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The strong Pc5 geomagnetic pulsations in the initial phase of the great magnetic storm of March 24, 1991

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Pc5 pulsations which were excited during the great magnetic storm of March 24, 1991 are analysed using the data from three French observatories located in the southern Indian Ocean at the subauroral and middle latitudes. The unusual strong Pc5 pulsations observed display features depending on the interval of occurrence: a quasi-noisy regime in the frequency range of 2.5–3.2 mHz characterizes the 04–10 UT interval, whereas the oscillations are nearly monochromatic with spectral maximum around 1.8–1.9 mHz in the 10–14 UT interval. The sharp change occurring at 10.17 UT could be associated to a sharp change in the magnetosphere structure or dynamics.

1. Introduction

The study of morphology and nature of the Pc5 ($f \sim$ 2–6 mHz) geomagnetic pulsations observed on the ground level have been the subject of many papers. A series of recent publications reported the observation of power enhancement of wave spectra at discrete frequencies (near 1.3 mHz, 1.7–1.9 mHz, 2.3–2.6 mHz and 3.2–3.5 mHz), which corresponds to field line resonance (Chen and Hasegawa, 1974; Southwood, 1974) apparently driven by magnetosphere cavity or waveguide modes (Ruohoniemi *et al.*, 1991; Samson *et al.*, 1991; Harrold and Samson, 1992; Samson and Harrold, 1992; Walker *et al.*, 1992; Ziesolleck and McDiarmid, 1994).

Field line resonances can be excited by several relatively broad sources such as Kelvin-Helmoltz instabilities, transient day reconnection, step variations of the solar wind dynamic pressure (Dunlop *et al.* (1994) and references therein). It is well established that, on the Earth's surface, Pc5 waves propagate with small azimuthal wave numbers to the West in the morning side, and to the East in the afternoon.

Geomagnetic pulsations Pc5 are typical phenomena at high latitudes during recovery phases of magnetic storms and substorms (see for example, Engebretson *et al.*, 1983). The maximum of the Pc5 amplitudes are usually observed in a relatively narrow geomagnetic latitude range (typically 68°–72°). Their region of occurrence coincides with the auroral oval. The amplitude of Pc5 sharply decreases in function of their distance from the generation region. Pc5 pulsations with amplitudes larger than 10 nT are seldom observed at latitudes lower than 60°.

It is well known that the development of strong magnetic storms leads to a significant reconstruction of large scale structures of the magnetosphere. For instance, auroral zones can extend to subauroral and even middle latitude areas. In such extreme situations, Pc5 pulsations can be observed at unusually low latitudes and, in such instances, the analysis of geomagnetic observations at subauroral and middle latitudes provides useful information. An exceptional strong magnetic storm happened on March 24, 1991. According to Bell *et al.* (1997), it belongs to the "super storm" class for it is characterized by an exceptionally large geomagnetic sudden commencement (SSC) occurring at 03.41 UT (Araki *et al.*, 1997), *Dst* = –298 nT (24 UT) and *AE* as large as ~4000 nT at 04–05 UT. The *Dst* index decreased in the 04–10 UT interval from +63 nT to –98 nT and increased in the 10–14 UT interval from –98 nT to –57 nT.

The global burst of long period ($T \sim$ 10 min) geomagnetic pulsations at 12–14 UT was observed by Fujitani *et al.* (1993), Liu *et al.* (1993), Reddy *et al.* (1994). Fujitani *et al.* (1993) using multi-stations data from several meridian chains demonstrated the global character of the 12–14 UT Pc5's, having the strongest amplitudes in the afternoon sectors and periods independent on latitudes. The properties of these pulsations are different from those of typical Pc5 caused by field line resonance. Liu *et al.* (1993), using CW-HF Doppler frequency sounding system and fluxgate magnetometers at the station of Taiwan, showed beautiful sinusoidal oscillations with phase differences of 15°–77°. Reddy *et al.* (1994) found similar oscillations with coherent backscatter radar and magnetometer records. These observations were interpreted in terms of compressional cavity mode resonance in the inner magnetosphere and associated ionospheric electrical field penetrating from high latitude toward the magnetic equator.

Occurring before the global burst of Pc5 pulsations with periods of about 10 min, discussed by Fujitani *et al.* (1993), Liu *et al.* (1993), and Reddy *et al.* (1994), we have observed another type of unusual Pc5's with shorter periods. The aim of our paper is to study these strong Pc5 pulsations occurring in the 06–10 UT time interval during these untypical conditions, i.e. in the initial phase of the magnetic storm.

2. Data and Results

In this paper, the morphological peculiarities of Pc5 pulsations are analysed using digital one minute sampling data obtained from the French observatories located in the Southern Indian Ocean. The coordinates of these stations are listed in Table 1.

The SSC occurring at 03.41 UT led to the development of a large magnetic substorm. Even in the late local morning at $L = 3.6$ (PAF) the amplitude of the H-component reached 1800 nT (in comparison, the maximum amplitude was 2300 nT at auroral observatory Sodankyla (SOD), located in the northern hemisphere ($\Phi' = 63.9°$, $\Lambda' = 109°$, $L = 5.1$). The electrojet very quickly shifted towards the equator, whereas the current intensity sharply changed along meridians, what can be noticed by comparison of the records from CZT and AMS: at AMS located at a lower latitude than CZT, but 30°

Table 1. List of the observatories used in this study.

Station name	Abb. code	Geographic		Corrected		L	MLT
		lat.	long. E	lat.	long.		
Kerguelen (Port aux-Français)	PAF	–49.35	70.20	–58.25	121.55	3.61	UT + 3.4
Crozet (Port Alfred)	CZT	–46.43	51.87	–53.47	105.55	2.82	UT + 2.4
Amsterdam (Martin de Vivies)	AMS	–37.83	77.57	–48.51	137.88	2.28	UT + 4.5

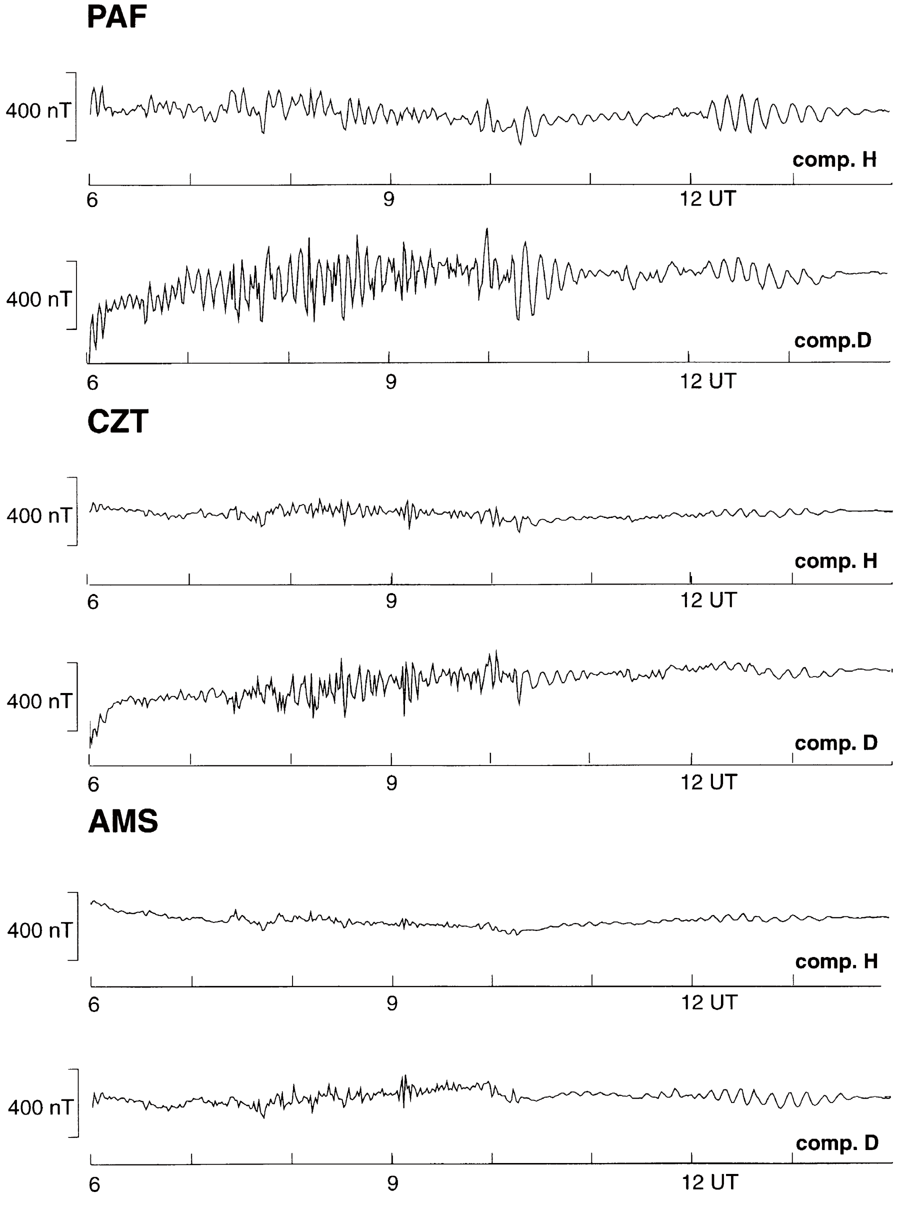

Fig. 1. H and D magnetograms in the interval 06–14 UT on March 24, 1991 for PAF, CZT and AMS. Note the change in the pulsation regime occurring at 10.17 UT.

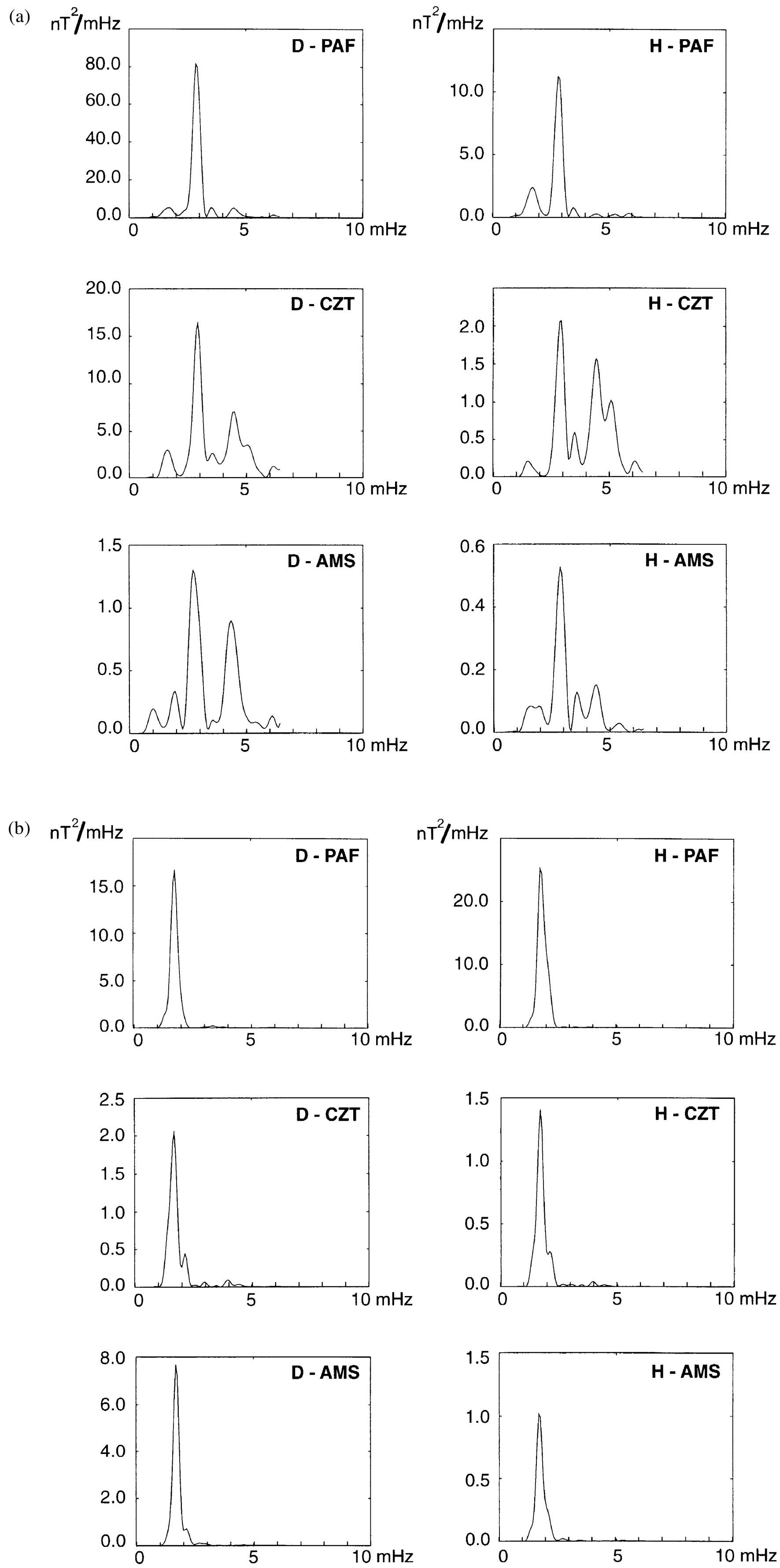

Fig. 2. *H* and *D* spectra of PAF, CZT and AMS computed for 08–09 UT (a) and 12–13 UT (b). Note the strong change in frequency content between the two selected intervals: the afternoon regime is nearly monochromatic.

farther East, the substorm amplitude was larger than at CZT. This observation is consistent with the evolution of the *AE* index which was as large as ~4000 nT at 04–05 UT and very rapidly decreased to ~800 nT at 07–08 UT.

Magnetic pulsations in the Pc5 range were observed in all three stations during the recovery phase of this substorm. Non-filtered pulsations data are presented in Fig. 1. The Pc5 observations can be subdivided into two intervals: 04–10 UT and 10–14 UT. The first Pc5 regime is characterized by quasi-noisy pulsations with amplitudes decreasing with latitudes (which can be clearly seen if we compare for instance the *H*-component values reached at PAF (150–160 nT) with those observed at CZT (60–70 nT) and at AMS (30–40 nT). The *D*-component amplitudes at all stations were twice larger than the *H*-component. The pulsations look like a separate packet structure occurring simultaneously at all latitudes, which means that either their sources are the same irregular impulses on the magnetopause or they are the result of the superposition of several simultaneous sources.

Spectral analysis (performed with the periodogram method using a Hamming window) shows that the main peak (both in *H* and *D* components) appears in the range 2.5–3.2 mHz at all three stations (Fig. 2(a)). The detailed study of the late morning pulsations filtered in the frequency range 2.0–3.5 mHz (Fig. 3) shows clear phase delay between AMS and CZT (30° longitude difference). We can infer that the waves propagated from noon (AMS) to morning (CZT) side of the magnetosphere (Fig. 3(a)), with a small azimuthal wave number (m ~ 2–3). In the afternoon, the geomagnetic pulsations in the frequency range 1.5–2.0 mHz (Fig. 3(b)) propagated in the opposite direction, from noon towards the evening side (i.e. from CZT to AMS). This observation supports the hypothesis of a subsolar source location (Dunlop *et al.*, 1994).

In the 06–10 UT interval, Pc5 pulsations were observed at many stations, located in the local morning and near noon (Europe, Greenland). In contrast to typical morning Pc5's, the pulsations described above have similar spectra, characterized by the relatively narrow maximum of 2.5–3.2 mHz independent on latitude (for example, from Godhavn, $\Phi' = 77°$, 04–08 MLT to Amsterdam, $\Phi' = 48°$, 10–14 MLT) with the maximum of amplitude (~500 nT) in the morning at Narssarssuaq ($\Phi' = 67°$). The lower latitude stations (CZT and AMS) spectra display a second maximum at 4–5 mHz, the largest peak being in the *D*-component at CZT.

A sharp change in pulsation regime occurs at 10.17 UT. The quasi-noisy character of pulsations suddenly changed into more regular, monochromatic oscillations. The spectral maximum shifts towards lower frequencies: 1.5–2.0 mHz (Fig. 2(b)). In addition, at PAF and AMS, the polarization vector sense of rotation changed: counterclockwise before 10.17 UT and clockwise after 10.17 UT. The new regime was essentially monochromatic, displaying the most beautiful waves in the 12.00–13.30 UT interval. This burst of Pc5 pulsations was observed in a large longitudinal range, from geomagnetic meridian 80° to meridian 210°, with the same period of about 9–10 min (Fujitani *et al.*, 1993). As before, the period was independent of latitudes, and the amplitudes of the *H*-component of Pc5 decreased with decreasing latitudes (from ~200 nT at PAF to ~40 nT at CZT and AMS). The amplitudes of the first Pc5 regime (2.5–3.2 mHz) were larger in the morning sectors of the Earth, but those of the second one (1.5–2.0 mHz) larger in the afternoon.

In addition, a comparison of data at two pairs of nearly conjugate points, namely Kerguelen-Nurmiervi and Crozet-Borok, showed in-phase variation of *H*-component and out-of-phase variation of *D*-component. This supports the presence of the fundamental harmonic of standing waves.

To summarize, the main pecularities of the pulsations analysed above are 1) the latitude independency of their spectrum, in both regimes, quasi-noisy as well as nearly monochromatic, and 2) the sudden disappearance of the 2.5–3.2 mHz pulsations at 10.17 UT. This observation is at variance with the properties of the Pc5 pulsations observed during the great magnetic storm of March, 13, 1989, which was analysed by Bolshakova *et al.* (1995), using the Scandinavian meridian chain and PAF and CZT data. They showed that the main maximum in the late morning Pc5 spectrum shifted from 3.3 mHz at PAF to 5.6 mHz at CZT, according to the field line resonance theory.

3. Discussion

The main pulsation period in the interval 6–10 UT was practically the same (T ~ 6 min; f ~ 2.5–3.2 mHz) in all stations, independent on latitudes. The similarity of wave spectra at various latitudes and the nearly simultaneous appearance of separate wave packets allow us to conclude that they originated from a common source, for example, trigerred by a succession of impulses. Independence of the main spectral peak on latitudes over a considerably large latitude range, the narrow frequency range, and the amplitude of *D*-component larger than *H*-component at every latitude, do not fit with local field line resonances theory.

Several other assumptions may be imagined in order to predict the Pc5 pulsation generation in our case.

It could be the result of modulation (ringing) of a three dimensional field aligned current system (Lam and Rostoker, 1978; Lam, 1989), but this mechanism is very doubtful because the Pc5 pulsations were observed near local noon, after the end of the substorm at the given meridian.

Another possibility relies upon instabilities on the boundary between the low latitude boundary layers (LLBL) and the magnetopause, as it was proposed by Sonnerup (1980) and Engebretson *et al.* (1983). They observed similar Pc5 pulsations simultaneously in an extended latitude region both from Earth surface stations and on board the satellite Explorer 45 during the strong magnetic storm of August 5, 1972. The low latitude boundary layer was observed at L ~ 4.5 during the storm time.

Kivelson *et al.* (1984) and Crowley *et al.* (1987) proposed a mechanism of wave generation connected with fast mode resonance of the entire magnetospheric cavity located between the magnetopause and the inner turning point or at least the sunward half of the cavity. Because of the radial gradient of Alfven speed, the turning point of waves could coincide with the plasmapause. According to analytical models of a global compression mode (for instance, Kivelson *et al.*, 1984) the waves are reflected, on one side, on the sharp gradient of the magnetic field of the magnetopause and, on the other side, on the plasma density gradient near the plasmapause. The poloidal global mode is characterized by azimuthal electric field oscillations and radial motions of the plasma. In the meridian plan the frequency of poloidal fluctuations must be L-independent. The model cavity frequencies are sensitive to the magnetopause location. This model does not explain the stability of observed spectra both in 06–10 UT and 12–14 UT intervals with respect to geomagnetic conditions during such a strong magnetic storm.

The most relevant mechanism might be the model of wave guide modes proposed by Samson and Harrold (1992), Walker *et al.* (1992), Harrold and Samson (1992). The pulsations could be initiated by solar wind disturbances perturbing the magnetopause. As a result, waveguide modes would be excited in the cavity formed between the magnetopause and the turning point, where Alfven waves are reflected with phase speeds matching the disturbance speed. Each disturbance would emit a wave packet growing and decaying with a time scale controlled by the response of the magnetosphere state and the losses in the ionosphere. The azimuthal phase velocities of waveguide model should be comparable to the velocities of disturbances moving along the magnetopause near local dawn. The observed azimuthal wave number $m \sim 2$–3 for ~2.5 mHz oscillations corresponds to a velocity on the magnetopause of about 300 km/s (Ruohoniemi *et al.*,1991), which is not contradictory with results of Samson and Harrold (1992).

In addition, it is interesting to mention that the spectra maxima (~2.7–2.8 mHz in the 06–10 UT, ~1.8–1.9 mHz in the 12–14 UT) are consistent with some of the discrete peaks (1.3 mHz, 1.9 mHz, 2.7 mHz and 3.3 mHz) discussed by Samson *et al.* (1991), Walker *et al.* (1992), Samson and Harrold (1992), Ziesolleck and McDiarmid (1994).

A sharp change in the pulsation regime occurred simultaneously at all stations at 10.17 UT. Frequencies suddenly decreased from 2.5–3.5 mHz to 1.5–2.0 mHz with a maximum at 1.8 mHz, and the polarization became clockwise. At the same time, a short negative magnetic bay was observed on the nightside of the magnetosphere. Since Interplanetary Magnetic Field (IMF) data is not available, we can only assume that these events originated in a new compression of the magnetosphere by the solar wind. The increase displayed by the *Dst* index supports this suggestion.

It is difficult to explain why the 2.5–3.2 mHz pulsations suddenly turned off. A second difficulty arises from the existence of only one maximum in the spectra. According to Zhu and Kivelson (1994), compressional pulsations in the daytime magnetosphere are characterized by very low frequencies, are nearly monochromatic and extend over regions several Re large in the radial direction. This description matches the 12–14 UT Pc5's, which might be therefore identified as compressional waves caused by fluctuations of the solar wind dynamic pressure, as proposed by Fujitani *et al.* (1993).

Finally, the second maximum at 4–5 mHz in the Pc5 spectra showed in Fig. 2 could result from Alfven field line resonance at a geomagnetic latitude of about 50°, provided by the second harmonic of the global mode. This peak is observed only in CZT and AMS, not in PAF, due to a strong wave dumping with increasing distance from the resonance region as it is predicted by theory (see, for instance, Chen and Hasegawa, 1974).

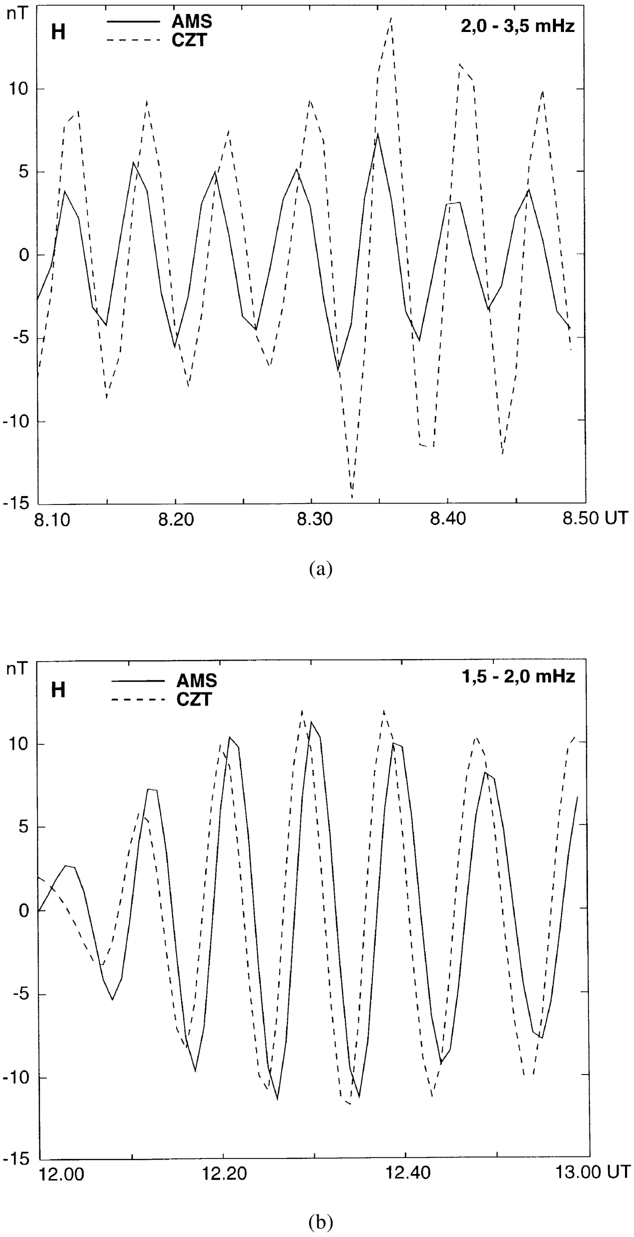

Fig. 3. Comparison between the band-filtered H-component variations at AMS and CZT: (a) 08.10–08.50 UT (2.0–3.5 mHz); (b) 12.00–13.00 UT (1.5–2.0 mHz). Note the change of phase delay between the two intervals.

4. Conclusion

The intense Pc5 pulsations observed at unusual low latitudes during the great magnetic storm of March 24, 1991, cannot be classified as typical morning Pc5's connected with substorm developments and field line resonances. The pulsation spectrum in the 06–10 UT, as well as in the 12–14 UT interval, in contrast to typical Pc5, has only one latitude independent peak.

In addition, in contrast to ordinary Pc5's the reported pulsations were observed in the initial phase of this very strong storm. We propose that the source of the 06–10 UT pulsations is located near the subsolar point, in accordance with a previous assumption made by Dunlop *et al.* (1994). In our opinion, the most likely generation model refers to the magnetospheric MHD waveguide/cavity mode proposed by

Samson *et al.* (1991), Walker *et al.* (1992), Samson *et al.* (1992). These rather unusual properties emphasize the dynamics of the magnetospheric processes triggered by this great magnetic storm, as seen from this restricted set of observatories.

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