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Globally Coordinated Magnetic Observations Along 210° Magnetic Meridian during STEP Period: 1. Preliminary Results of Low-Latitude Pc 3's

K. YUMOTO[1], Y. TANAKA[1], T. OGUTI[1], K. SHIOKAWA[1], Y. YOSHIMURA[1], A. ISONO[1],
B. J. FRASER[2], F. W. MENK[2], J. W. LYNN[3], M. SETO[4],
and 210° MM MAGNETIC OBSERVATION GROUP

[1]*Solar-Terrestrial Environment Laboratory, Nagoya University, Toyokawa, Aichi 442, Japan*
[2]*Department of Physics, University of Newcastle, Newcastle, N.S.W. 2308, Australia*
[3]*Electronics Research Laboratory, DSTO, Salisbury, SA 5018, Australia*
[4]*Tohoku Institute of Technology, Sendai 982, Japan*

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The Solar-Terrestrial Environment Laboratory (STEL), Nagoya University, is carrying out multinationally coordinated magnetic observations along the 210° magnetic meridian from high latitudes, through middle and low latitudes, to the equatorial region, spanning $L = 9.05$–1.03, in cooperation with 14 institutes in Japan, Australia, USA, and Russia during the STEP period of 1990–1997. In this paper, we introduce in detail the project of global magnetic observations along the 210° magnetic meridian, and illustrate preliminary results of power spectrum and cross correlation analysis of low-latitude pulsations at the 6 chain stations installed in 1990.

The results can be summarized as follows: (1) There are two spectral peaks in the Pc 3 range. A shorter-period component in the 10–20 sec range exhibits standing field-line resonance behavior around $L = 1.58$, while the longer-period component in the 20–50 sec range indicates three different characters, a standing field-line oscillation at $L > 2.1$, a second-harmonic cavity resonance oscillation in the plasmasphere, and propagating-mode waves with phase delays from lower to higher latitudes. (2) An ssc with $\delta H \sim 215$ nT magnitude at $L = 1.22$ on March 24, 1991, was found to stimulate cavity-mode Pc 3 pulsations with duration <20 min and identical 15.5 and 25.3 mHz frequencies over the $L = 1.14$–2.13 low-latitude region.

1. Introduction

A major new international scientific program, the Solar Terrestrial Energy Program (STEP), commenced in 1990 and will continue for seven years in order to trace the flow of energy and plasma from the upstream solar wind, through the magnetosphere and ionosphere to the biosphere. The ionospheric signatures of magnetospheric energy transfer process can be recorded on the ground using appropriate magnetometer networks. Topical Group 2.2 (Project Leader: Prof. S. Kokubun, Dept. Earth & Planet. Phys., Univ. Tokyo, Japan), set up by Working Group No. 2 for the STEP, is concerned with COordinated ground-based Magnetic Observations for Studies on response of the Magnetosphere and magnetosphere-ionosphere coupling (COMOSM).

Japanese ground-based observation teams proposed a globally coordinated magnetic observation program during the STEP period to study energy and plasma transfer processes and global auroral dynamics (see *Solar Terrestrial Environmental Research in Japan*, Vol. 14, 1990). In order to efficiently organize the observations, working plans were grouped into four regional categories, i.e., the polar region, the high-latitude conjugate region, middle and low latitudes, and the equatorial zone. The Solar-Terrestrial Environment Laboratory (STEL), Nagoya University, takes care of the multinationally coordinated magnetic observations along the 210° magnetic meridian, in cooperation with Tohoku University (THU), Tohoku Institute of Technology (TIT), Kakioka Magnetic Observatory (KMO), and Tokai University (TKU) in Japan; the University of Newcastle (UNC), the Defence Research Centre, Salisbury (DSTO), CSIRO Tropical Ecosystems Research Centre (TERC) and IPS Learmonth Solar Observatory (IPS) in Australia; the United States Geological Survey (USGS), and the University of Alaska (UAF) in USA; and the Institute of Physics of the Earth (IFZ), the Institute of Space Research and Radiowaves (IKIR), the Institute of Cosmophysical Research and Aeronomy (YaKFIA), and the Institute of Terrestrial Magnetism and Radiowave Propagation (IZMIRAN) in Russia.

In this paper, we will introduce the 210° magnetic meridian project, and illustrate some preliminary results. We carried out power spectrum and cross correlation analysis of low-latitude pulsations observed at the 6 chain stations installed in 1990, to investigate the unresolved global propagation and energy coupling mechanisms of low-latitude magnetic pulsations in the Pc 3 frequency range (see YUMOTO, 1986, 1988).

2. Observation and Data

The organized magnetic field ground network data potentially make it possible to study both temporal and spatial variations in the magnetospheric processes. In order to identify global, latitudinal structures and propagation characteristics of ULF waves from higher to equatorial latitudes, and to understand the global generation mechanism of these phenomena, magnetic observations will be carried out along the 210° magnetic meridian during the STEP period. Table 1 summaries station names, geographic and geomagnetic coordinates, and L values of established and proposed observation sites. Additional high time resolution instruments will be installed at the latter sites during the STEP period. The corrected geomagnetic coordinates and L values are calculated at each station for 100 km altitude for January 1, 1991, using the IGRF-85 model. Abbreviations of institutes and organizations which kindly support the globally-coordinated ground-based observations or collaborate with the STE Lab's magnetic observation team are given in the last column in Table 1. PTWC, PRV, WNSS, IPS, POB, and DAC are abbreviations of Pacific Tsunami Warning Center, Private house, Weipa North State School, IPS Radio and Space Services at Learmonth, Police Office in Birdsville, and Dalby Agriculture College, respectively.

In July, 1990, we installed the first fluxgate magnetometer systems of the array at Moshiri (MSR), Chichijima (CBI) and Kagoshima (KAG) in Japan, and Adelaide (ADE), Birdsville (BSV) and Weipa (WEP) in Australia. Figure 1 shows these 210° magnetic meridian stations in geomagnetic coordinates. The BSV site (L = 1.57) is located near the magnetic conjugate point of MSR (1.60) in Japan. The CBI (L = 1.14), WEP (1.18) and ADE (2.13) sites are located near the same meridian as the conjugate point stations. The KAG site (1.22) is situated ~2° north of the conjugate point of Darwin (1.18) which is located ~12° west in geomagnetic longitude of the WEP station. At Ewa beach (EWA; L =

Table 1. Geographic and corrected geomagnetic coordinates, L values, and supporting institutes for the 210° magnetic meridian chain stations. Geomagnetic parameters are calculated by using the IGRF-1985 model for 100 km altitude for each station on January 1, 1991.

Station name	Abbr.	Geographic		Geomagnetic		L	Support/collabo.
		Lat.	Long.	Lat.	Long.		
Zhokhova isl.	ZHI	76.24	152.74	70.59	210.61	9.05	YaKFIA, IZMIRAN
Chokurdakh	CHD	70.62	147.89	64.75	211.78	5.50	YaKFIA, IFZ
Magadan	MGD	59.97	150.86	53.70	218.34	2.85	IKIR
St. Paratunka	PTK	52.94	158.25	46.49	225.60	2.11	IKIR
Moshiri	MSR	44.37	142.27	37.76	212.96	1.60	STEL
Onagawa	ONW	38.43	141.47	31.79	212.25	1.38	THU
Kagoshima	KAG	31.48	130.72	25.23	201.99	1.22	STEL
Chichijima	CBI	27.15	142.30	20.65	212.74	1.14	KMO
Ewa Beach	EWA	21.32	202.00	22.72	269.05	1.18	PTWC/USGS, TKU
Guam	GUA	13.58	144.87	9.02	215.18	1.03	USGS
Wewak	WEW	-3.55	143.62	-14.08	215.00	1.06	PRV
Darwin	DAW	-12.40	130.90	-23.22	202.42	1.18	TERC, UNC
Weipa	WEP	-12.68	141.88	-23.06	214.07	1.18	WNSS, UNC
Learmonth	LMT	-22.22	114.10	-34.36	184.64	1.47	IPS, UNC
Birdsville	BSV	-25.83	139.33	-37.08	212.86	1.57	POB
Dalby	DAL	-27.18	151.20	-37.30	226.53	1.58	DAC, UNC
Adelaide	ADE	-34.67	138.65	-46.72	213.34	2.13	DSTO

1.18, $\Phi \sim 270°$), Hawaii, the same magnetometer system was installed in January, 1991.

In June, 1991, fluxgate magnetometer systems were also installed at Onagawa (ONW: L = 1.38) in Japan, at Wewak (WEW: 1.06) in Papua New Guinea, and at Guam (GUA: 1.03) in USA. We completed installation of the magnetometer systems at Dalby (DAL: 1.58), Darwin (DAW: 1.18), and Learmonth (LMT: 1.47) in Australia in the summer of 1991. We are now planning to extend the 210° magnetic meridian chain to northern high latitudes in Siberia in 1992, in cooperation with IFZ, IKIR, YaKFIA and IZMIRAN in Russia. The proposed stations are located at St. Paratunka (L = 2.11), Magadan (2.85), Chokurdakh (5.50), and Zhokhova island (9.05).

Magnetic variation data (ΔH, ΔD, ΔZ, dH/dt, dD/dt, dZ/dt) from MSR, KAG, WEP, BSV and ADE are obtained by means of a ring-core-type fluxgate magnetometer, with the same data logging system (DCR-3, KOSMO Ltd.) at all stations and a time signal generator as shown in Fig. 2. The sensitivity of ordinary analogue outputs $V_O(\Delta H, \Delta D, \Delta Z)$ in the 0–2.5 Hz frequency range is ±300 nT/±10 volt. The time-derivative components (V_{TD}) are obtained by putting an analogue circuit at output terminals of the ordinary components (V_O). The frequency response curves of output voltages (V_{TD}) and phase shifts $\Delta\Phi(V_{TD} - V_O)$ for the differential components (dH/dt, dD/dt, dZ/dt) are shown in Figs. 3(A) and 3(B), respectively, against the magnetic field variations $V_O(\Delta H, \Delta D, \Delta Z)$. The time-derivative components in the frequency range of <0.1 Hz exhibit essentially the same frequency response as an induction magnetometer. This permits ready comparison of the records with other different instruments. The noise level of the magnetometer system is less than 0.1 nT rms equivalent. The 6 magnetic components (ΔH, ΔD, ΔZ, dH/dt, dD/dt, dZ/dt) and time pulses (1 min, 1 hr, 24 hr) are recorded on a digital cassette tape using the digital data logger with a sampling rate of 1 sec and 16 bit resolution of 0.012 nT/LSB. Each cassette tape holds 21 days data. Fluxgate magnetometer data from CBI station, the Kakioka Magnetic

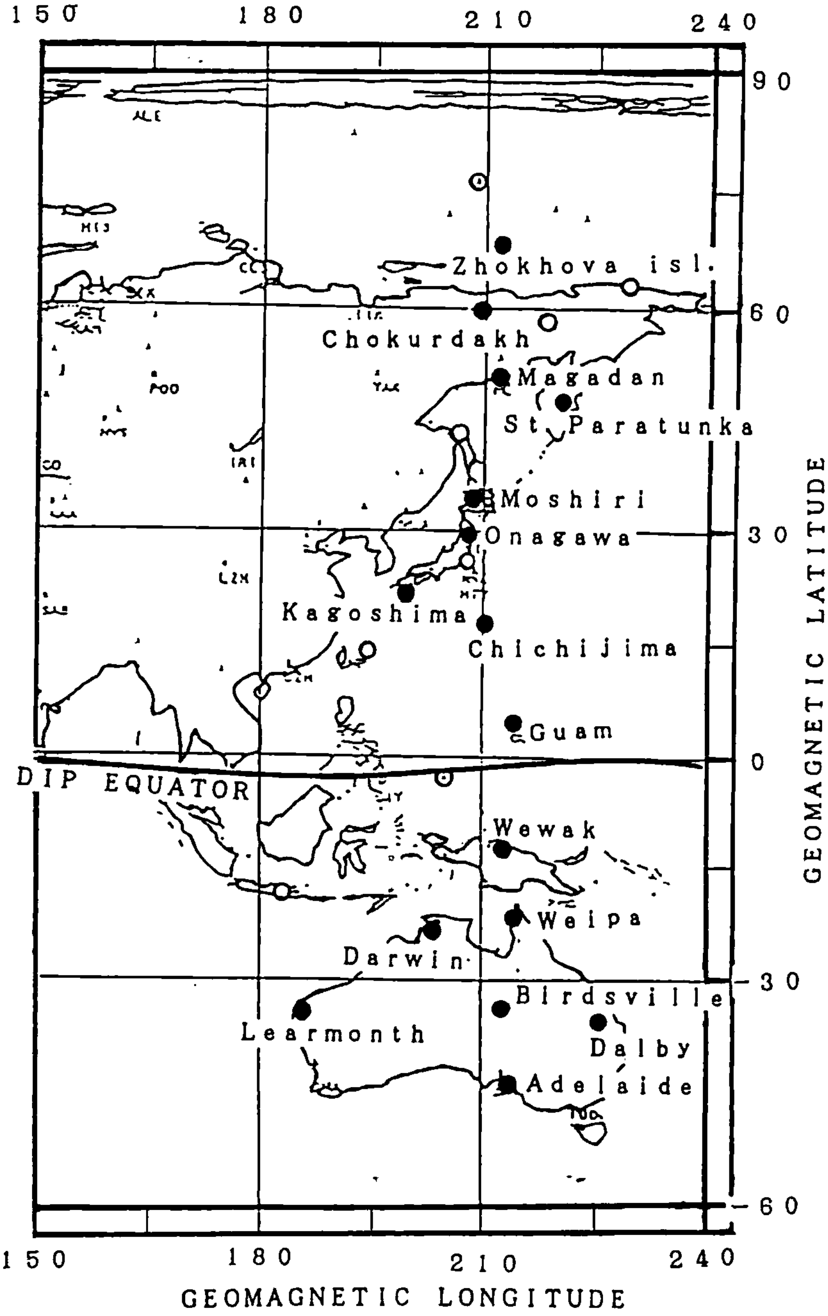
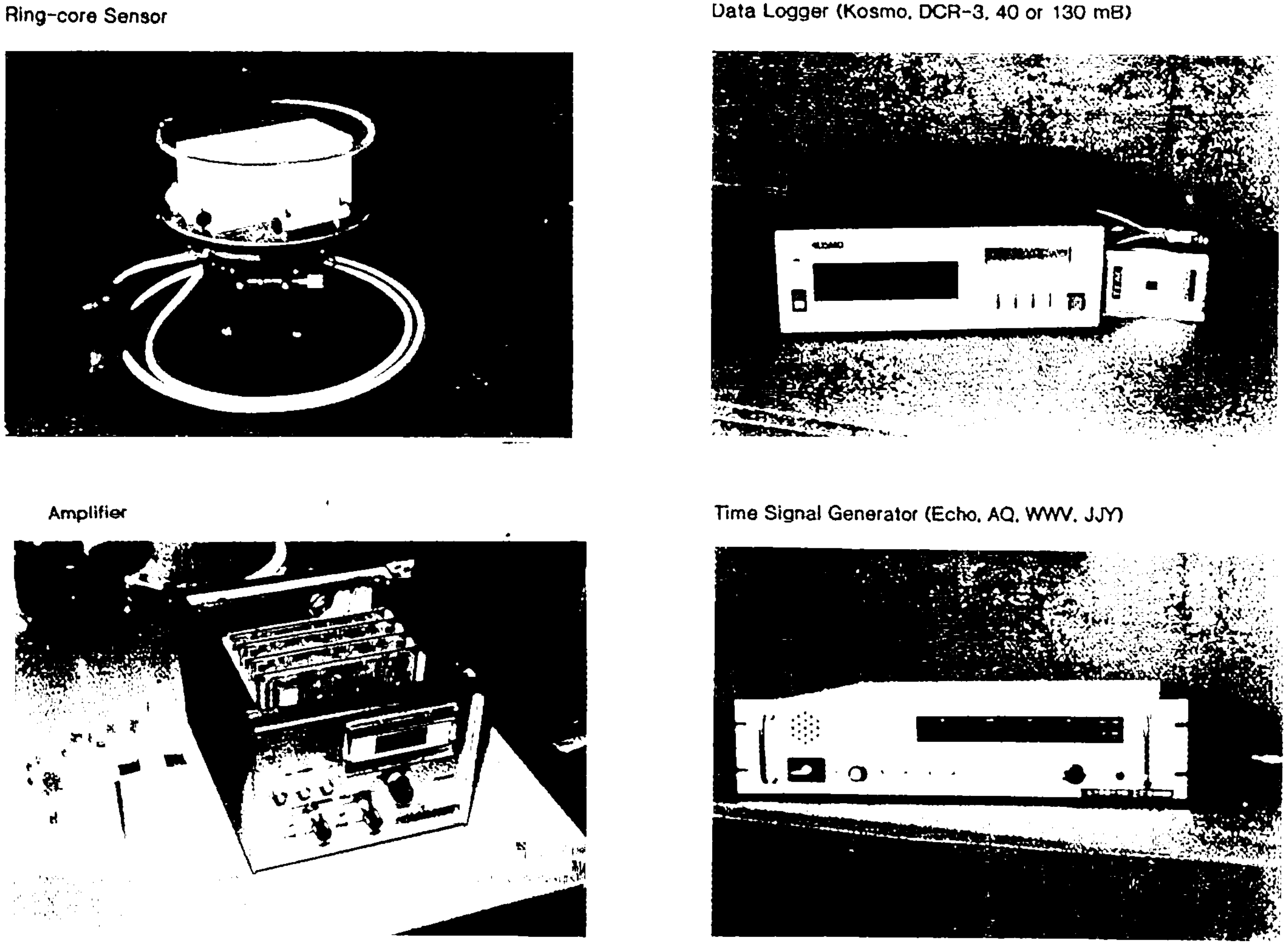


Fig. 1. Map showing the locations of 210° magnetic meridian chain stations in geomagnetic coordinates.

Observatory, are registered by the same logging system. The pulse signals (1 min, 1 hr, 24 hr) from the time signal generator, which are maintained accurate to within +/– 25 ms by automatic comparison with standard radio transmissions from WWVH (Maui, Hawaii), JJY (Koganei, Japan) and Omega, are also recorded on the digital cassette tape to check the crystal clock inside the data logger.

It is planned to continue routine magnetic observations along the 210° magnetic meridian chain stations during the STEP period. For effective data exchange and analyses, the



Ring-core Sensor

Data Logger (Kosmo, DCR-3, 40 or 130 mB)

Amplifier

Time Signal Generator (Echo, AQ, WWV, JJY)

Fig. 2. Fluxgate magnetometer system consisting of ring-core sensor, amplifier (Tokin LTD., TRM-20 and handmade), cassette tape digital data recorder (Kosmo LTD., DCR-3A), and time signal generator (Echo LTD, AQ-200).

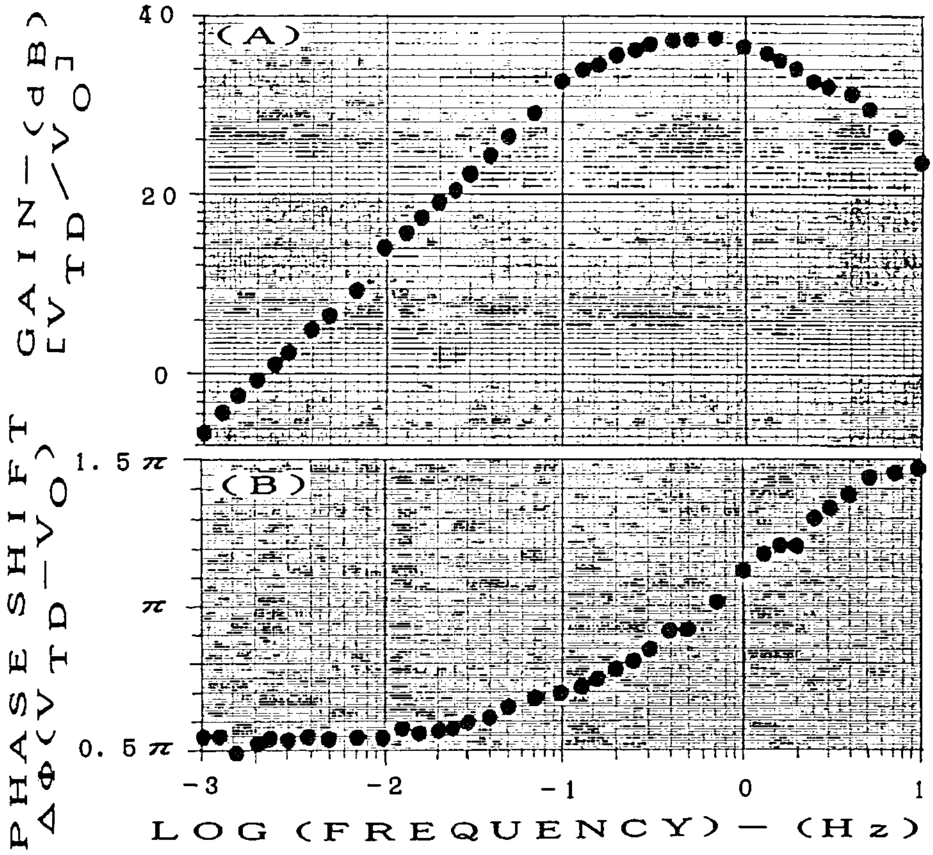


Fig. 3. Frequency response curves of (A) output voltage (V_{TD}) and (B) phase shift $\Delta\Phi(V_{TD} - V_O)$ of (dH/dt, dD/dt, dZ/dt) components against magnetic field variation $V_O(\Delta H, \Delta D, \Delta Z)$. The time-derivative components in the frequency range <0.1 Hz exhibit nearly the same frequency response as an induction magnetometer.

magnetic data will be compiled for the international research community through the cooperation of the data analysis group of the STE Lab., Nagoya Univ. One min-averaged magnetic data and a data catalogue will be opened to the public by means of the STEP networks, and also through appropriate international networks (see Annual Report of STEL, Nagoya Univ., 1990). The distribution of high time resolution 1 second data will be limited to the STEP scientists, who can collaborate with the project team of magnetic observations along the 210° magnetic meridian (MM). The high time resolution data will be used only in conjunction with other data sets provided by the scientists performing these studies. The contact person for the collaboration is K. Yumoto, STE Lab., Nagoya Univ.

3. Power Spectral Analysis of Low-Latitude Pc 3's

In order to clarify the latitudinal variation in spectral power of low-latitude Pc 3 pulsations, we analyzed magnetic data obtained simultaneously at the 6 stations during the period July 26 to August 20, 1990. The spectral power curve for each 2048 sec data block was calculated using the Fast Fourier Transform method.

Figure 4 shows superimposed power spectral curves of H-component magnetic variations during 03–19 local time (LT) at 135°E geographic longitude on August 14, 1990, as a function of corrected geomagnetic latitude of the stations (WEP, KAG, MSR, ADE). It is found that there are two dominant spectral components. One, in the 20–50 sec period range shows a larger power at higher latitude, i.e., ADE (L = 2.13), and decreases with decreasing magnetic latitude. The other, in the 10–20 sec period range, shows maximum power around MSR and BSV (L = 1.57–1.60), and decreases with increasing distance from these stations. This spectral structure could be seen in all the analyzed power spectra during the period July 26 to August 20, 1990.

We statistically examined latitudinal profiles of the longer and shorter period components of low-latitude Pc 3 signals, by passing these through the Finite Impulse Response digital bandpass filter (RABINER, 1971) centered on the event's dominant frequency.

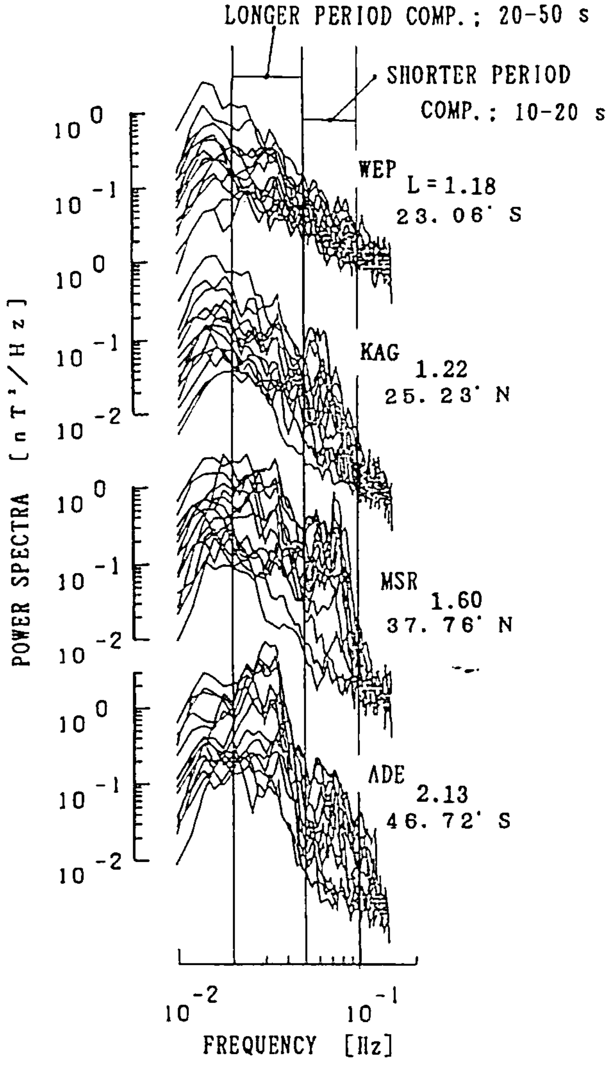


Fig. 4. Superimposed power spectra of H-component Pc 3 magnetic variations observed at the 210° magnetic meridian stations (WEP: L = 1.18, KGS: 1.22, MSR: 1.60, ADE: 2.13) on August 14, 1990.

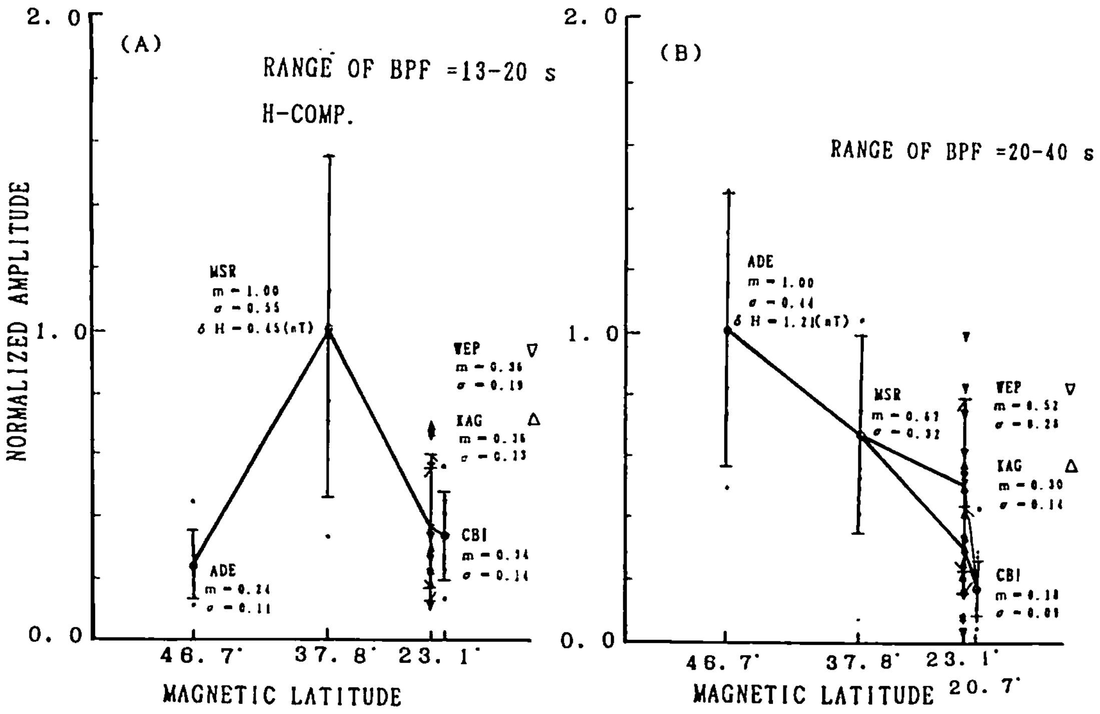


Fig. 5. Latitudinal profiles of normalized amplitudes of (A) shorter-period and (B) longer-period Pc 3 pulsations observed at 210° magnetic meridian chain stations between L = 1.14 and L = 2.13. m, σ, δH indicate the mean value of normalized amplitude ranges, the standard deviation, and the averaged amplitude range, respectively.

The averaged amplitude range and standard deviation of the shorter period component were plotted as a function of absolute magnetic latitudes of the 6 stations, and found to be δH = 0.11 + 0.05 nT, 0.45 + 0.25 nT, and 0.16 + 0.09 nT at ADE, MSR (BSV), and WEP, respectively (see Fig. 5(A)). For the longer period component at L = 2.13, 1.60 (1.57), and 1.18 these are δH = 1.21 + 0.53 nT, 0.81 + 0.39 nT, and 0.50 + 0.25 nT, respectively (see Fig. 5(B)). Averaged D-component amplitudes of both the shorter and longer period of Pc 3's are smaller than half that for the H components, but show latitudinal profiles similar to the longer-period H components.

4. Latitudinal Phase Structure of Low-Latitude Pc 3's

Phase relationships of the shorter and longer period Pc 3 magnetic pulsations detected simultaneously at the L = 1.14–2.13 array stations were also examined with the objective of identifying modes of the ULF waves.

An example of amplitude-time records of H and D components at the 6 stations, after bandpass filtering in the shorter period Pc 3 range, is shown in Fig. 6 for the interval 0329–0335 UT on July 28, 1990. Cutoff periods and cutoff power level of the FIR filter for this event are 15.0–20.0 sec and –60 dB, respectively. A maximum in amplitude of the H-component shorter-period Pc 3's appears at MSR and BSV at L = 1.57–1.60. Correlation function coefficients of the H-component amplitude-time records at (CBI, MSR), (CBI, KAG), (MSR, BSV), (WEP, BSV) and (ADE, WEP) for this interval were found to have peak coefficients for specific phase displacements of (ρ_{xy} = 0.50, θ_{xy} = 160°), (0.68, 0°), (0.99, 0°), (0.65, 180°), and (0.80, −20°), respectively. The D components show nearly in-phase relationships with peak coefficient for $\theta_{xy} \sim 0°$ among all stations in the individual

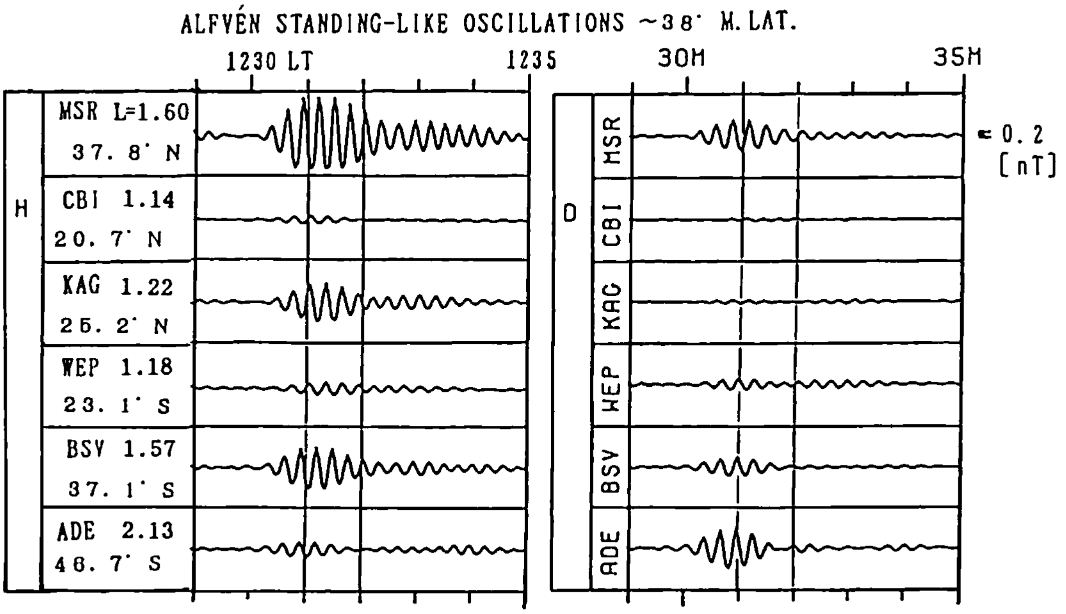


Fig. 6. H- and D-component amplitude-time records of shorter-period Pc 3's at the 210° magnetic meridian stations of MSR, CBI, and KAG in the northern hemisphere and WEP, BSV, and ADE in the southern hemisphere on July 27, 1990. Sensitivity of the records is represented by a 0.2 nT scale on the right.

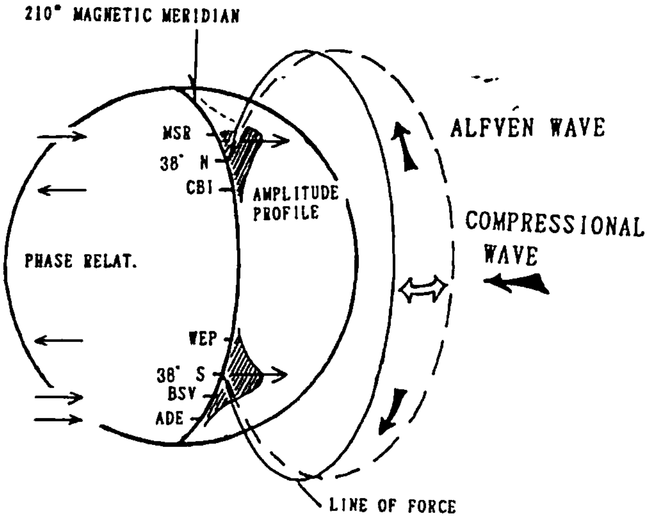


Fig. 7. Schematic illustration of a possible model for the shorter period (10–20 sec) Pc 3 magnetic pulsations at low latitudes; torsional Alfvén resonance oscillation around 38° magnetic latitude.

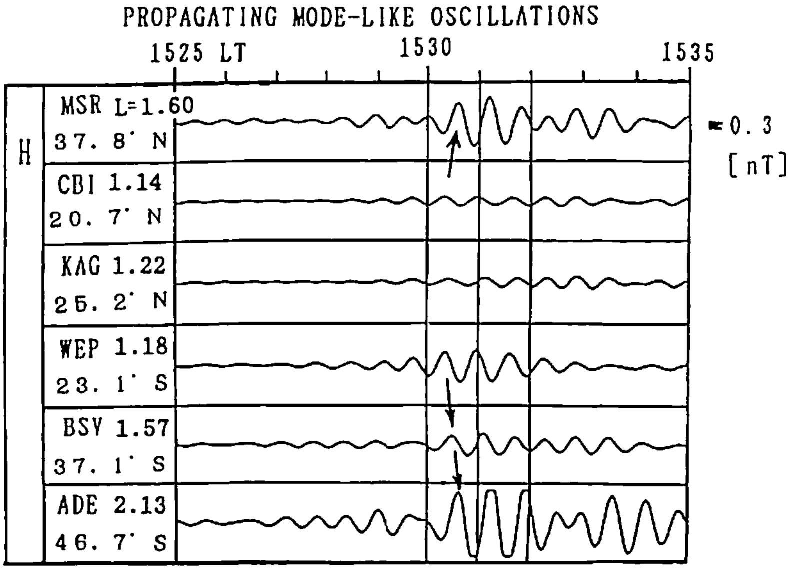


Fig. 8. One example of amplitude-time records of longer-period Pc 3's observed at the 210° magnetic meridian stations of MSR, CBI, and KAG in the northern hemisphere and WEP, BSV, and ADE in the southern hemisphere on July 27, 1990. Sensitivity of the records is represented by a 0.3 nT scale on the right.

hemisphere, and out-of-phase relation of ($\rho_{xy} = 0.90$, $\theta_{xy} = -180°$) between the magnetic conjugate stations of MSR and BSV. The H-component shorter-period Pc 3's exhibit phase reversal around the amplitude maximum. This is evidence of a standing field-line resonance oscillation (e.g., CHEN and HASEGAWA, 1974; SOUTHWOOD, 1974) around $L \sim 1.57$ as shown in Fig. 7.

After passing through the narrow-band digital filter, the same cross correlation analysis was performed for the longer period (20–50 sec) low-latitude Pc 3's. We found three different types of phase relationships as follows.

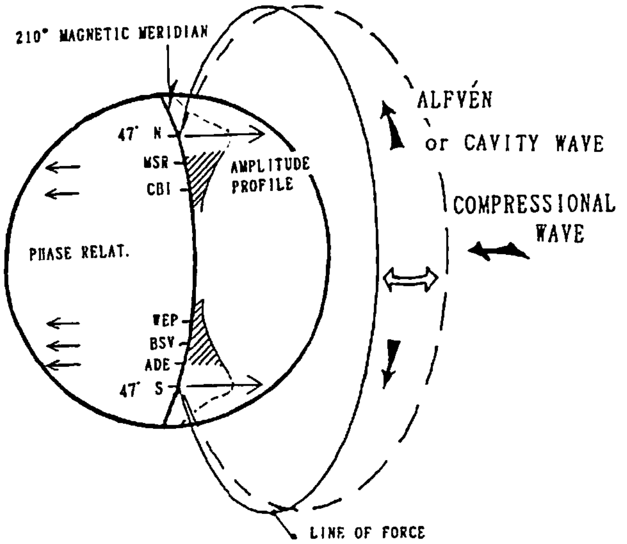
(a) All H-component magnetograms at $L = 1.1$–2.1 show nearly the same phase relationship in both the northern and southern hemisphere. The D components show nearly the same phase relationship in the same hemisphere, but an out-of-phase character between the northern and southern conjugate stations.

(b) The H- and D-components at MSR and BSV show almost in-phase and out-of-phase characteristics, respectively. However, both the H- and D-components show phase delay of ~45° from lower to higher latitude.

(c) The phase delays on amplitude-time records from $L = 1.18$ to 1.57 and from 1.57 to 2.13 are larger than 90° as shown in Fig. 8.

Signals of type (a) and (b) may be associated with a standing field-line resonance oscillation with a demarcation line at $L > 2.1$ and a second-harmonic cavity resonance oscillation in the plasmasphere (see Fig. 2 of ITONAGA *et al.*, 1992; YUMOTO and SAITO, 1983; ALLAN *et al.*, 1986), respectively, as shown in Fig. 9(A). The type (c) signals could be explained by a propagating HM wave mode as illustrated in Fig. 9(B).

(A) TORSIONAL ALFVÉN RESONANCE OSCILLATION AT ≧47° M. LAT.
or CAVITY RESONANCE OSCILLATION IN THE PLASMASPHERE



(B) PROPAGATING OSCILLATIONS

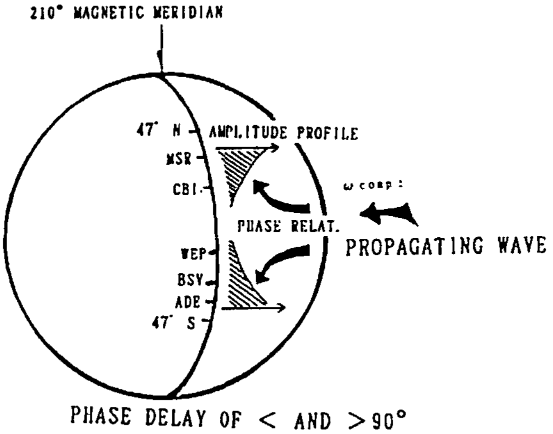


Fig. 9. Schematic illustration of possible models for the longer period (20–50 sec) Pc 3 magnetic pulsations at low latitudes; (A) torsional Alfvén resonance oscillation at >48° magnetic latitude or a second-harmonic cavity resonance oscillation. (B) propagating mode Pc 3 waves at low latitudes.

5. Evidence of Cavity-mode Low-Latitude Pc 3's

Two types of spectra are predicted by MHD theory (YUMOTO and SAITO, 1983; KIVELSON and SOUTHWOOD, 1986; ALLAN *et al.*, 1986; YUMOTO *et al.*, 1990). One is the continuous shear Alfvén spectrum with spatially varying resonant frequencies. The other is the discrete compressional spectrum with spatially independent eigen frequencies (see LEE and LYSAK, 1990). However, except for low-latitude Pi 2 pulsations (YUMOTO, 1990; SUTCLIFFE and YUMOTO, 1991; ITONAGA *et al.*, 1992), few satellite and ground-based observations of the global mode or the coupling between these two modes have been reported.

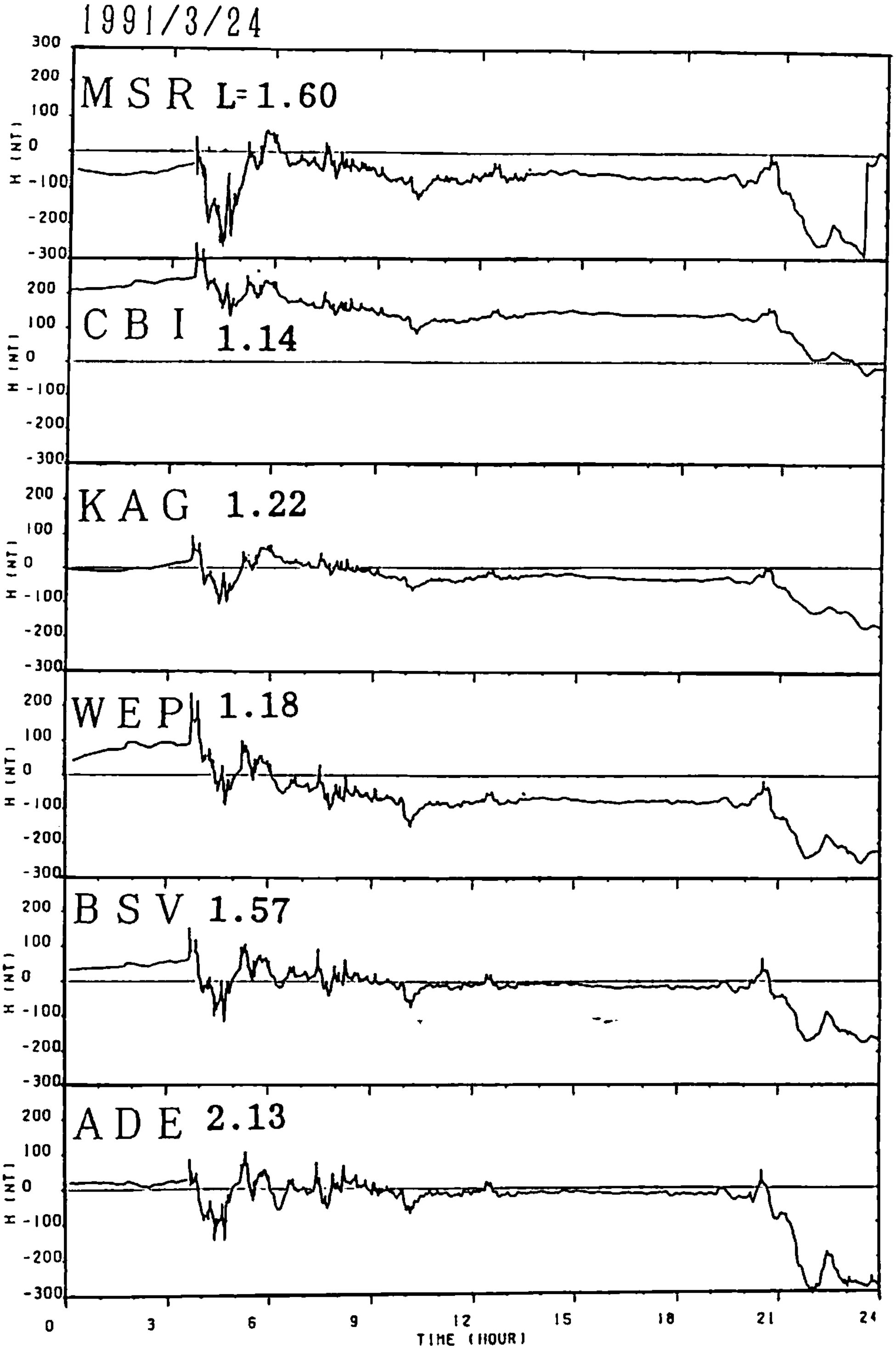


Fig. 10. H-component amplitude-time records of ssc storm event observed simultaneously at the 210° magnetic meridian chain stations of MSR, CBI, and KAG in northern hemisphere and WEP, BSV, and ADE in southern hemisphere on March 24, 1991.

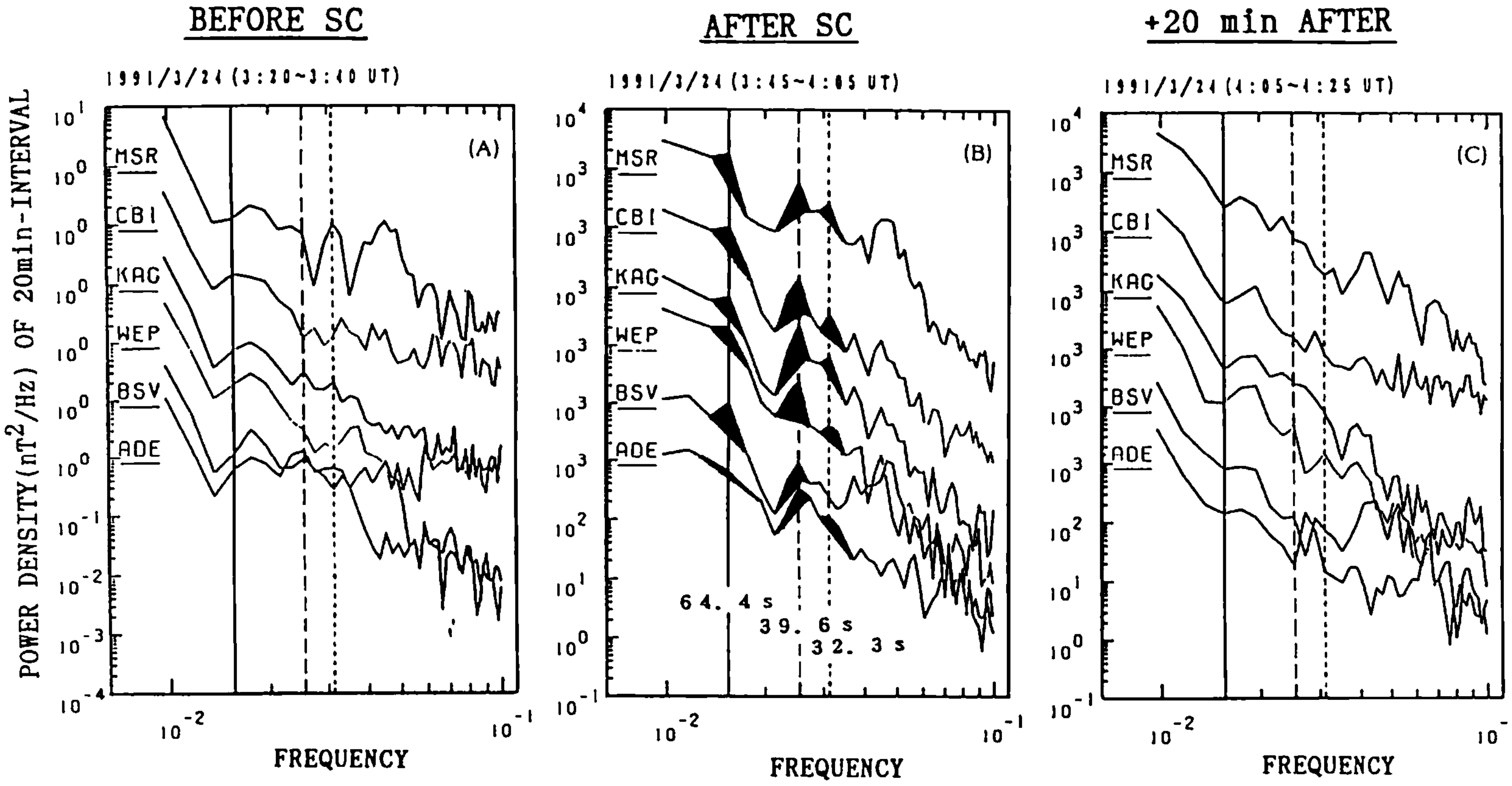


Fig. 11. Superimposed power spectra of H-component magnetic variations observed at the 210° magnetic meridian stations (MSR, CBI, KAG, WEP, BSV, and ADE) in the intervals (A) 0320–0340 UT just before the event, (B) 0345–0405 UT and (C) 0405–0425 UT just after the ssc event at 0342 UT on March 24, 1991.

The meridional chain station data have been examined in order to investigate whether or not such cavity mode oscillations can be stimulated by impulsive source waves, e.g., ssc and si, in the real inner magnetosphere. Figure 10 shows one example of H-component magnetograms obtained at the meridional chain stations of MSR, CBI, KAG, WEP, BSV, and ADE on March 24, 1991. A ssc occurred at 03:42 UT. The magnitude of the initial impulse (ssc) was $\delta H \sim 202$ nT at Kakioka Magnetic Observatory. This is among the largest ssc events observed at Kakioka. Magnetograms during the period 03:40–09:00 UT show an asymmetry between the northern and southern hemisphere, caused by asymmetries of the field-aligned and ionospheric current systems formed during the magnetic storm. Further statistical, quantitative study of the asymmetry will be detailed in a future paper.

Power spectrum densities of 20-min interval pulsation data at the 6 chain stations were calculated as shown in Fig. 11 to examine if a cavity mode oscillation can be stimulated after the impulsive ssc event. The left, middle and right panels indicate superimposed power spectral curves of H-component magnetic variations observed during the period 03:20–03:40 UT just before the ssc event, and in the intervals 03:45–04:05 UT and 04:05–04:25 UT just after the event, respectively. Power spectrum levels of pulsations after the ssc event became $>10^3$ times higher than those before the event. The local standing field-line oscillation in the shorter-period Pc 3 range with maximum amplitude at MSR and BSV (L = 1.57–1.60) was also activated after the ssc event. It is noteworthy that spectral peak around 15.5 mHz, which did not exist before the ssc but appeared after the event, shows exactly the same frequency at the different L = 1.1–2.1 locations, and similar power levels of $\gtrsim 10^3$ (nT^2/Hz). This frequency is indicated by a solid vertical line (64.4 s) in the panels. Higher harmonic components at 25.3 and 31.0 mHz were also stimulated after the ssc event. The right panel shows that these global mode Pc 3 pulsations with the same frequency at different locations continued for about 20 min. These wave features can be explained by invoking a cavity mode oscillation in the plasmasphere or in the magnetosphere. However, further simultaneous global observations from high to low latitudes are needed to clarify the wave characteristics, latitudinal amplitude and phase structure of such events, and to establish the cavity mode Pc 3 pulsations existing in the real magnetosphere.

6. Summary and Conclusion

The preliminary results of the analyses of low-latitude Pc 3 pulsation data recorded along the 210° magnetic meridian can be summarized as follows.

(1) There are two spectral peaks of low-latitude Pc 3's (see Figs. 4 and 5). One component is in the 20–50 sec period range and shows a larger power at higher latitude, e.g., ADE (L = 2.13), decreasing with decreasing magnetic latitude. The other component is in the 10–20 sec period range and shows maximum power around MSR and BSV (L = 1.57–1.60), decreasing with increasing distance from the stations.

(2) Latitudinal phase and amplitude structures of the shorter period Pc 3's imply a standing field-line resonance oscillation around $L = 1.58$ as illustrated in Fig. 7.

(3) Latitudinal phase and amplitude structures of the longer period Pc 3's indicate three different characters of a standing field-line oscillation at $L > 2.1$, a second-harmonic cavity resonance oscillation with smaller phase delay in the plasmasphere, and propagating-mode waves with larger phase delays from lower to higher latitudes as shown in Figs. 9(A) and 9(B).

(4) The ssc with $\delta H \sim 215$ nT magnitude at $L = 1.22$ on March 24, 1991, was found to stimulate cavity-mode Pc 3 pulsations with a duration time of <20 min, with the same frequency and similar power density over $L = 1.14$–2.13.

Results (1) and (2) suggest that there is a peculiar region around $L = 1.57$ where a standing field-line resonance oscillation can be excited easily in the deep inner magnetosphere. The inner peculiar region may be associated with the plasma wave turbulence disc observed by the Akebono (Exos-D) satellite (OYA *et al.*, 1991). Question (3), whether the longer-period Pc 3 waves can be interpreted as a field-line oscillation at $L > 2.1$ or a second-harmonic cavity resonance oscillation in the plasmasphere, will be clarified by analyzing simultaneous observation data from higher latitudes along the 210° magnetic meridian. The "propagating" mode of longer-period low-latitude Pc 3's, having larger amplitude at higher latitude and phase delay from lower to higher latitudes, cannot be explained by using the existing theory. Further observational and theoretical studies are needed to interpret and establish the evidence of "propagating" mode Pc 3 pulsations at low latitudes.

Future studies using the globally coordinated 210° magnetic meridian stations will be focused on obtaining unique information on (1) ULF wave energy transfer processes from high latitude through middle and low latitudes to the equatorial region, (2) coupling processes of magnetospheric disturbances at auroral, middle, low and equatorial latitudes, and (3) conjugacy of fine-scale geophysical phenomena observed in the northern and southern hemisphere.

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