic field measurements between 0800-0900 UT on the 7^{th} March 2004. A clear substorm bay can be seen in both components around 0825 UT, maximising at the 66-68° latitudes (GIL-RAB-FSM-FSI), and having a local maxima at FSM where the substorm bay is -320 nT in the H- and -280nT in the D-component. Since the largest bays are located at FSM evidence this is a strong indication that FSM was close to the centre of the substorm current wedge [6]. Following this time, clear, quasi-periodic pulsations were observed, again clearest between 66-68°.

Figure 3 shows the filtered (20-200s) H- and D-component magnetometer data for the same interval, 0800-0900 UT on the 7^{th} March 2004. Large-amplitude Pi2 pulsations are observed between 0825-0900 UT, following substorm onset. The amplitudes maximise around 66-68°, and interestingly are maximised in the D-component (160 nT peak-to-peak) at FSM, but at RAB (96 nT peak-to-peak) in the H-component. The filtered wavetrain observed at GIL is surprisingly periodic. A Pi2 wavetrain following expansion phase onset is rarely monochromatic and the pulsations in both the H- and D-components at GIL are both remarkably quasi-periodic in the 0825-0900 UT interval.

Figure 4 shows the H- and D-component power spectra between 0800-0900 UT. Data were subjected to high-pass filtering at 300s and Hanning windowed. Clear in both H- and D-components are two discrete peaks in the power spectra: one between 5-6 mHz and one between 8-9 mHz. The 5-6 mHz peak tends to be prevalent in one particular meridian, that of the "Churchill Line", whereas the 8-9 mHz peak is pervasive over the entire dataset. We concentrate on the clear 8-9 mHz frequency peak prevalent at all latitudes and longitudes.

From top to bottom, Figure 5 shows complex demodulation [4] analysis of high-pass filtered (at 300s) H and D signals, as well as the amplitude and phase of the 8.8 mHz component, along with the ellipticity, and the polarisation angle of the wave for the 8.8 mHz demodulate from GIL. For a dominantly Alfvénic field line resonance, it has been shown that the perturbations in the magnetosphere are rotated through 90° upon transmission through a uniformly conducting ionosphere to the ground [5]. Therefore a toroidally (azimuthal magnetic field perturbation) polarised wave in the magnetosphere is expected to be dominated by the H-component when measured by a ground-based magnetometer. Evident from Figure 5 is that the 8.8 mHz component peaks shortly after substorm onset, that the phase of both the H- and D-components is approximately constant through the period of maximum amplitude, and the ellipticity is approximately zero, indicative of linear polarisation. These characteristics all suggest that the GIL station lies under the 8.8 mHz resonant field line.

Figure 6 shows the amplitude and phase characteristics of the 8.8 mHz component from complex demodulation of the "Churchill Line" magnetometers at 0828 UT; just after expansion phase onset. Immediately obvious is the amplitude maxima at GIL and the 180° phase change across the amplitude peak in the H-component, as well as a smaller amplitude peak and phase change in the D-component. These characteristics support the conclusion that the 8.8 mHz waves represent a driven field line resonance, the resonant field line lying close to GIL.

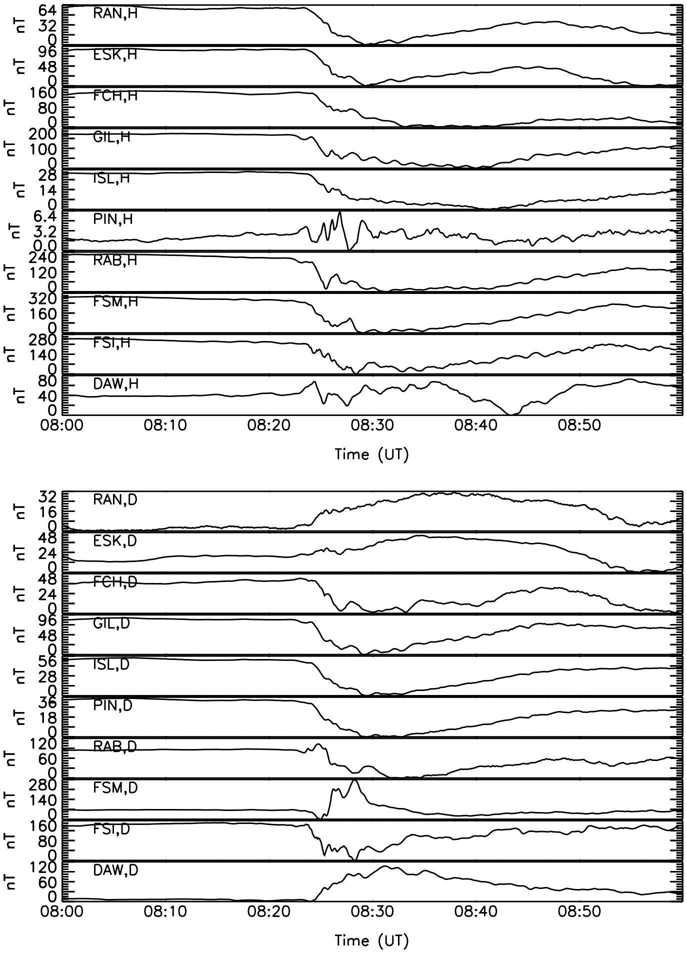

Fig. 2. The raw (a) H- and (b) D-component magnetograms from 0800-0900 UT from the 7^{th} March 2004.

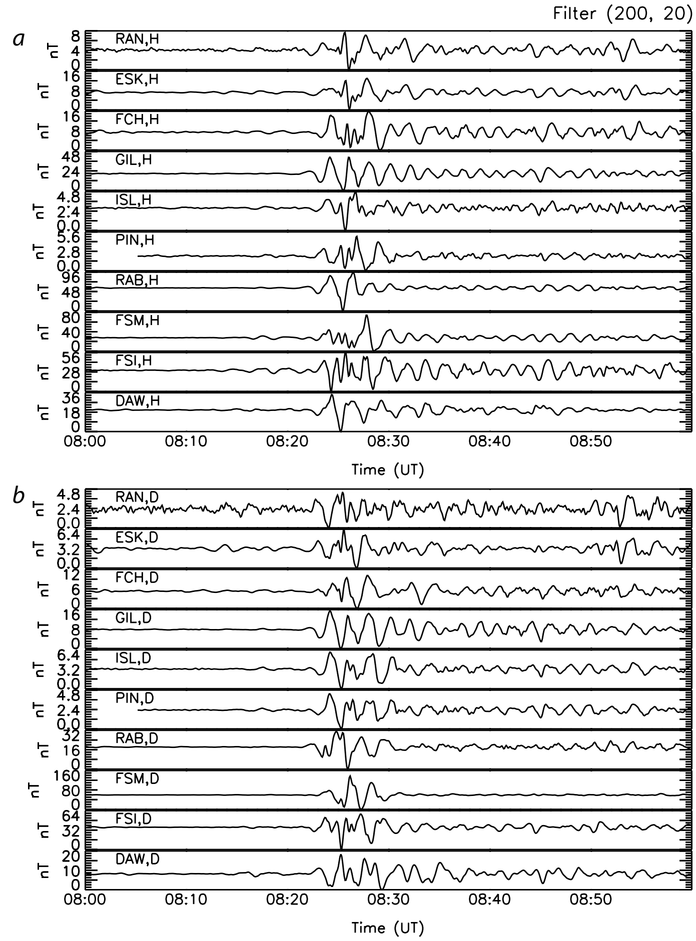

Fig. 3. Band-pass (20-200s) filtered (a) H- and (b) D-component magnetograms from 0800-0900 UT from the 7^{th} March 2004.

Figure 7 shows the variation in amplitude and phase of the 8.8 mHz component from complex demodulation as a function of longitude. The H-component amplitude peaks around RAB, but there is a D-component maxima at FSM. However, the H-component phase reveals the central location of the westward electrojet as being close to both the RAB and FSM stations, as the phase peaks at these stations, and decreases to both the east and west. This means that the phase propagation of the 8.8 mHz component is westward to the west of FSM and eastward of RAB, which is consistent with the entral location of the westward electrojet being located between RAB and FSM.

The ellipticity of the wave is the ratio of the minor axis to the major axis of the ellipse formed by the two wave components. The polarization angle is the azimuth of the ellipse measured positive clockwise from H. If the two components are the same size, the wave is circularly polarized and the ellipticity is unity. If the ellipticity is +(–) 1, then H (D) leads D (H) and the wave is clockwise (anticlockwise) polarized. Figure 8 shows the ellipticity and polarisation characteristics of the 8.8 mHz component magnetic field as a function of longitude. These characteristics are well–known for mid-latitude Pi2s (see [11] Figure 1), but are somewhat more complicated at high-latitudes (see [11] Figure 5). Mid-latitude Pi2s exhibit solely anti-clockwise polarisation, and the polarisation angle determines the location of the magnetometer within the SCW. Figure 8 shows broadly the same features as [11] Figure 1: zero polarisation between RAB-GIL (318-332°) indicating the central meridian between the upward and downward field-aligned current regions, anti-clockwise polarisation to the west of this meridian, but interestingly clockwise polarisation eastward of the GIL-RAB meridian (c.f.,[11] Figure 5). Future work will include a comparison between the mid-latitude ellipticities and polarisations of Pi2 signatures, and those at high latitudes.

The cross-phase technique [16] allows the determination of the fundamental resonant toroidal eigenfrequency of a field line that lies at the mid-point of two latitudinally separated magentometers. It is generally assumed that this technique does not work in the nightside magnetosphere/ionosphere perhaps due to the lack of ionospheric conductivity. Figure 9 shows the cross-phase between the ISL:PIN magnetometers for the entire day of the 7^{th} March 2004 as a function of frequency. From Figure 9, it can be seen that there is a clear 8-9 mHz negative cross-phase peak between 0800-0930 UT, confirming that the eigenfrequency of the field lines increases with decreasing L (the peak is negative as the ISL:PIN magnetometer pair shown is poleward:equatorward respectively).

Figure 10 shows the fundamental toroidal mode eigenfrequency as a function of latitude for the interval 0825-0900 UT

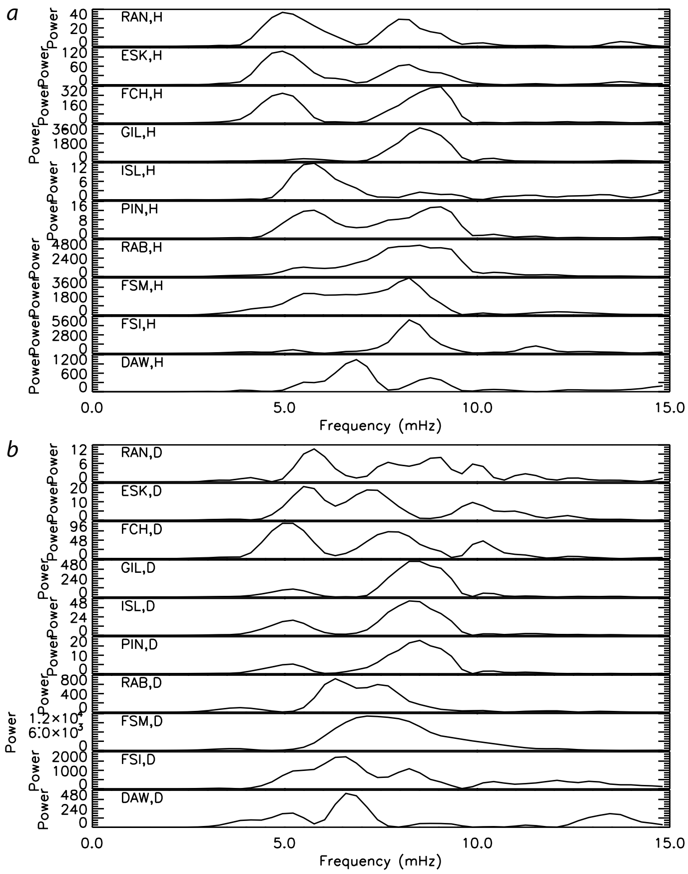

Fig. 4. High-pass (at 200s) filtered power spectra of the (a) H- and (b) D-component magnetograms from 0800-0900 UT from the 7^{th} March 2004. The power scale is in arbitrary units.

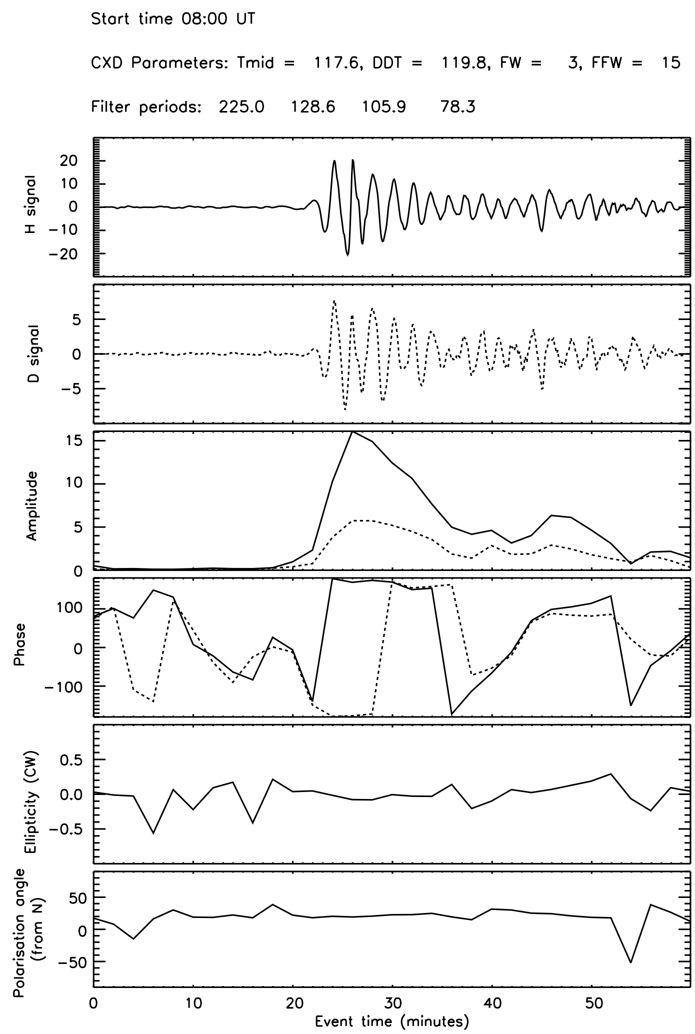

Fig. 5. Complex Demodulation[4] results of the 8.8 mHz frequency peak at GIL. From top to bottom Figure 5 shows the H and D amplitudes (high-pass filtered at 200s), the amplitude and phase of the 8.8mHz component of the signals, and the ellipticity and polarisation of the magnetic perturbations.

for the magnetometer pairs that could be extracted from the data. The bore sites are marked by arrows, and the discrete 8.8 mHz frequency peak is marked by the dashed line. Remarkably, the 8.8 mHz resonant peak observed at GIL lies within errors close to the resonant local toroidal field line eignefrequency as obtained from the cross-phase technique. This is indeed strong evidence that frequency of the 8.8 mHz observed frequency Pi2 perturbations is clearly determined by the nightside field line geometry.

4. Discussion and Conclusions

As seen clearly in Figures 2 and 3, the isolated substorm on this day is, as expected, clearly associated with the onset of a burst of Pi2 pulsation activity. Data, for example GIL, shows the classic substorm response of a Pi2 wavetrain "riding on" the substorm bay. The largest amplitude Pi2 response is seen on the latitudes of 66-68°. Interestingly, at these latitudes the Pi2 is extremely monochromatic; at other latitudes, the Pi2 waveform appears to be more broad-band and irregular, in keeping with the Pi2 classification. Of the pulsation classifications introduced by [7], only the Pi2 category has become synonymous with a single physical process. Even though the wavepacket observed, for example, at GIL, cannot be described as irregular, we continue to label the waves observed

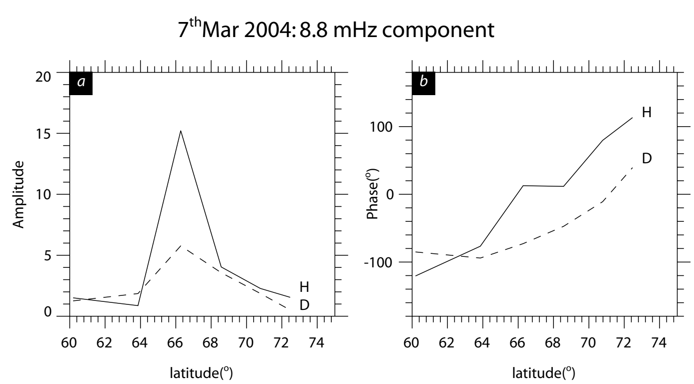

Fig. 6. Complex Demodulation of the latitudinal variation of the 8.8mHz H- and D-component (a) amplitude peaks and (b) relative phase at 0828 UT on the 7^{th} March 2004.

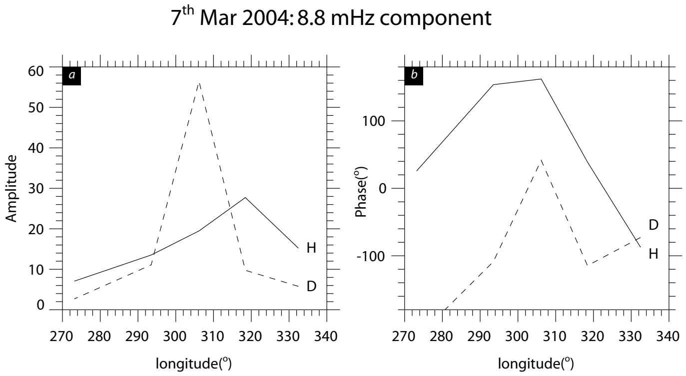

Fig. 7. Complex Demodulation of the longitudinal variation of the 8.8mHz H- and D-component (a) amplitude peaks and (b) relative phase at 0828 UT on the 7^{th} March 2004.

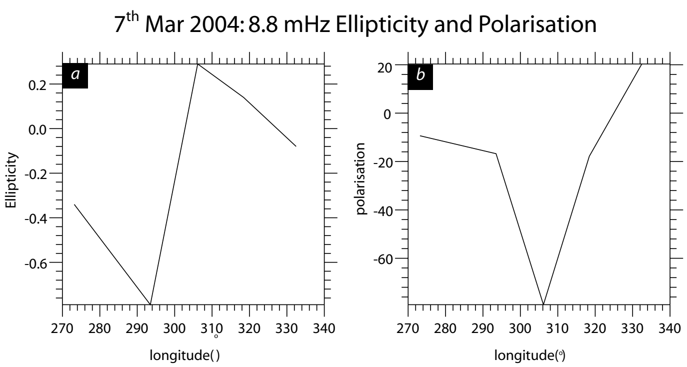

Fig. 8. Ellipticity and Polarisation characteristics of the 8.8mHz H- and D-component magnetograms on the 7^{th} March 2004.

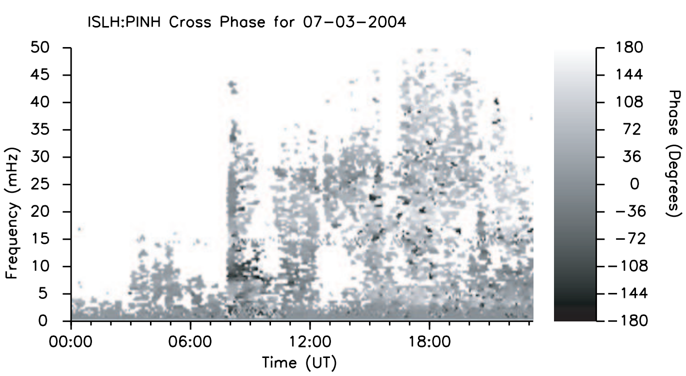

Fig. 9. Cross-phase results from the ISL and PIN H-component magnetometer data for the period 0-24 UT on the 7^{th} March 2004.

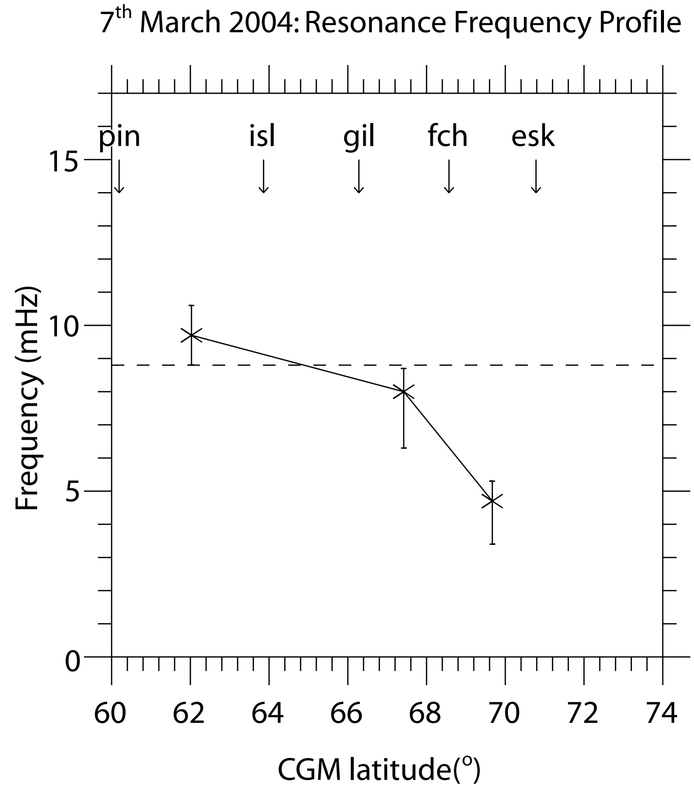

Fig. 10. Resonance Frequency Profile for the interval 0825-0900 UT for the available magnetometer pairs (the boresites of which are denoted by the vertical arrows) derived from the cross-phase technique (see text for details).

during this event as Pi2s because of their global characteristics and their association with the onset of a substorm.

The monochromatic nature of this pulsation provides the opportunity to investigate the relationship between Pi2 periodicity and the Alfvén continuum. Figure 6 shows clearly that the dominant Pi2 pulsation power has the characteristics of a toroidal mode 8.8 mHz FLR. The amplitude peaks at latitudes where the Pi2 is most monochromatic, consistent with a bouncing Alfvén wave source generating a field–aligned current around 66-68° CGM. The wave polarisation characteristics at GIL (Figure 5) demonstrate linear polarisation, also consistent with an FLR at this latitude. Most significantly, Figures 9 and 10 demonstrate that the cross-phase technique can work for a limited period of time following substorm onset. Usually cross-phase does not work on the nightside, which is usually attributed to rapid and perhaps critical damping by the nightside ionosphere. However, perhaps as a result of additional ionospheric conductivity arising from auroral precipitation following substorm onset, sufficient coherency enabled three pairs of stations to be used to recreate three discrete points along the Alfvén continuum. Remarkably, within the margins of error, these results showed that the 8.8 mHz frequency would be expected to resonate around the latitude of Gillam, at exactly the same location as the observed maximum. This demonstrates very clearly, at least for this event, that the dominant Pi2 frequency is indeed determined by the bounce time of Alfvén waves. Moreover, this also points to the relevant bounce path of the Alfvén waves being between conjugate ionospheres. Given that these waves are excited by disturbances in the near-equatorial CPS, one might expect an antinodal velocity perturbation in the equatorial plane for these standing Alfvén waves. This is entirely consistent with the conclusions drawn from the cross-phase results.

The longitude dependence of the Pi2 amplitudes shown in Figure 7 appears to be approximately consistent with the longitude dependence of the bay amplitudes seen in Figure 2. Further analysis, and data from additional mid-latitude magnetometers, may allow a closer correspondence between the Pi2 waveforms and the magentic bays to be established. This will be considered in future publications. In conclusion, we believe that this is the first time that the cross-phase technique has been applied successfully to the determination of the Alfvén continuum in the nightside magnetosphere. In combination with the characteristics of the Pi2 waveforms, this has enabled us to show for the first time that the dominant element in the Pi2 pulsation response can be characterised as a field line resonant enhancement in the Alfvén continuum. This suggests that a significant contribution to determining Pi2 structure may come from a natural frequency resonant response of the nightside magnetosphere, including the subsequent excitation of a classical field line resonance, rather than being determined by driver periodicities such as the flow burst structure within BBFs.

Acknowledgements

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References

1. Akasofu, S.-I., Polar and Magnetospheric Substorms, D. Reidel, Norwell, Mass., 1968.
2. Angelopoulos, V., Baumjohann, W., Kennel C. F., Coroniti F. V., Kivelson M. G., Pellat R., Walker R. J., Lühr H.,and Paschmann G., Bursty bulk flows in the inner central plasma sheet, *Journal of Geophysical Research, 97*, 4027-4039, 1992.
3. Baumjohann, W. and Glaßmeier, K. H., The transient response mechanism and Pi2 pulsations at substorm onset—Review and outlook, *Planetary and Space Science, 32*, 1361-1370, 1984
4. Beamish, D., Hanson, H. W. and Webb, D. C., Complex demodulation applied to Pi2 geomagnetic pulsations. Geophysical Journal of the Royal Astronomical Society 58: 471-493, 1979.
5. Hughes, W. J., and Southwood, D. J., The screening of micropulsation signals by the atmosphere and ionosphere, *Journal of Geophysical Research, 81*, 3234, 1976.
6. Cramoysan, M., Bunting, R., and Orr, D., The use of a model current wedge in the determination of the position of substorm current systems, *Ann. Geophys., 13*, 583, 1995.
7. Jacobs, J. A., Kato, Y.,Matsushita, S. and Troitskaya, V. A. Classification of geomagnetic micropulsations, *Journal of Geophysical Research, 69*, 180, 1964.
8. Kepko, L. E., and Kivelson M. G., Generation of Pi2 pulsations by bursty bulk flows, *Journal of Geophysical Research, 104*, 25021, 1999.
9. Kepko, L. E., Kivelson M. G. and Yumoto K., Flow bursts, braking, and Pi2 pulsations,*Journal of Geophysical Research, 106*, 1903, 2001.
10. Kepko, L., Kivelson M. G. McPherron, R. L. and Spence, H. E., Relative timing of substorm onset phenomena,*Journal of Geophysical Research, 106*, doi: 10.1029/2003JA010285, 2004.
11. Lester, M., Hughes, W. J., and Singer, H. J., Polarisation patters pf Pi2 magnetic pulsations at the substorm current wedge, *Journal of Geophysical Research, 88*, 7958, 1983.
12. Lester, M., Hughes, W. J., and Singer, H. J., Longitudinal Structure in Pi2 Pulsations and the Substorm Current Wedge, *Journal of Geophysical Research, 89*, 5489, 1984.
13. Olsen, J., Pi2 pulsations and substorm onsets: A review, *Journal of Geophysical Research, 104*, 17499, 1999.
14. Rostoker, G., J. C. Samson, F. Creutzberg, T. J. Hughes, D. R. McDiarmid, A. G. McNamara, A. Vallance Jones, D. D. Wallis and L. L. Cogger, CANOPUS - A ground based instrument array for remote sensing the high latitude ionosphere during the ISTP/GGS program, Space Sci. Rev., 71, 743-760, 1995.
15. Takahashi, K. and Lee, D.-H. and Nosé, M., Anderson, R. R. and Hughes, W. J.,CRRES electric field study of the radial mode structure of Pi2 pulsations,*Journal of Geophysical Research, 106*, 108, doi: 10.1029/2002JA009761, 2003
16. Waters, C. L., F. W. Menk, and B. J. Fraser, The Resonance Structure of Low Latitude Pc3 Geomagnetic Pulsations, *Geophys. Res. Lett.*, 18, 2293, 1991.