POWER SPECTRAL AND POLARIZATION CHARACTERISTICS OF Pi 2 PULSATIONS AT HIGH LATITUDES

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Abstract: Latitudinal power spectra and polarization characteristics of Pi 2 pulsations in the vicinity of the auroral oval are investigated. It is confirmed that the polarization characteristics are dependent on the position of the auroral breakup and the westward traveling surge (WTS). Particularly, an emphasis is placed on the two latitudinal reversals in the sense of polarization *i.e.*, the ellipticity changes negative in the center region of WTS. The amplitude distribution of Pi 2 pulsations in latitude indicates that the maximum amplitude is located in the equatorward portion of the westward electrojet.

1. Introduction

Pi 2 pulsations are irregular fluctuations of the geomagnetic field with period mainly from 40 to 150 s (JACOBS *et al.*, 1964). JACOBS and SINNO (1960) pointed out that the maximum amplitude of Pt^{-} (pulsation trains associated with a negative bay) occurs in the vicinity of the auroral oval. In order to study the propagation characteristics of Pi 2 pulsations ROSTOKER (1967) made a multistation experiment with all stations lying in approximately geomagnetic latitude 56°N. It has been found that the polarization characteristics disagree with previous results that Pi 2 pulsations are polarized anticlockwise after local midnight and clockwise before local midnight. Using an array of magnetometers which are located along a line of approximately constant geomagnetic longitude, OLSON and ROSTOKER (1975, 1977) have investigated the power spectral characteristics of Pi 2 pulsations at high latitudes. Their results showed that the peak in Pi 2 energy is at the center of the substorm-enhanced electrojet. Unfortunately, they did not discriminate between Pi 2-band noise and Pi 2 pulsations. The selection of Pi 2 pulsations is a particular problem at high latitudes where there is substantial electrojet noise, which might be misinterpreted as a Pi 2 signal. A study by ROSTOKER and SAMSON (1981) designed to extract only the polarized component from the high latitude recordings. In order to ensure that the polarized pulsations are in fact Pi 2's, they were also compared with pulsations occurring at lower latitude stations. The maximum intensity of Pi 2 pulsation was at the southern borders of the substorm-enhanced westward and eastward electrojets, not at the center as indicated by the results of OLSON and ROSTOKER.

The Pi 2 pulsations have received much attention primarily because of their close relationship with substorm onsets (SAKURAI and SAITO, 1976). SAITO *et al.* (1976) proposed a model that Pi 2 pulsations are due to a transient torsional oscillation of the closed magnetic field lines in the plasma sheet excited by an earthward plasma flow. The satellite-ground observations of Pi 2 pulsations at synchronous orbit have been examined by SAKURAI and MCPHERRON (1983). They intended that a polarization reversal at satellite occurs around midnight during quiet magnetic conditions, left-handed pre-midnight and right-handed post-midnight. As mentioned previously, this result is not similar to that obtained from ground-based studies at stations equatorward of the auroral electrojet. LESTER *et al.* (1983) showed that there was no systematic variation in ellipticity with respect to the local time. This supports ROSTOKER's view for the polarization characteristics of Pi 2 pulsations at middle latitude. Much of the earlier work on the polarizations of ground-based Pi 2 pulsations, particularly high latitude Pi 2's, appears to lead to inconsistency and controversy. The purpose of the present study is to investigate the power spectra and the polarization characteristics of Pi 2 pulsations in the vicinity of the auroral oval, in order to confirm how the polarization of Pi 2 pulsations with respect to WTS changes and where the maximum amplitude of Pi 2 pulsations relative to auroral electrojets is located in latitude. In Section 2 three Pi 2 pulsations which occur in different positions with respect to WTS are selected. The power spectral estimates are given in Section 3. In Section 4 the degree of polarization and ellipticity are evaluated. The latitude profiles of auroral electrojet currents are constructed in Section 5. Finally the discussion and conclusion are given in Section 6.

2. Selection of Data

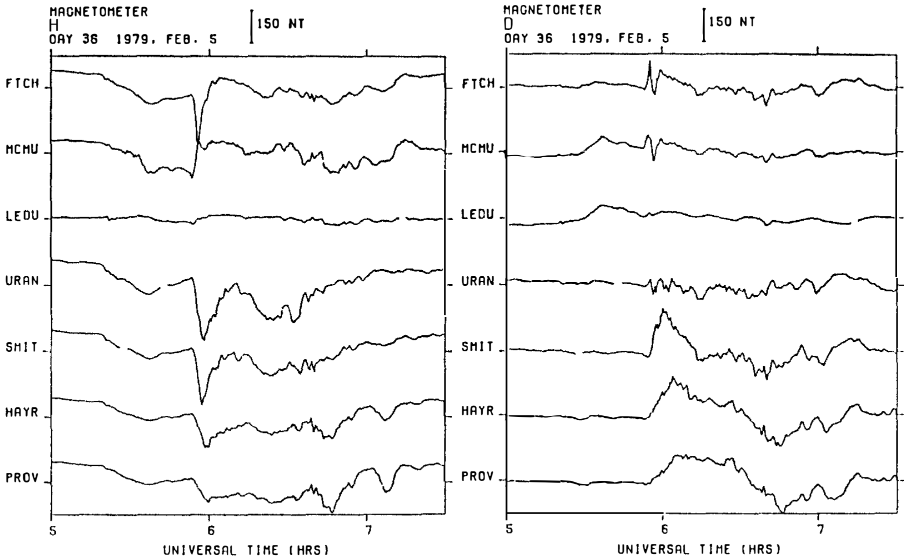
The geomagnetic coordinates and code names of the stations are given in Table 1. The Pi 2 pulsations were selected first by a visual inspection of the standard magnetograms from Newport. The Pi 2 pulsations at Newport are generally quasi-monochromatic in frequency and have a clearly well-defined spectral peak. SAMSON and OLSON (1980) have proposed the data adaptive polarization filter in order to extract the polarized signals from the random noise associated with the auroral electrojets. The application of this technique makes it possible to investigate the power spectral components and the polarization parameters of the Pi 2 pulsations at high latitudes.

Table 1. Geomagnetic coordinates and code names for stations whose data are used in this study.

Station	Code name	Geomagnetic Latitude (°N)	Geomagnetic Longitude (°E)
Fort Providence	PROV	67.5	292.0
Hay River	HAYR	67.3	294.3
Fort Smith	SMIT	67.3	299.7
Uranium City	URAN	67.4	304.3
Fort Chipewyan	FTCH	66.3	303.1
Fort McMurray	MCMU	64.2	303.5
Leduc	LEDU	60.6	302.9

(a) The western region of WTS; February 5, 1979: Day 36

The normal magnetograms from the Alberta array are shown in Fig. 1. The figure indicates that the first substorm began at 0520 UT by the indication of gradual decrease of *H*-component at all stations. The substorm intensification began at 0552



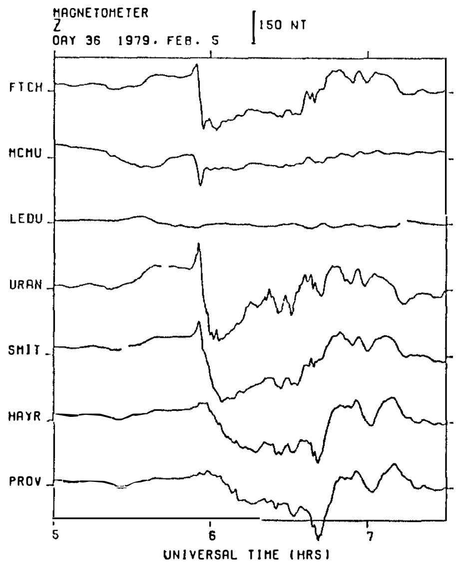


Fig. 1. Normal magnetograms for the H-, D- and Z-components at the Alberta array on day 36, 1979.

UT. From the positive change of D-component the initial substorm onset was started in the eastern region of our observational stations. The center of the auroral electrojet current is located somewhere between MCMU and FTCH by the indication of the opposite sign of Z-component. Figure 2 shows polarized pulsation signals in the frequency range after the application of the data adaptive polarization filter. It is clearly seen that there are three Pi 2 pulsation trains during the time interval presented. The first Pi 2 pulsations were observed coincidently with the first substorm onset of a negative change of H-component.

(b) The center region of WTS; February 9, 1979; Day 40

The normal magnetograms from the Alberta array are shown in Fig. 3. The first substorm was triggered at 0902 UT by the indication of the sudden decrease of H-component at all stations. Contrary to the previous event the D-component of all stations shows negative changes at the time of the initial substorm onset. This means that the downward FAC contributes to the negative changes of the D-component.

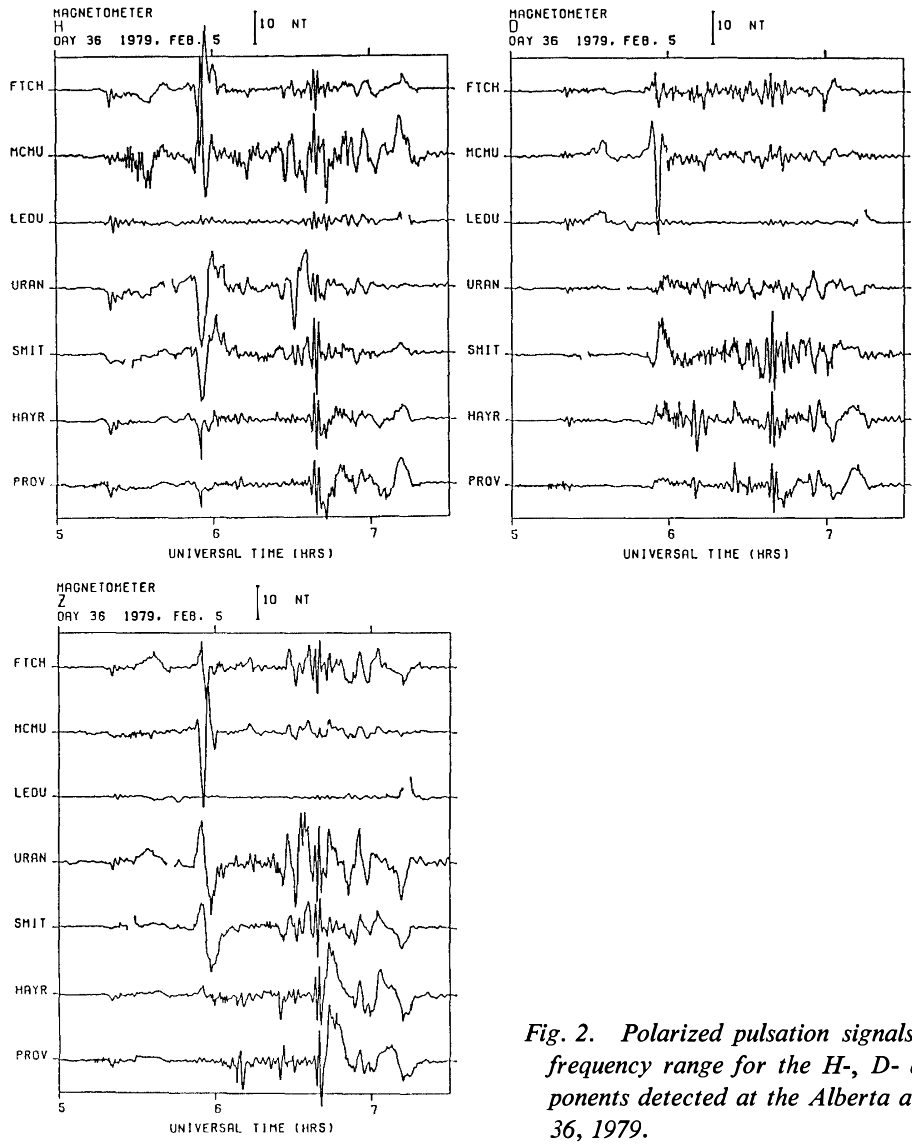


Fig. 2. Polarized pulsation signals in the Pi 2 frequency range for the H-, D- and Z-components detected at the Alberta array on day 36, 1979.

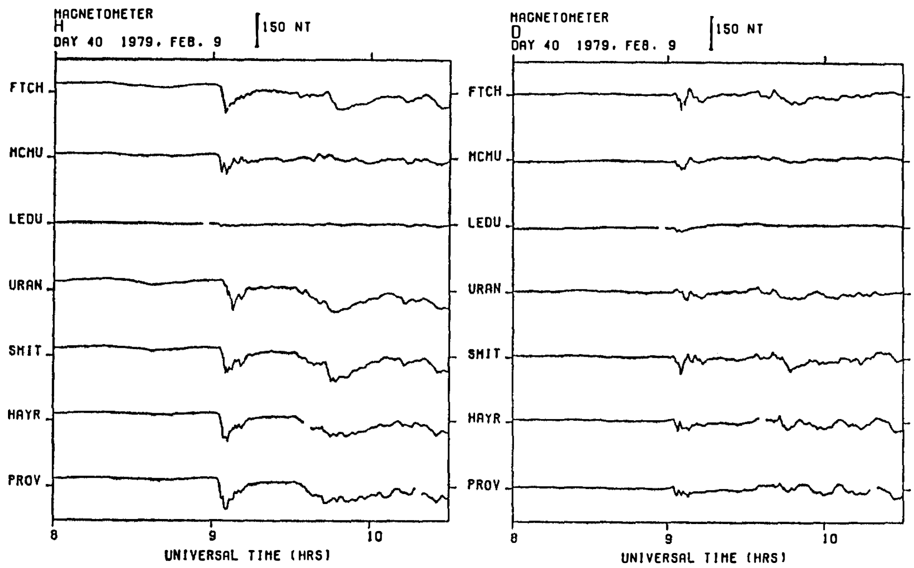
The westward electrojet current flows near MCMU. Figure 4 presents the data after the application of the data adaptive polarization filter. The first Pi 2 pulsations were observed at 0902 UT corresponding to the first substorm onset.

(c) The eastern region of WTS; June 29, 1979; Day 180

The normal magnetograms from the Alberta array are given in Fig. 5 which shows a very calm period. The sharp negative change of H-component cannot be seen in this interval, since auroral electrojet current flows far from the Alberta array. But it is recognizable that there are two decreases of H-component at 1050 and 1105 UT. Figure 6 shows the data after the application of the data adaptive polarization filter. Undoubtedly, there are clear two Pi 2 pulsations corresponding to two decreases of H-component in the normal magnetograms.

3. Power Spectral Estimates

In order to estimate the power spectrum of multiple geophysical time series (vector



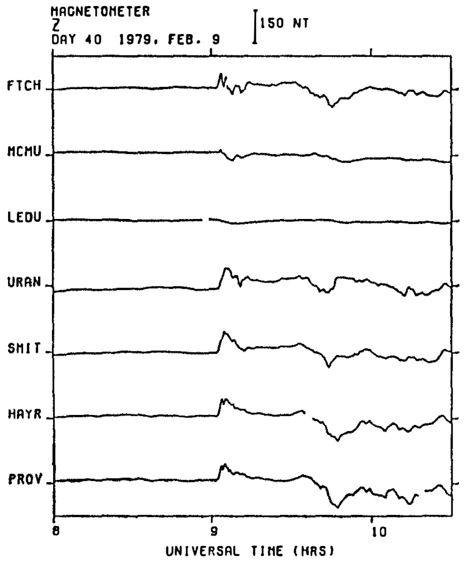


Fig. 3. Normal magnetograms for the H-, D- and Z-components at the Alberta array on day 40, 1979.

process) SAMSON (1983) has constructed the estimators of the spectral representations of pure states, which are based on a number of optimality criteria. The three estimators have been compared with each other, Bartlett-principal component estimator (BPC), minimum prediction error estimator (MPE), and minimum degree of polarization estimator (MDP). All the estimators can be written in the form;

$$a(j)v = S\underline{\mu}_1{}^+ N_E{}^{-1/2} \underline{z}(j) \underline{N}_E{}^{1/2} \underline{\mu}_1 \,, \qquad (1)$$

where μ_1 is the eigenvector of $\underline{N}_E{}^{-1/2}\underline{S}\,\underline{N}_E{}^{-1/2}$, $\underline{\mu}_1{}^+\underline{\mu}_1=1.0$, and $S=1.0$ for BPC, $S=(\lambda_1-\lambda_n)/\lambda_1$ for MPE, and $S=1-(\sum_{l=2}^{n}\lambda_1{}^2(\lambda_1\sum_{l=2}^{n}\lambda_1))^{1/2}$ for MDP, where the λ_j ($j=1$, n) are the eigenvectors for $\underline{N}_E{}^{-1/2}\underline{S}\,\underline{N}_E{}^{-1/2}$. The power spectra of the pure states can be determined from

$$P^2(j) = a^2(j)\underline{v}^+(j)v(j) = z^+(j)z(j) \,. \qquad (2)$$

In the application of the estimators to the Pi 2 pulsations the spectral window has

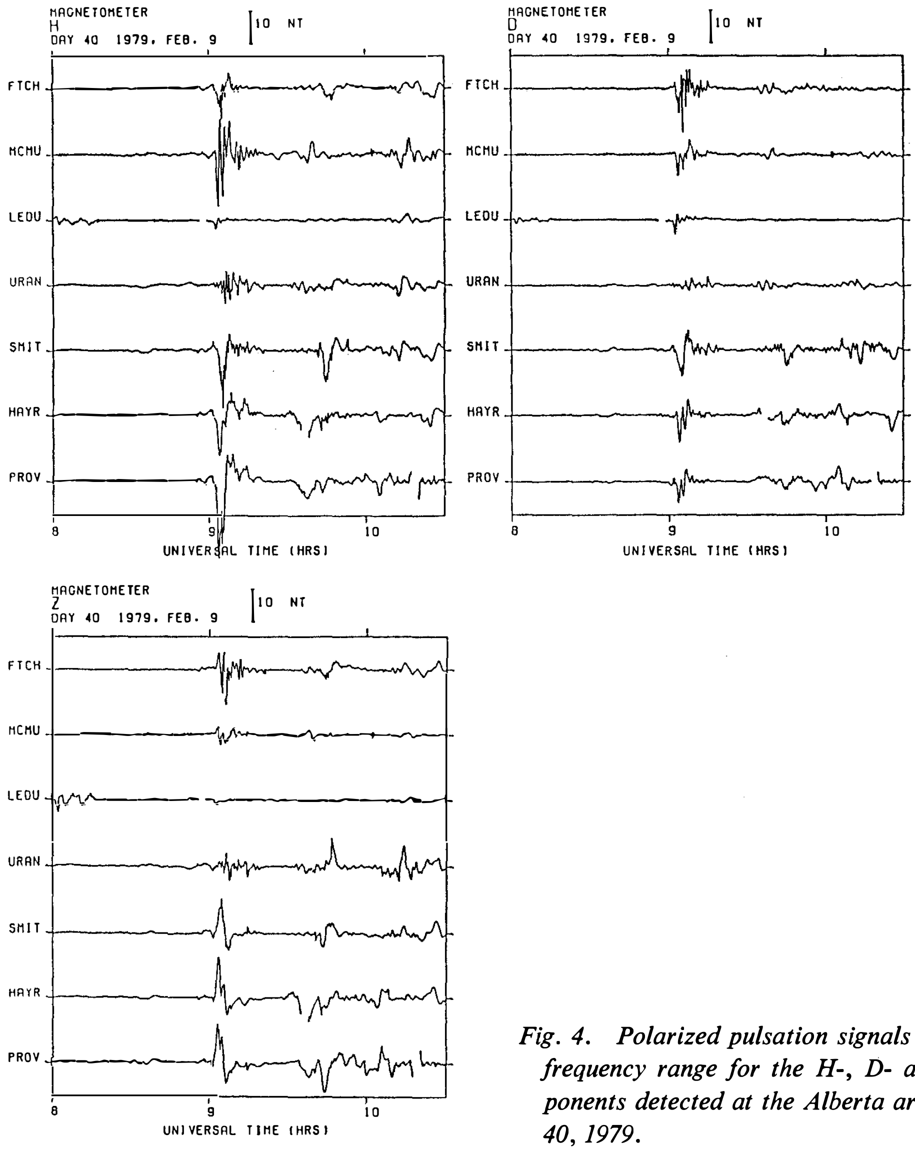


Fig. 4. Polarized pulsation signals in the Pi 2 frequency range for the H-, D- and Z-components detected at the Alberta array on day 40, 1979.

7 degrees of freedom. All the data were detrended with 5 mHz high pass filter before transforming to frequency domain. The pure state power spectra for day 36, February 5, 1979 observed in the western region of WTS are shown in Fig. 7. Note that this power is the sum of the pure state power in all three spatial directions *H*, *D*, and *Z*. The 8.3 mHz peak shows at all stations except MCMU. The 8.3 mHz pulsations for this event are identified as the Pi 2's. The other spectral peaks are considered to be due to pulsations from other sources. The pure state power spectra for day 40, February 9, 1979, are shown in Fig. 8. This example is Pi 2's observed in the center region of WTS. There are mainly four spectral peaks at LEDU, 5, 7.5, 10, and 14 mHz. But the spectral peak at 10 mHz predominates at lower latitude stations. Another interesting feature in these spectra is that three peaks predominate at HAYR and SMIT. The 3.3 mHz pulsations are clearest at HAYR. Since these 3.3 mHz pulsations have peak intensities at much higher latitudes than the Pi 2's, we infer that they

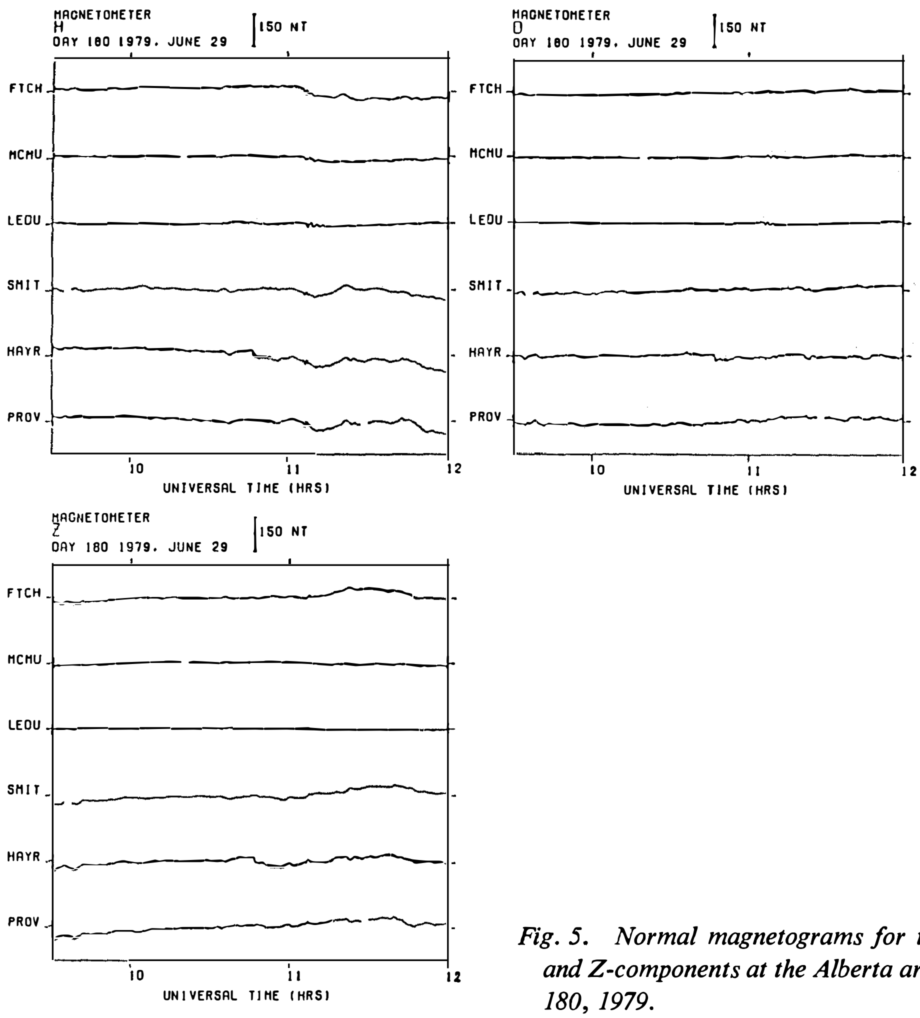
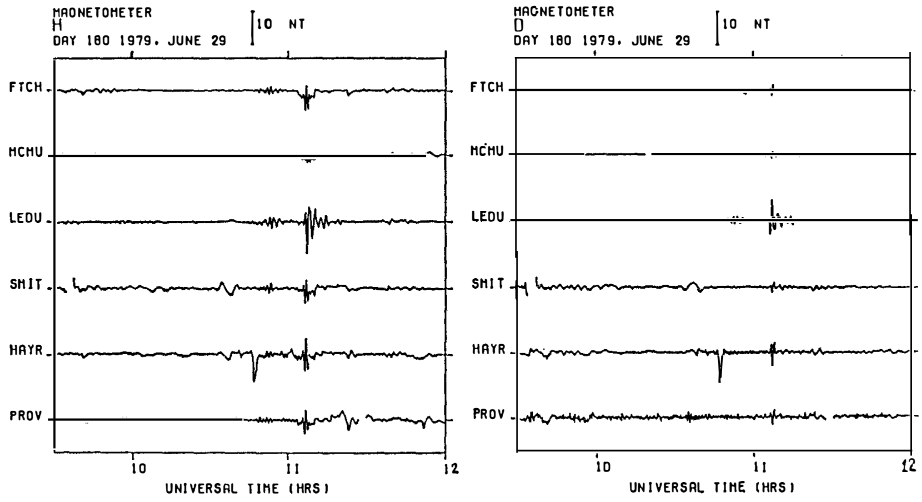


Fig. 5. Normal magnetograms for the H-, D- and Z-components at the Alberta array on day 180, 1979.

have a distinctly different source. Finally the pure state power spectra for day 180, June 29, 1979 are shown in Fig. 9. This is an example of Pi 2 pulsations observed in the eastern region of WTS. At LEDU there is a single peak with 7.5 mHz. But going to the high latitude stations they have several peaks in common. It is considered that the peaks except 7.5 mHz are due to the westward auroral electrojet. The three peaks, 7.5, 12, and 18 mHz at PROV are seen in the figure.

4. Ellipticity and Degree of Polarization

If U is the unitary matrix of eigenvectors, the U*SU can be expanded in terms of three uncorrelated stochastic process which are unpolarized, partially polarized and purely polarized. If $\lambda_1 \gg \lambda_2 \gg \lambda_3$ are the three eigenvalues, then the relative power in each process is given by $R_1=(\lambda_1-\lambda_2)/(\lambda_1+\lambda_2+\lambda_3)$ for purely polarized, $R_2=(\lambda_2-\lambda_3)/(\lambda_1+\lambda_2+\lambda_3)$ for partially polarized, and $R_3=3\lambda_3/(\lambda_1+\lambda_2+\lambda_3)$ for unpolarized. In addition, the three-dimensional degree of polarization β^2 which does not equal the percent polarization is expressed (SAMSON, 1973; OLSON and SAMSON, 1980; SAMSON and OLSON, 1981),



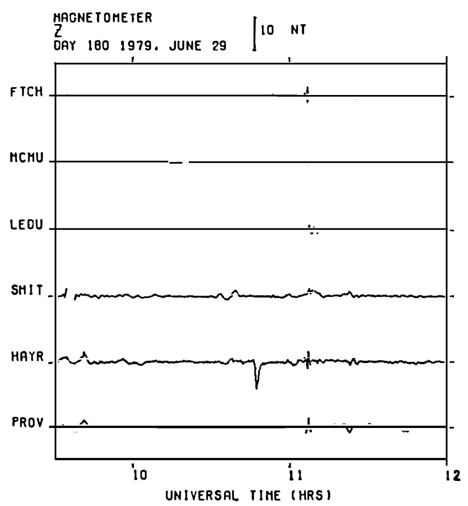


Fig. 6. Polarized pulsation signals in the Pi 2 frequency range for the H-, D- and Z-components detected at the Alberta array on day 180, 1979.

$$\beta^2 = \frac{3(TrS^2)-(TrS)^2}{2(TrS)^2} . \tag{3}$$

The estimates of the degree of polarization for the seven stations on day 36, February 5, 1979, are given in Fig. 10. At LEDU the spectrum is highly polarized near 10 mHz, which corresponds to the secondary peak of power spectrum. At all other stations except MCMU the Pi 2 power spectral peaks are accompanied by clear peaks in the degree of polarization. For the Pi 2 observed in the center region of WTS the estimates of the degree of polarization on day 40, February 9, 1979, are given in Fig. 11. Contrary to the previous event the spectrum at MCMU is highly polarized over the whole Pi 2 region near 7.5 mHz. Although the Pi 2 power spectral peaks are accompanied by broad peaks in β^2 at all other stations, the degree of polarization is not high. Finally, for the Pi 2 observed in the eastern region of WTS the estimates of the degree of polarization on day 180, June 29, 1979, are given in Fig. 12. Unfortunately, the clear Pi 2 power spectral peaks are not accompanied by broad peaks in β^2.

On day 36, February 5, 1979, the latitudinal logarithmic power of the three com-

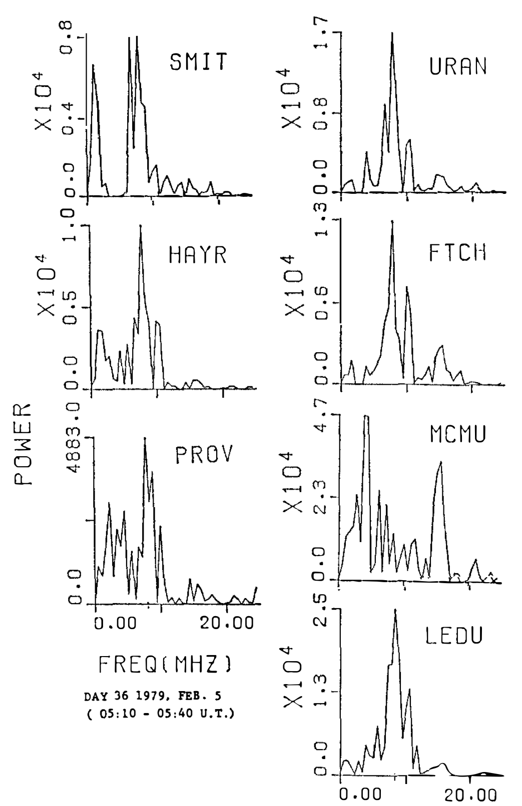


Fig. 7. Pure state total power spectra of the Pi 2 pulsations on day 36, 1979.

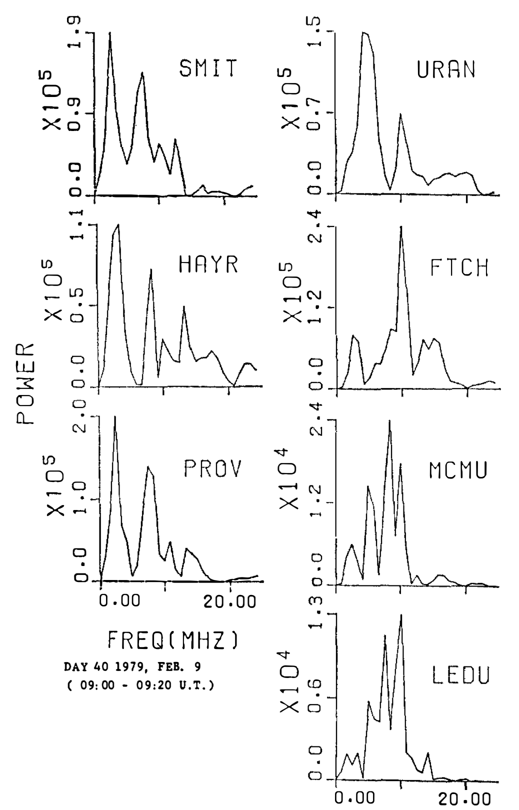


Fig. 8. Same as Fig. 7 but for day 40, 1979.

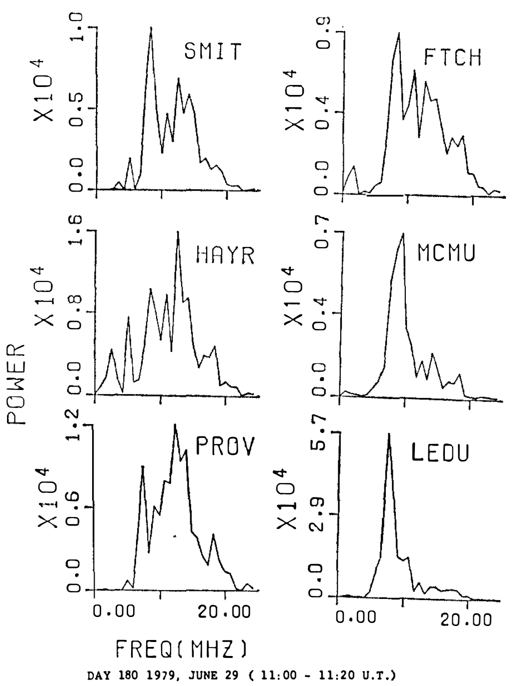


Fig. 9. Same as Fig. 7 but for day 180, 1979.

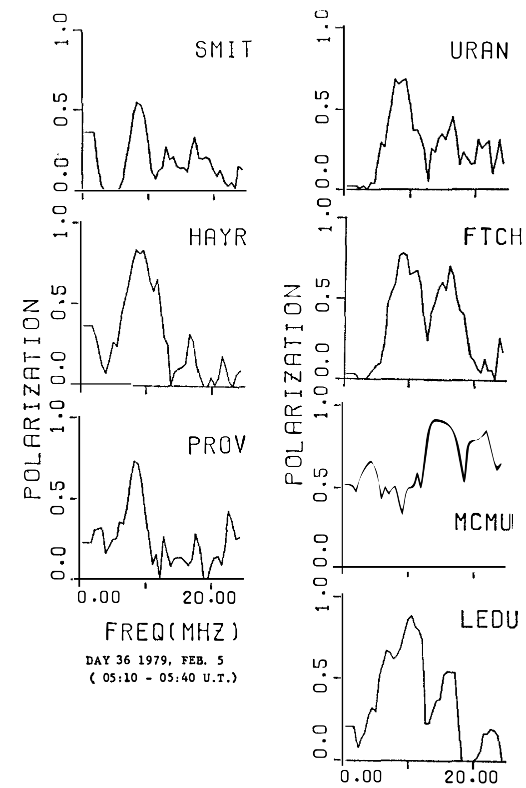


Fig. 10. Estimates of the degree of polarization for the Pi 2 pulsations on day 36, 1979.

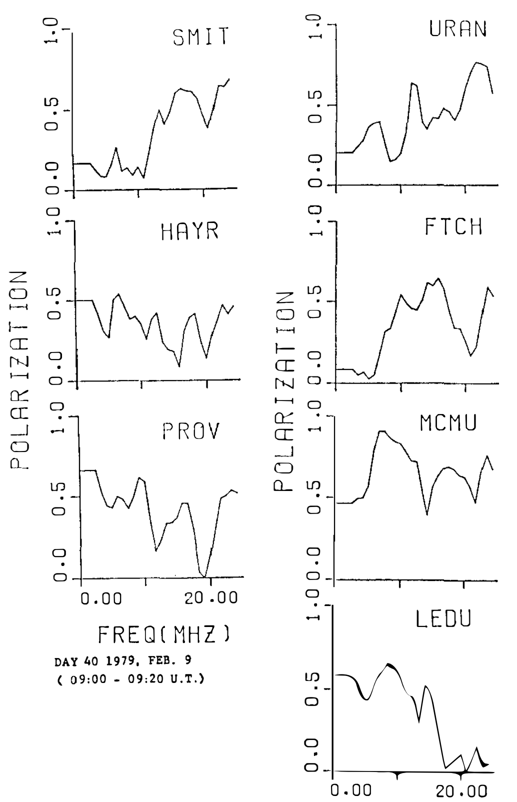


Fig. 11. Same as Fig. 10 but for day 40, 1979.

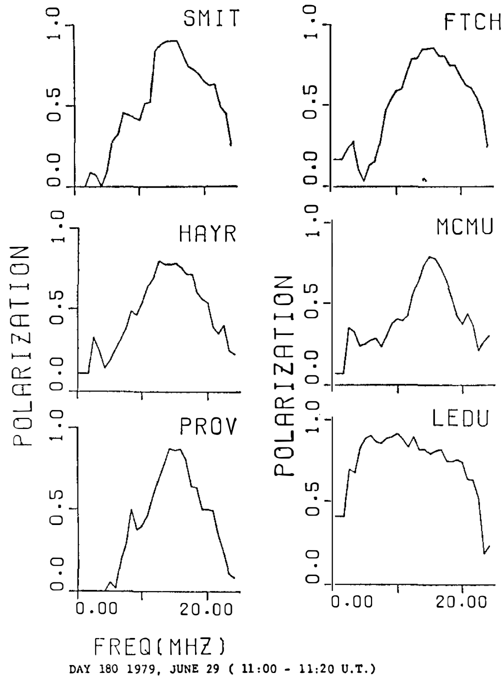


Fig. 12. Same as Fig. 10 but for day 180, 1979.

ponents of the magnetic field fluctuations corresponding to Pi 2 frequency band is illustrated in the upper panel of Fig. 13. The ellipticity and the orientation of major axis are shown in the lower panel of Fig. 13. The solid line and circles indicate the ellipticity. The ellipticity is the ratio of the minor to major axis of the polarization ellipse. The ellipticity is negative for CW polarization in H–D plane along the geomagnetic field line. The dashed line and open circles indicate the polarization angle (theta), which is measured clockwise from the magnetic north. From the lower panel of Fig. 13 there is a clear latitudinal change in the sense of polarization from CC at LEDU, to CW at the other high latitude three stations. On day 40, February 9, 1979 in Fig. 14, there are two latitudinal changes in the sense of polarization from CC at LEDU, to CW at MCMU, to linear polarization at FTCH, again to CC at URAN. The linear polarization at FTCH corresponds to the minimum in the H-component of logarithmic power at 7.5 mHz. The polarization angle (theta) changes from the positive to the negative near MCMU. On day 180, June 29, 1979 in Fig. 15, there is also a clear latitudinal change in the sense of polarization from CC at LEDU, to CW at the other high latitude stations. The minimum in the H-component near MCMU, is corresponding to the polarization changes and the changes of the orientation angle. The polarization to the south of the demarcation is CC and CW to the north. These results are consistent with those given by LANZEROTTI and MEDFORD (1984) at low latitude stations. The wave ellipticities are found to be CC independent of local time at the stations of the equatorward of the auroral electrojets. But they appear to contradict those of KUWASHIMA (1978).

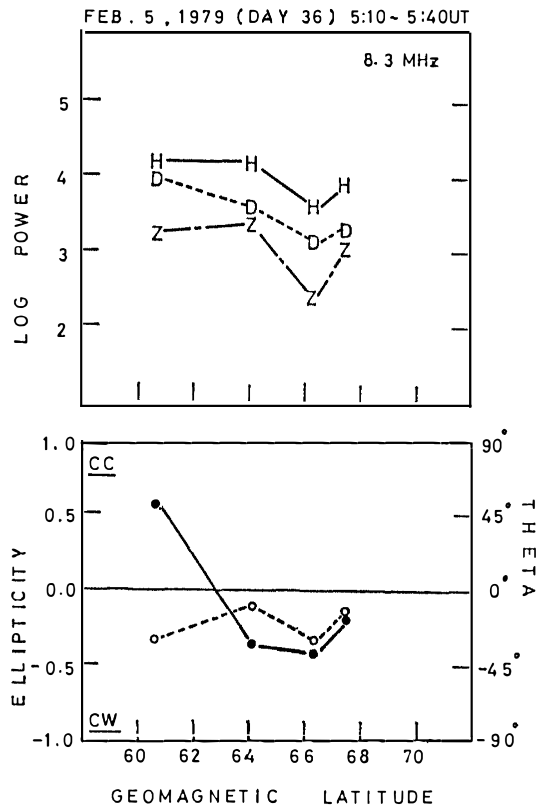


Fig. 13.

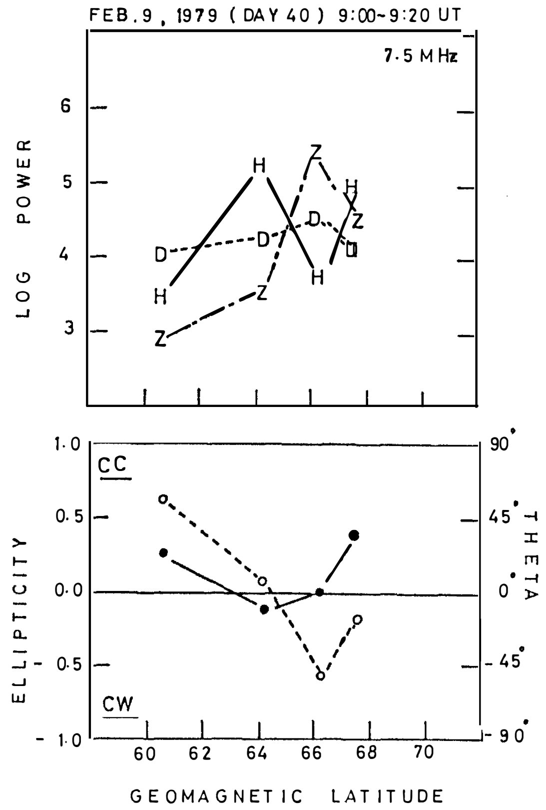


Fig. 14.

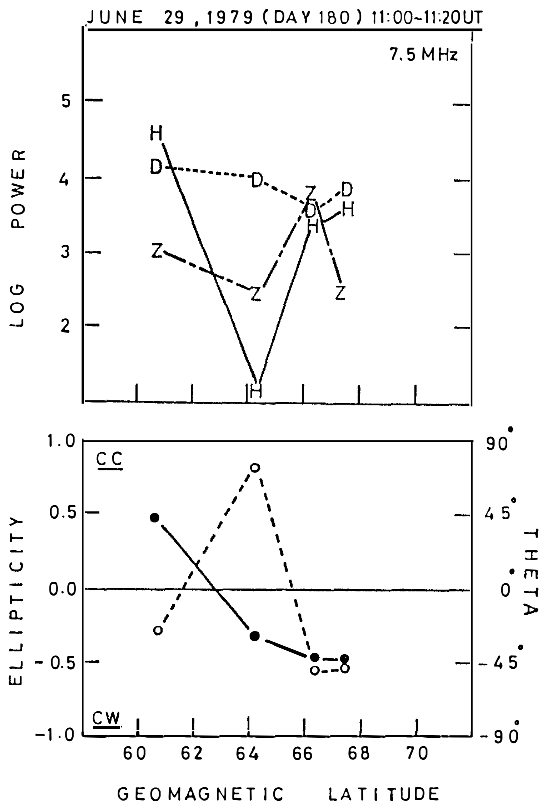


Fig. 15.

Fig. 13. Latitude profiles of the logarithmic power and the polarization parameters (H-D plane) of the 8.3 mHz Pi 2 pulsations in the interval 0510–0540 UT, day 36, 1979.

Fig. 14. Same as Fig. 13 but for the 7.5 mHz Pi 2 pulsations in the interval 0900–0920 UT, day 40, 1979.

Fig. 15. Same as Fig. 13 but for the 7.5 mHz Pi 2 pulsations in the interval 1100–1120 UT, day 180, 1979.

5. Latitude Profiles of Auroral Electrojet Current

In order to confirm the results obtained by ROSTOKER and SAMSON (1981) that the Pi 2 maximum amplitude relative to the auroral electrojet was located at the southern border of the eastward electrojet or at the southern border of the westward electrojet, the time sequential latitude profiles of the auroral electrojets are constructed.

(a) The center region of WTS; November 6, 1978; Day 310

The normal magnetograms are shown in Fig. 16, while the detrended data after application of the data adaptive polarization filters are shown in Fig. 17. Figure 18 shows the latitude profiles of auroral electrojet currents for the time interval during the event (ROSTOKER and SAMSON, 1980). From the latitude profiles of the auroral electrojet currents at 0750 UT and at 0755 UT it is evident that the westward electrojet was intensified with the equatorward border lying at 65–68°N in the Alberta sector. The maximum entropy spectra for three components of Pi 2 pulsations during the interval

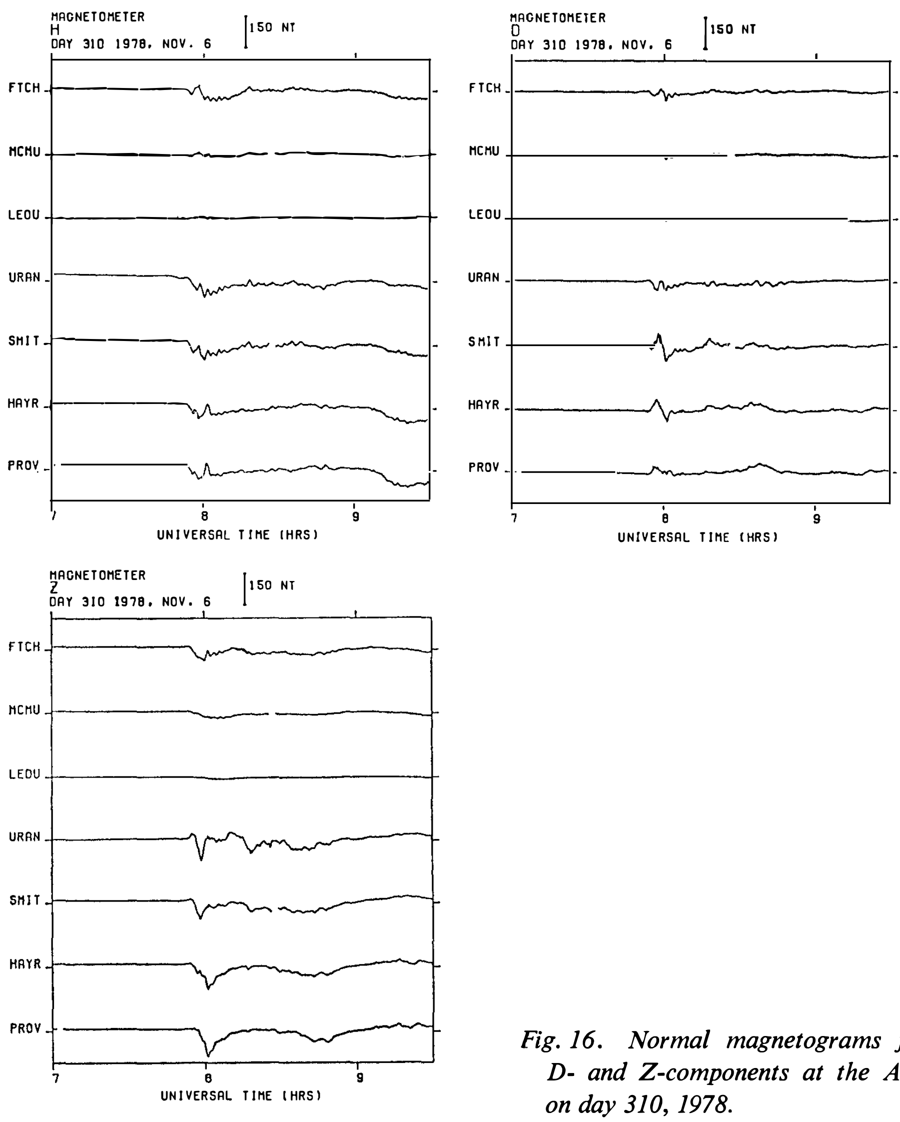


Fig. 16. Normal magnetograms for the H-, D- and Z-components at the Alberta array on day 310, 1978.

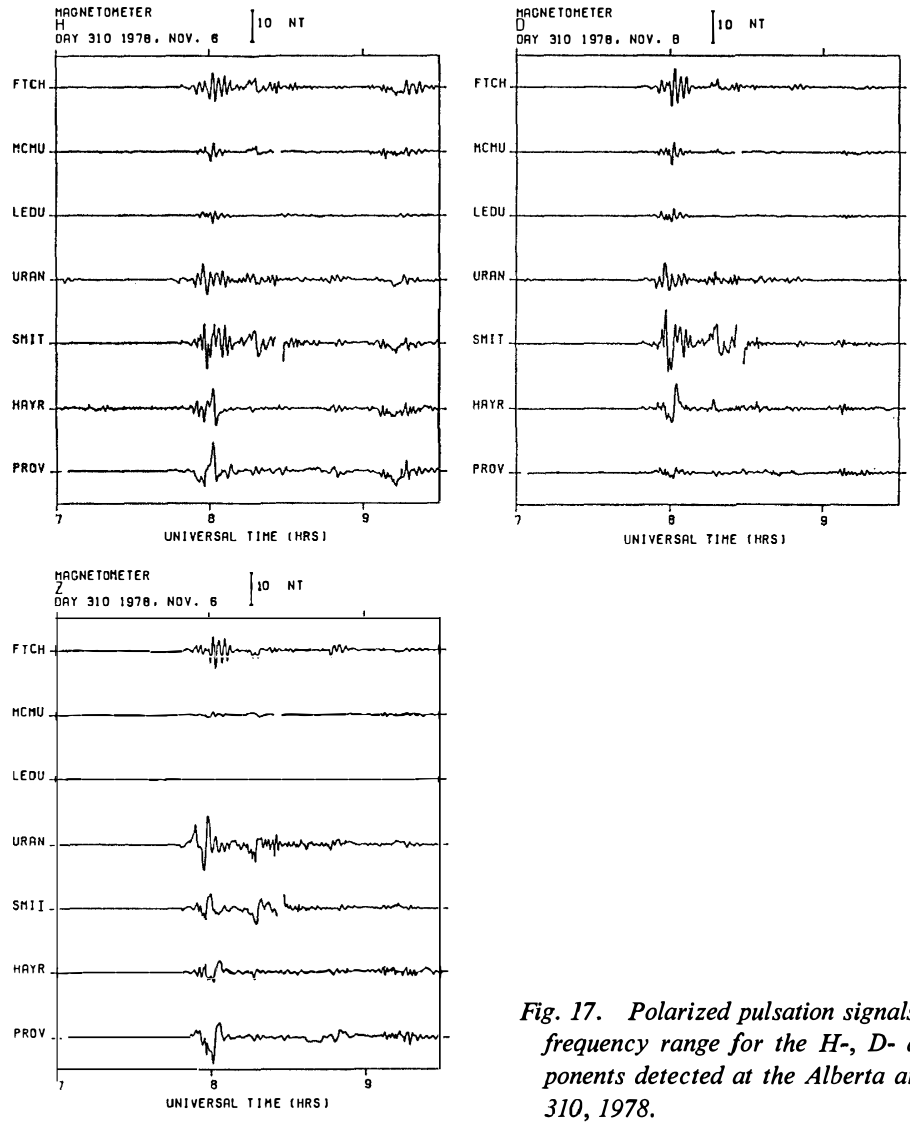


Fig. 17. Polarized pulsation signals in the Pi 2 frequency range for the H-, D- and Z-components detected at the Alberta array on day 310, 1978.

0750–0810 UT are shown in Figs. 19a–c. The Pi 2 pulsations can be identified as common spectral components of all spectra. The arrow shows the spectral component of Pi 2 pulsations. From the latitude profiles of the auroral electrojet currents in Fig. 18 the center of the westward electrojet is located at 68–69°N. But the maximum amplitude of Pi 2 pulsations lies at 61–64°N as is shown in Fig. 19. Therefore, the maximum amplitude of the Pi 2 pulsations is located in the equatorward portion of the westward electrojet.

(b) The western region of WTS; July 6, 1979; Day 187

The normal magnetograms are shown in Fig. 20. The first substorm expansion began at 0640 UT by the indication of a sudden decrease in *H*-component at all stations. The second substorm expansion was triggered at 0704 UT. The Pi 2 pulsations were almost coincident with the onset of a sharp negative change in *H*-component. Figure 21 presents the Pi 2 pulsations after the application of the data-adaptive polarization filters. Figure 22 shows the latitude profiles of auroral electrojet currents for the

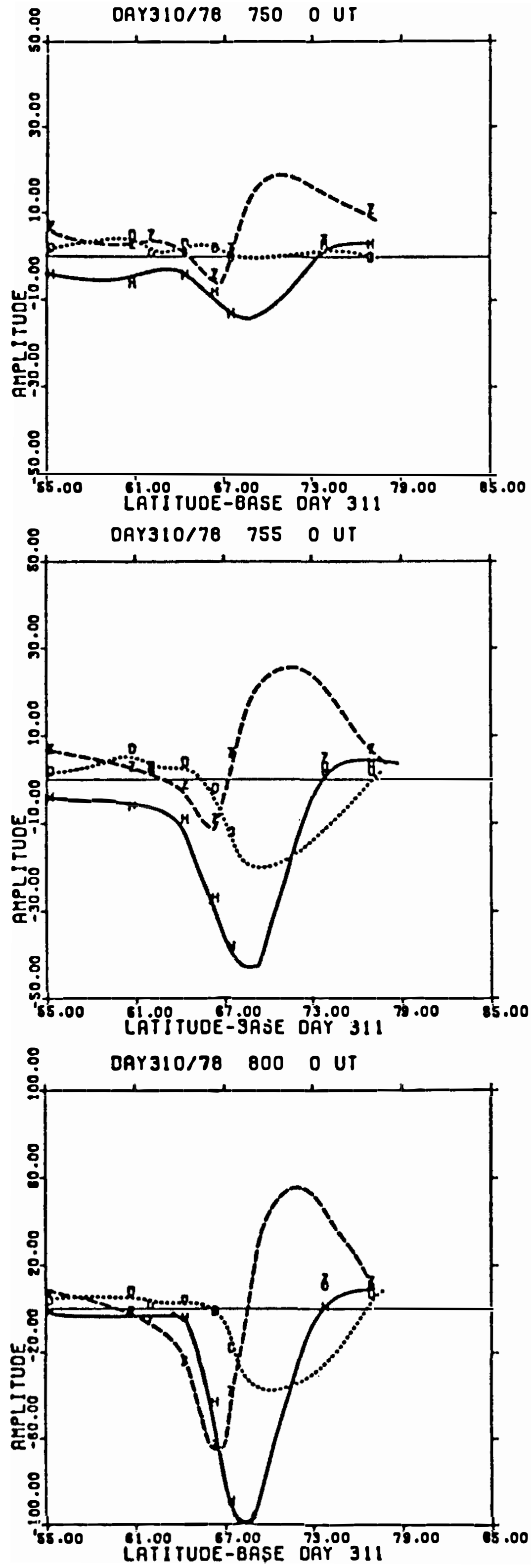


Fig. 18. Latitude profiles of auroral electrojet currents in the interval 0750–0800 UT on day 310, 1978.

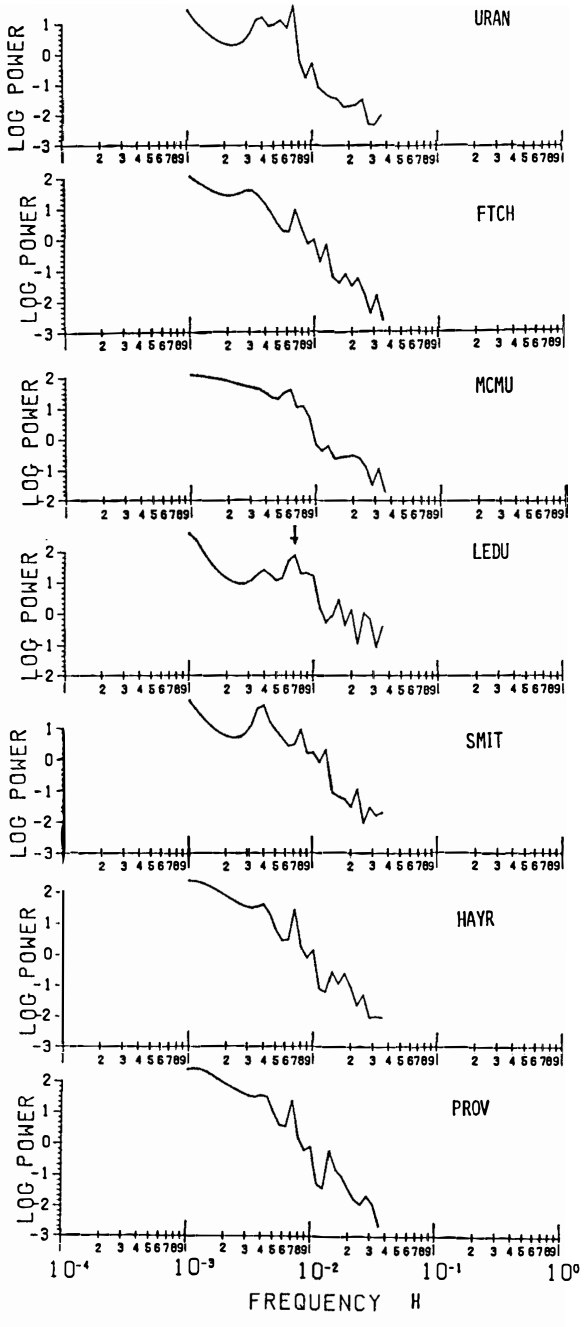


Fig. 19a.

Figs. 19a–c. The maximum entropy spectra for the H-, D- and Z-components of Pi 2 pulsations on day 310, 1978, November 6 (0750–0810 UT).

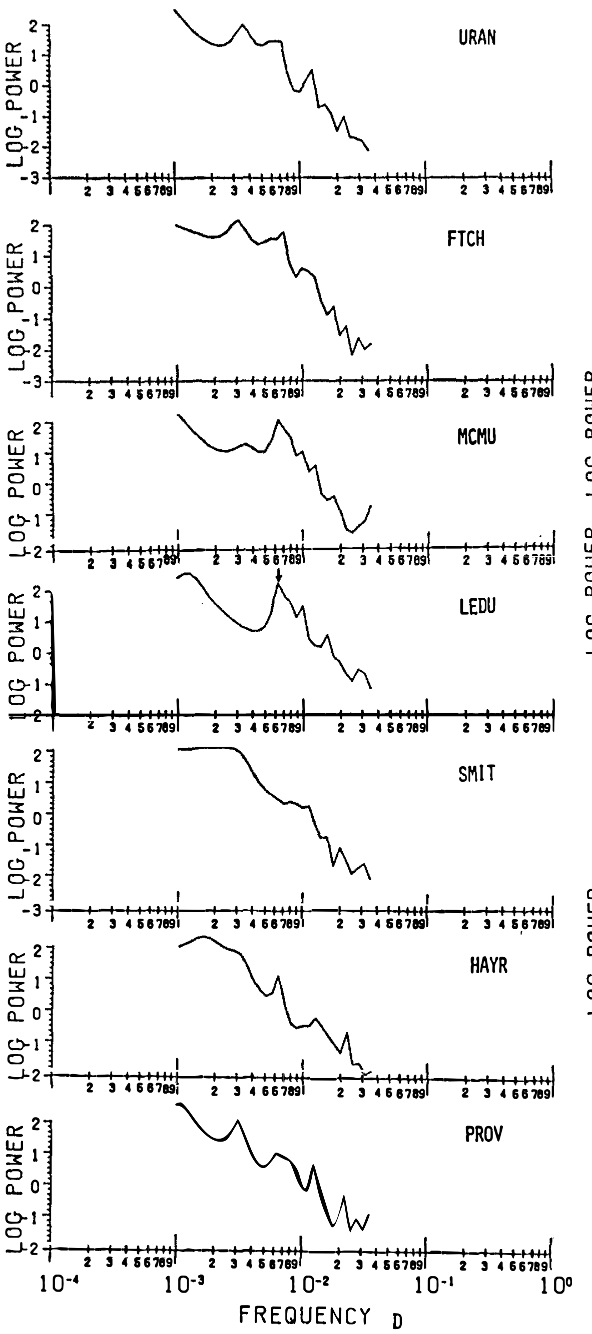


Fig. 19b.

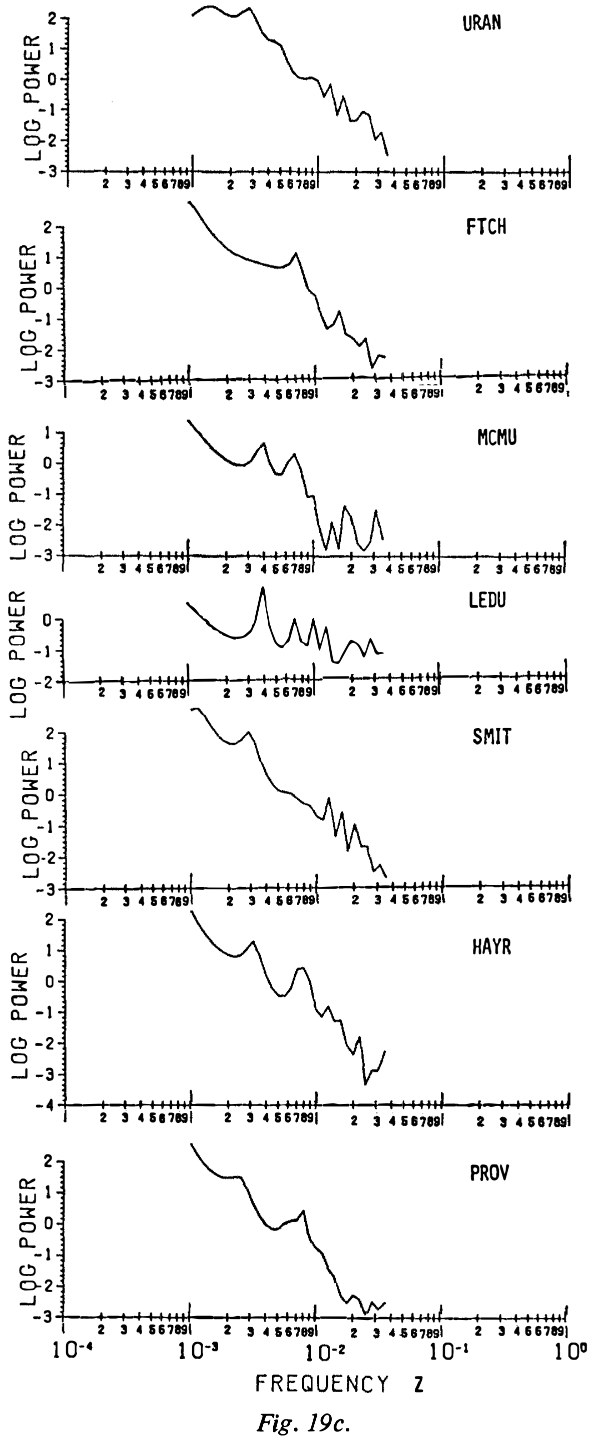


Fig. 19c.

time interval during the event. From the latitude profiles of auroral electrojet currents at 0645 UT and at 0646 UT it is clear that the westward electrojet current was intensified with the equatorward portion lying at 61–64°N in this event. The maximum entropy spectra for three components of Pi 2 pulsations during the interval 0640–0652 UT are shown in Fig. 23. It is evident that the spectrum of the *H*-component in LEDU shows a peak at 6 mHz with the second peak at 12 mHz. The outstanding

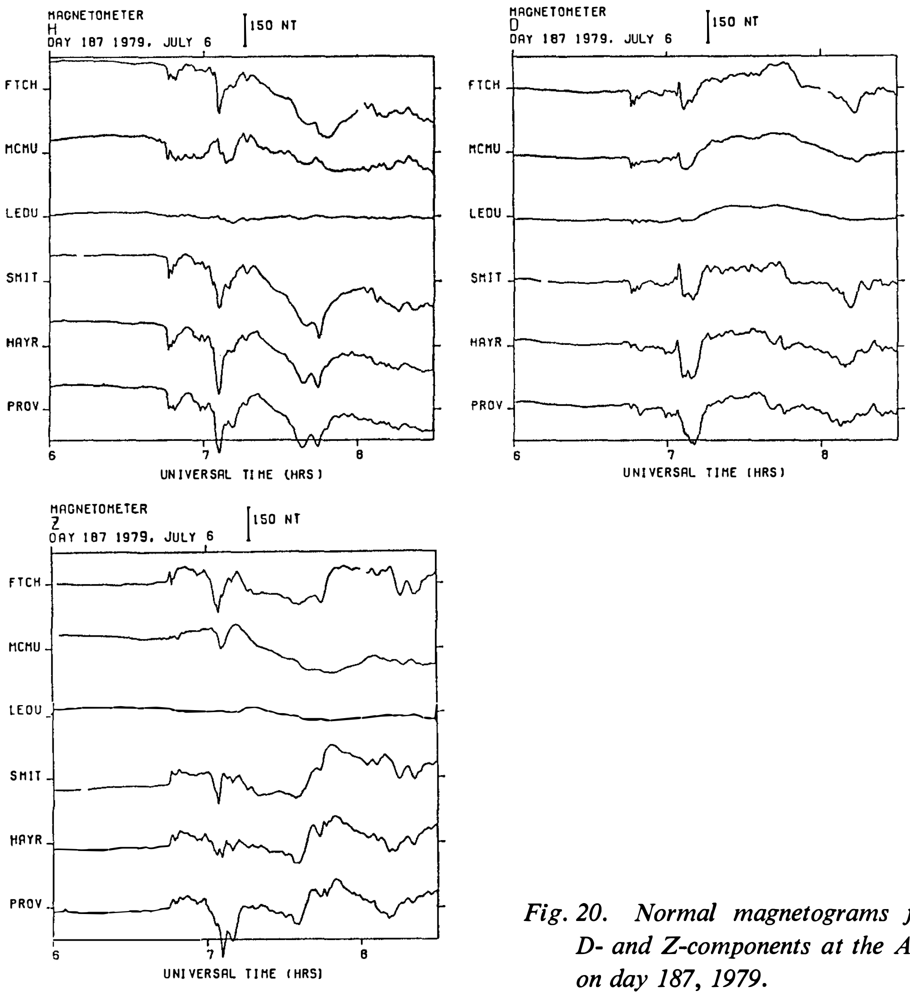


Fig. 20. Normal magnetograms for the H-, D- and Z-components at the Alberta array on day 187, 1979.

feature is a sharp peak at 6 mHz in the D-component spectrum in comparison with the H-component spectrum. The arrow shows the spectral component of Pi 2 pulsations. From the latitude profiles of auroral electrojet currents in Fig. 22 the center of the westward electrojet is located at 64°N. But the maximum amplitude of Pi 2 pulsations lies at 61°N from Fig. 23. This means that the maximum amplitude of the Pi 2 pulsations is located in the equatorward portion of the westward electrojet.

6. Discussion and Conclusion

It is generally accepted that the Pi 2 pulsations are transient wave phenomena associated with substorm onsets. The possible propagation and generation models of the Pi 2 pulsations will be briefly discussed in this section.

Substorm current circuit model: To determine the resonance frequency of the Pi 2 pulsations a simple parallel resonance circuit model with a pulse oscillator is considered (HIGUCHI, 1981). The admittance of the circuit becomes

$$Y=j\omega C+1/Z ,$$

where Z is impedance,

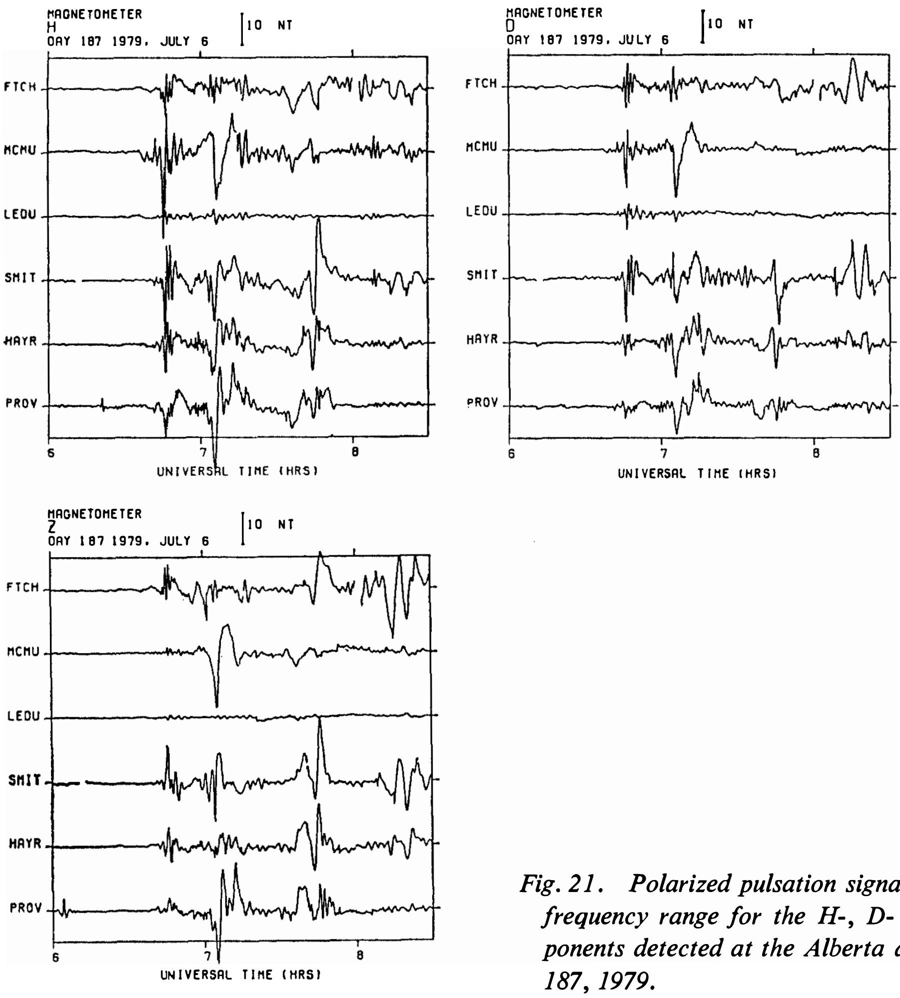


Fig. 21. Polarized pulsation signals in the Pi 2 frequency range for the H-, D- and Z-components detected at the Alberta array on day 187, 1979.

$$Z=R+j\omega L\ .$$

Therefore it is transferred to

$$Y=G+jB\ ,$$

where

$$G=R/(R^2+\omega^2L^2)\ ,$$

and

$$B=\omega(R^2C+\omega^2L^2C-L)/(R^2+\omega^2L^2)\ .$$

Here G is a conductance and B is a susceptance. If the parallel resonance condition is assumed, the susceptance should be zero, *i.e.*,

$$R^2C+\omega^2L^2C-L=0\ .$$

Finally, the resonance frequency is expressed as,

$$\omega_0=(1/LC-R^2/L^2)^{1/2}\ .$$

If $1/LC \gg R^2/L^2$, the resonance frequency is approximately written as;

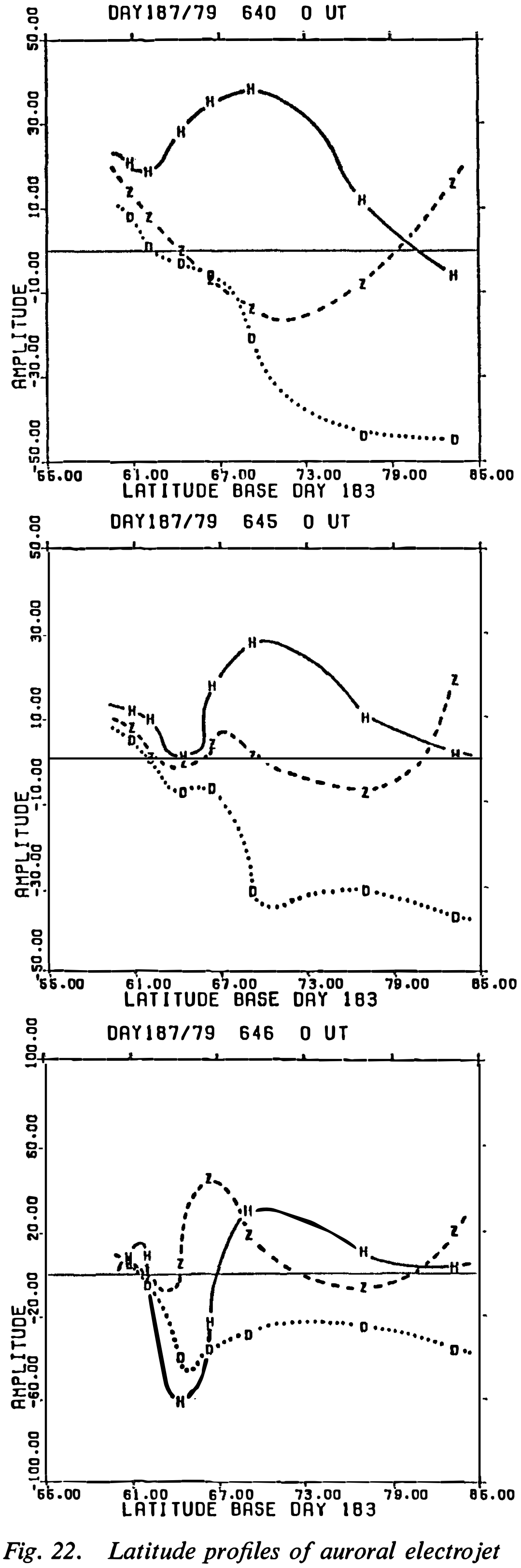


Fig. 22. Latitude profiles of auroral electrojet currents in the interval 0640–0646 UT on day 187, 1979.

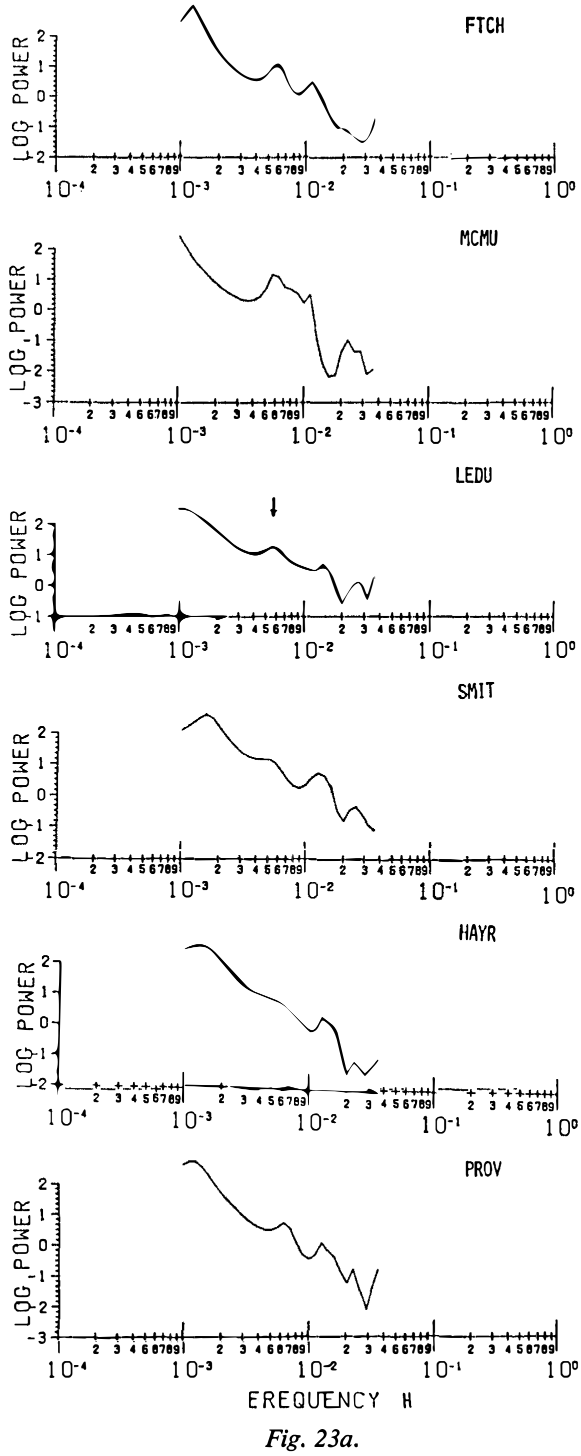


Fig. 23a.

Figs. 23a–c. The maximum entropy spectra for the H-, D- and Z-components of Pi 2 pulsations on day 187, 1979, July 6 (0640–0652 UT).

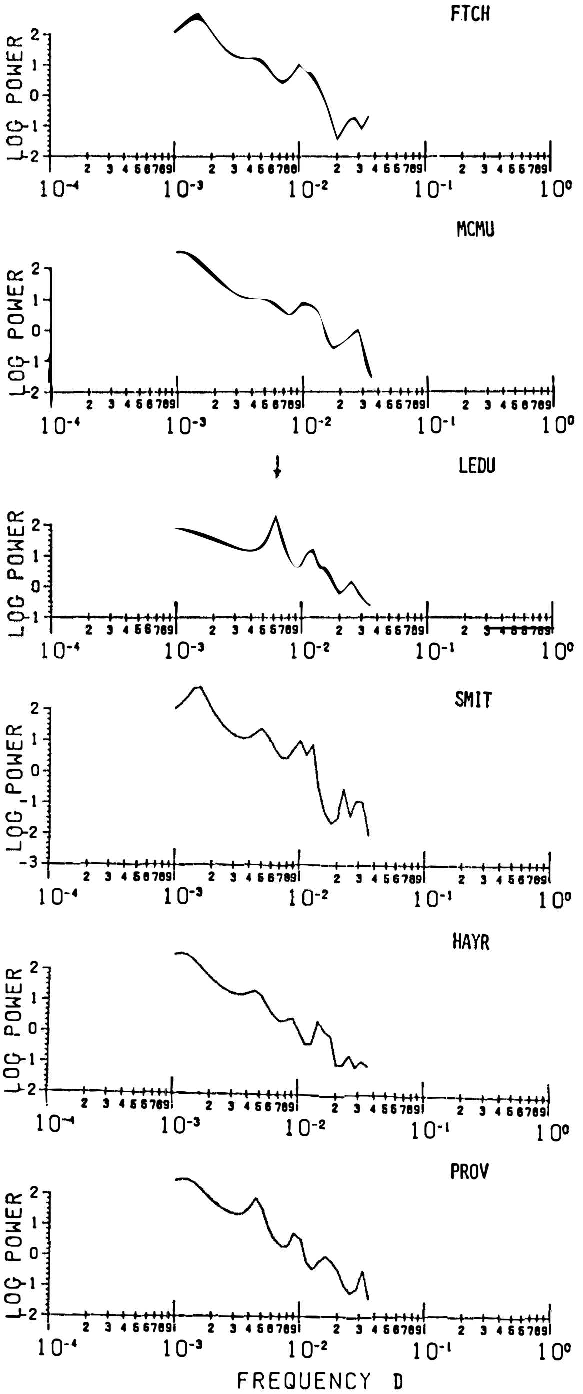


Fig. 23b.

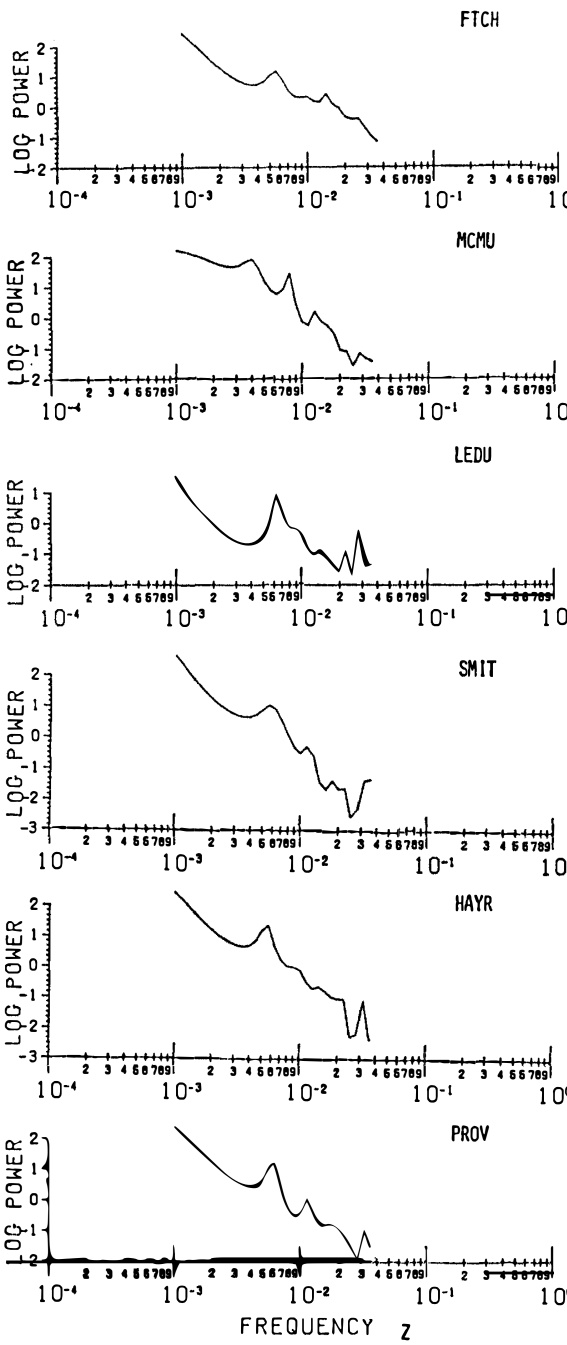


Fig. 23c.

$$f_0 = 1/2\pi(LC)^{1/2} \ .$$

From the substitution for the effective values of the circuit elements ($C=4F$, $L=50\ H$) the resonance frequency becomes $f_0=11.3$ mHz. The resonance frequency falls into the frequency range of Pi 2 pulsations. This is only a crude approximation. In reality the circuit elements should be distributed and not lumped. The transmission line equation whose inductance, capacitance and resistance per unit field line length are given by μ_0, ρ/B^2, and R, is expressed as;

$$\frac{\partial^2 J_F}{\partial X^2}=\left(\frac{R\rho}{B^2}\right)\frac{\partial J_F}{\partial t}+\left(\frac{\rho\mu_0}{B^2}\right)\frac{\partial^2 J_F}{\partial t^2}\,.$$

A general solution of the field-aligned current for infinite transmission line with constant voltage V_0 at one edge is

$$J_F(X,t)=\left(\frac{V_0}{\mu_0 V_a}\right)\exp\left(-\frac{Rt}{2\mu_0}\right)J_0\left\{\frac{jR}{2\mu_0}\left(t^2-\frac{X^2}{V_a{}^2}\right)\right\}^{1/2},$$

where J_0 is the Bessel function with zero-th order, and V_a is the Alfvén velocity.

The polarization studies by PASHIN *et al.* (1982) indicate four quadrants in the sense of polarization of Pi 2's near the auroral breakup and the location of the WTS. The polarizations are clockwise (CW) to the northwest and southeast, and counterclockwise (CC) to the northeast and southwest. They have proposed two cells current system model to simulate the polarization characteristics associated with oscillating upward FAC. Due to the westward movement of the upward FAC, the region of a different sense of polarization can be generated. They have considered two cases of current distribution. In the first case a circular equivalent current distribution which moves to the west during the course of the Pi 2 has been considered. The current distribution changes the strength periodically with time. It can be shown that the clockwise sense of polarization may be observed in the poleward of the current distribution, while the counterclockwise sense of polarization may be observed in the equatorward of the current distribution. In the second case they have considered an elliptic current distribution which shows four quadrants in the sense of polarization of Pi 2's. In a more detailed study near the WTS, SAMSON and ROSTOKER (1983) and SAMSON and HARROLD (1983) found two latitudinal changes in the sense of polarization, with CC equatorward of the WTS, *CW within the WTS*, and CC poleward of the WTS. The most complex region for the ellipticities is found in the center region with negative ellipticity. In this interval there are two latitudinal reversals in the sense of polarization, whereas outside there is only one as shown in the previous section. The region of CW polarization within the center region is near the region of the initiation of the breakup and the formation of the WTS. They also suggested that the high latitude reversal in this longitudinal interval is due to FAC associated with the Pi 2, whereas the low latitude reversal is due to ionospheric electrojets that oscillate 180° out of phase, giving a 180° latitudinal phase shift in the *H*-component. They have considered a FAC sheets model for the polarization of Pi 2's. The polarizations that are seen in the Pi 2's near the electrojet are most likely due to phase differences between the local net Hall current and the local net FAC, as well as a latitudinal motion of the FAC region. It has been assumed that the initial upward current occurs simultaneously in the restricted longitudinal region at the given latitude. This FAC pulse is partially reflected from the ionosphere and multiple reflections from both hemispheres give oscillating currents. Assuming the FAC function for a specific case, they have estimated the net field-aligned current and the latitudinally integrated Hall current. Because of the westward expansion the integrated Hall current will lag the net FAC.

The FAC and the Hall current are initially in phase and then as the FAC expands westward, the integrated Hall current begins to lag the net FAC.

Hydromagnetic wave resonance model: KUWASHIMA (1978), KUWASHIMA and SAITO (1981) have investigated the spectral and polarization characteristics of Pi 2 pulsations observed in a wide latitudinal range from the auroral region to the low latitude region in the southern hemisphere. The main observational results are summarized as follows; (a) The Pi 2 pulsations are simultaneously observed at the conjugate stations with similar waveforms. The Pi 2 pulsations show in-phase oscillations in the *H*-component, but out-of-phase oscillations in the *D*-component. (b) The period of Pi 2 pulsations is closely related to the location of auroral breakup. It becomes shorter (longer) when the auroral breakup occurs at lower (higher) latitude. From the above observational results a possible cause of Pi 2 pulsations could be an odd mode standing torsional oscillation of the field lines anchored in the northern and the southern auroral ovals. The fundamental period of the torsional oscillation is calculated by the bounce period of the Alfvén waves between the conjugate ionospheres along the geomagnetic field line. A model calculation shows that the period of Pi 2 pulsations is from 38 to 147.7 s in the latitude range between 65° and 71°. Therefore, the resonance frequency falls into the frequency range of Pi 2 pulsations.

Current-driven drift Alfvén instability model: With regard to a plausible generation mechanism of Pi 2 pulsations the drift Alfvén wave instability due to a current parallel to the geomagnetic field lines has been proposed. The field-aligned current associated with a velocity shear between the central plasma sheet and the low latitude boundary layer plasma is intensified when the shear velocity exceeds a critical value. The plasma in the central plasma sheet flows to the sunward direction, but the plasma in the low latitude boundary layer flows into the anti-sunward direction. Therefore, it is possible that the velocity shear (vorticity) creates the field-aligned currents. Since the maximum amplitude of the Pi 2 pulsations exists in the equatorward portion of the westward electrojet, it is suspected that the Pi 2 pulsations could be triggered at the boundary between the central plasma sheet and the low latitude boundary layer plasma. The dispersion relation of the drift Alfvén waves is modified by the current parallel to the static magnetic field. In particular, the coupled effects of the density gradient and the parallel current can modify the dispersion relation of the drift Alfvén waves. The instability occurs in a particular interval of wave numbers when the real part of the frequency is equal to $\omega_i^*/2$, where ω_i^* means ion drift frequency.

In conclusion it is confirmed that the polarization characteristics of Pi 2 pulsations are dependent on the positions of the auroral breakup and WTS. The ellipticity changes of the Pi 2 pulsations in the vicinity of the auroral oval are qualitatively consistent with the substorm current circuit model. The amplitude distribution of Pi 2 pulsations in latitude indicates that the maximum amplitude is located in the equatorward portion of the westward auroral electrojet.

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