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CHARACTERISTICS OF Pc 3 MAGNETIC PULSATIONS IN CONJUGATE AREA AROUND L=1.3–2.1

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Abstract: In order to establish both our theoretical and experimental researches on low-latitude Pc 3 magnetic pulsations, we carried out the Japan–Australia magnetic conjugate observations at Asahikawa (ASH; λ=142.2°, ϕ=43.93°, L=1.55), Onagawa (ONW; 141.48°, 38.43°, 1.30) in Japan and Birdsville (BSV; 139.3°, −25.83°, 1.55), *i.e.*, the conjugate point of ASH, Dalby (DAL; 151.2°, −27.18°, 1.56) and St. Kilda (SKD; 138.5°, −34.7°, 2.11) in Australia during the period from 20 July to 16 September 1986. From the analysis of these conjugate-station data, occurrence and polarization characteristics of low-latitude Pc 3 pulsations are found as follows; (1) The average amplitudes at SKD (L=2.1) is about 2.5 times of that at BSV (1.55). (2) The H-component amplitude at BSV in the winter hemisphere is larger than that at ASH in the summer hemisphere. (3) The polarizations at all northern (soushern) stations switch statistically from left- (right-) handed in the morning to right- (left-) handed in the afternoon. Where polarization senses are given by a view looking down onto the earth in each hemisphere. (4) However, the switch from L-H (R-H) to R-H (L-H) polarization at the conjugate northern (southern) stations (L=1.55) is found not to be always occurring near local noon, and sometimes occur at ~5 and ~17 h local time. (5) The abrupt changes of major axis orientations of Pc 3 polarization ellipses appear to coincide with the E-layer ionization enhancement and depression, associated with local sunrise and sunset, respectively.

1. Introduction

It has been generally considered that polarization changes of magnetic pulsations observed on the ground are related to the resonant structure of hydromagnetic oscillation in the magnetosphere (CHEN and HASEGAWA, 1974; SOUTHWOOD, 1974; LANZEROTTI *et al.*, 1974; YUMOTO, 1985). A switch in the Pc 3 polarizations near local noon at low latitudes has been interpreted by a switch in sign of the azimuthal wave propagation direction (FRASER and ANSARI, 1985; SAKA and KIM, 1985; YUMOTO *et al.*, 1985b). Some authors think that the observations can be better explained by a Kelvin-Helmholtz instability source with a switch in the azimuthal propagation direction being produced by the separation of the solar wind flow around the nose of the magnetopause (*e.g.*, SOUTHWOOD, 1983). However, at lower latitudes dominant frequency and activity of Pc 3 pulsations are more effectively controlled by the interplanetary magnetic field (IMF) intensity and the IMF cone angle, respectively (see reviews of YUMOTO, 1986; VERÖ, 1986). On the basis of simultaneous ground-satellite observations of Pc 3 pulsations, WOLFE *et al.* (1985) and YUMOTO *et al.* (1985a) concluded that upstream waves transmitted through the magnetosheath and the magnetopause can be a major source of low-latitude Pc 3 pulsations. YUMOTO and SAITO (1983) theoretically demonstrated that low-latitude Pc 3 pulsations at $L \sim 1.2$–3.0 on the ground are a superposition of diverse coupled-resonance oscillations excited by the compressional source waves in the plasmasphere, *e.g.*, fundamental ($L=1.7$–2.6) and higher harmonic (2.0–L_{pp}) standing field-line oscillations, a trapped oscillation (1.7–L_{pp}), and the compressional Pc 3 source waves.

In order to clarify which of these postulated oscillations in the Pc 3 frequency range dominates at low latitudes, and to establish our theoretical studies, we have carried out the Japan–Australia magnetic conjugate observation in area around $L=$ 1.3–2.1. In the present paper, we will summarize polarization and occurrence characteristics of low-latitude Pc 3 pulsations with respect to the ionospheric conditions above each station.

2. Observation and Data

Conjugate magnetic observations were carried out at Asahikawa (ASH), Onagawa (ONW), Japan, and Birdsville (BSV), Dalby (DAL), St. Kilda (SKD), Australia, from 20 July to 16 September, 1986, in order to establish our theoretical and experimental researches on low-latitude Pc 3 magnetic pulsations. Figure 1 shows the geographic coordinates, locations of magnetic conjugate points and L values. The magnetic conjugate points were calculated from 1985 international geomagnetic field reference (IGRF) model. The BSV site ($L=1.55$) is the magnetic conjugate point of Asahikawa in Japan. The ONW (1.30) and SKD (2.11) sites are located near the same meridian of the conjugate points. The DAL site is located near the same latitude and $\sim 12°$ east in geographic longitude of the conjugate station, BSV.

Magnetic pulsation data signals at ASH, BSV, DAL, and SKD were obtained by means of rulfmeters (ring-core-type ULF fluxgate magnetometer) with equipped with similar instruments and data collection techniques. Induction magnetometer data from the Onagawa magnetic observatory are also analyzed to clarify polarization characteristics of Pc 3 pulsations observed simultaneously at the lower latitude during the period of the campaign. Magnetic signals in the frequency range of 0–2.5 Hz obtained by the rulfmeters during a period of one week were registered on an analog cassette tape with extremely low speed (0.18 mm/s). Time signals (1 min, 10 min, 1 h, and 24 h) were also registered on the cassette tape, and they were automatically kept within ± 25 ms accuracy by means of the WWVH (Maui, Hawaii) and JJY (Koganei, Japan) standard radio waves. The analog pulsation signals for one week per one cassette tape were reproduced at a high speed with 254 times speed-up ratio. Amplitude and time resolutions of the reproduced magnetic data of rulfmeters are 0.07 nT and 0.5 s, respectively.

Station	Geographic Long.	Geographic Lat.	Conjugate Point Long.	Conjugate Point Lat.	L =
Asahikawa	142.20°	43.97°	139.37°	-26.07°	1.55
Onagawa	141.48°	38.43°	139.37°	-20.89°	1.30
Birdsville	139.33°	-25.83°	142.18°	43.95°	1.55
Dalby	151.20°	-27.18°	158.44°	44.13°	1.56
St.Kilda	138.50°	-34.70°	143.23°	53.44°	2.11

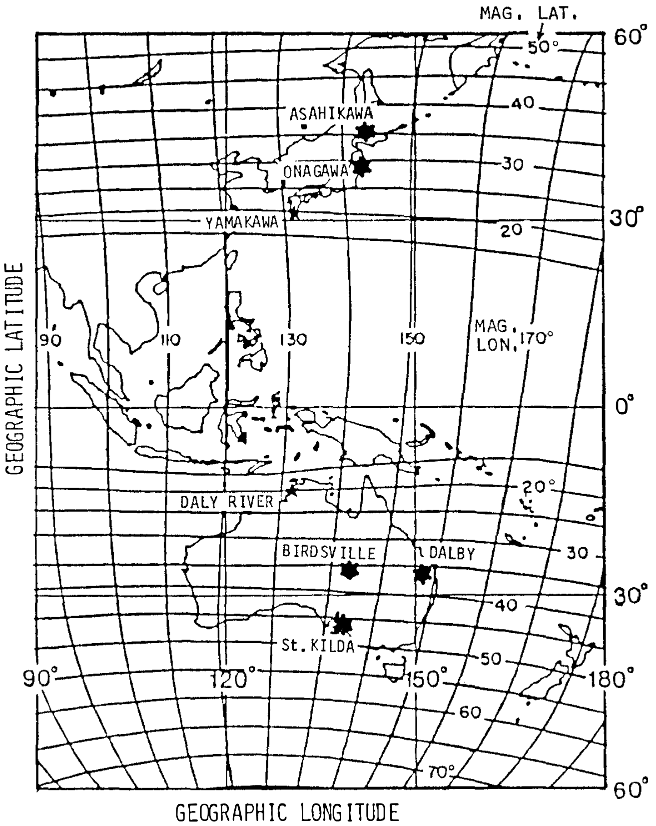

Fig. 1. Map showing the locations of stations in conjugate area around L = 1.3–2.1, for coordinated magnetic observations from July 20 to September 16, 1986. The conjugate points of the stations are calculated by using the 1985 IGRF model.

3. Pc 3 Activities at Low-Latitude Conjugate Station

Activities of low-latitude Pc 3 pulsations detected simultaneously near the conjugate stations (L=1.5–2.1) are firstly clarified to examine whether or not there is a northern and southern asymmetry. An example of Pc 3 amplitude-time records in the H and D component at ASH, ONW, BSV, DAL, and SKD is shown in Fig. 2. Each H (top) and D (bottom) magnetogram are shown after having been passed through a narrow band filter centered at the dominant frequency of individual event. Simultaneous enhancements and depressions of the Pc 3 pulsation activity with ~20 min to ~4 h durations can be seen in the interval from ~0400 to ~1800 local time (LT) of ASH. Impulsive signals during the period from ~1900 to ~0200 ASH LT are Pi 2 magnetic pulsations associated with substorms. In order to avoid contamination from Pi 2 pulsations in the midnight sector, the magnetic data from 1900 to 0300 ASH LT are excluded in the present analysis. Figure 3 shows an example of expanded

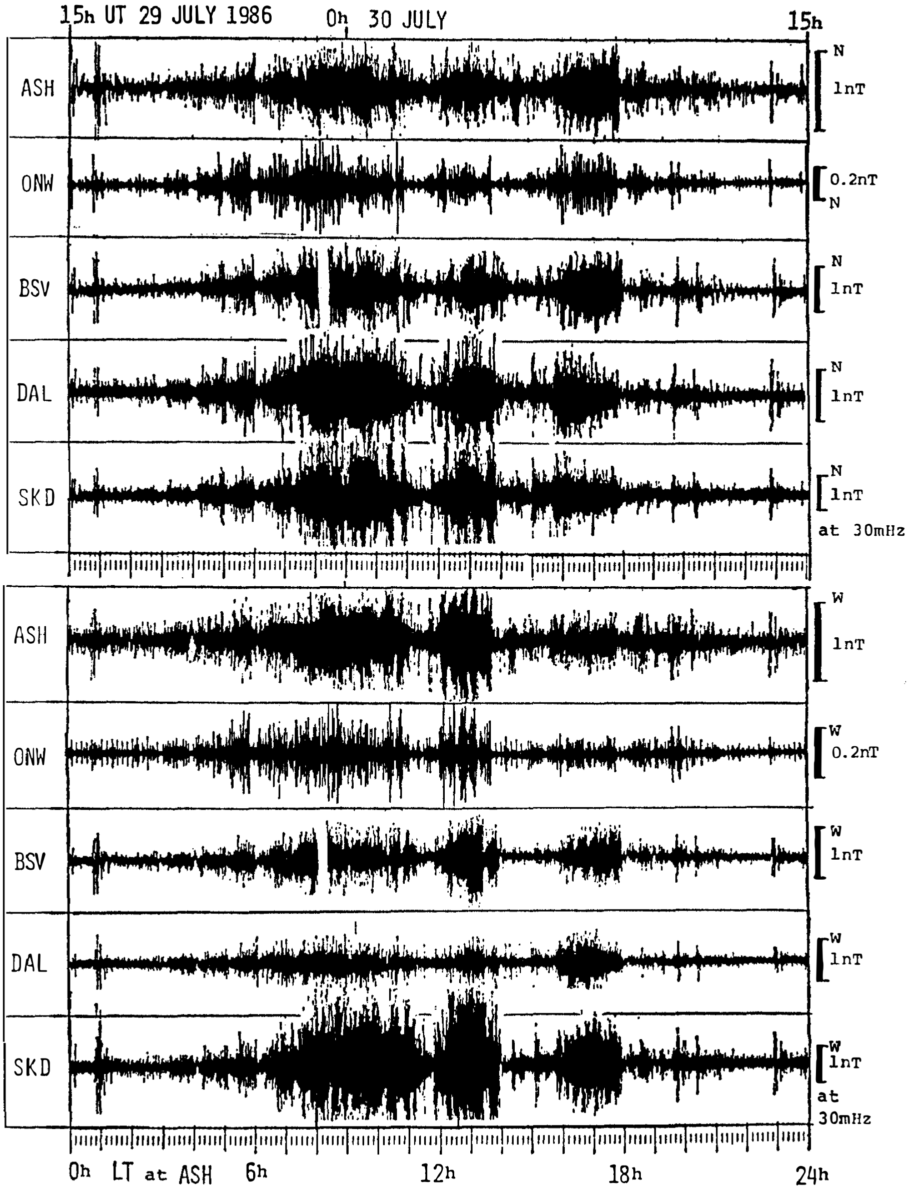

Fig. 2. An example of amplitude-time records of low-latitude Pc 3 pulsations in the conjugate area around L=1.3–2.1. The magnetic data have been filtered through a narrow band-pass filter centered at the dominant frequency of 30 mHz for the event on July 29–30, 1986.

amplitude-time records of low-latitude Pc 3 pulsations obtained simultaneously for the interval of 0350–0410 UT on 3rd August 1986. The center frequency of narrow band filter for the event is 45 mHz. By visual inspection it is found that although Pc 3 wave packets with ~3–5 min duration appear concurrently among each component, a small difference can be seen in the wave forms and the phases between the *H* and *D* components, especially, at the DAL (L=1.56) and SKD (2.11) southern stations which are separated ~12° east in geographic longitude and ~9° south in geographic latitude, respectively, of the BSV site. On the other hand, the Pc 3 wave forms at ASH (1.55) and ONW (1.30) in the northern hemisphere show a quite similarity in each component.

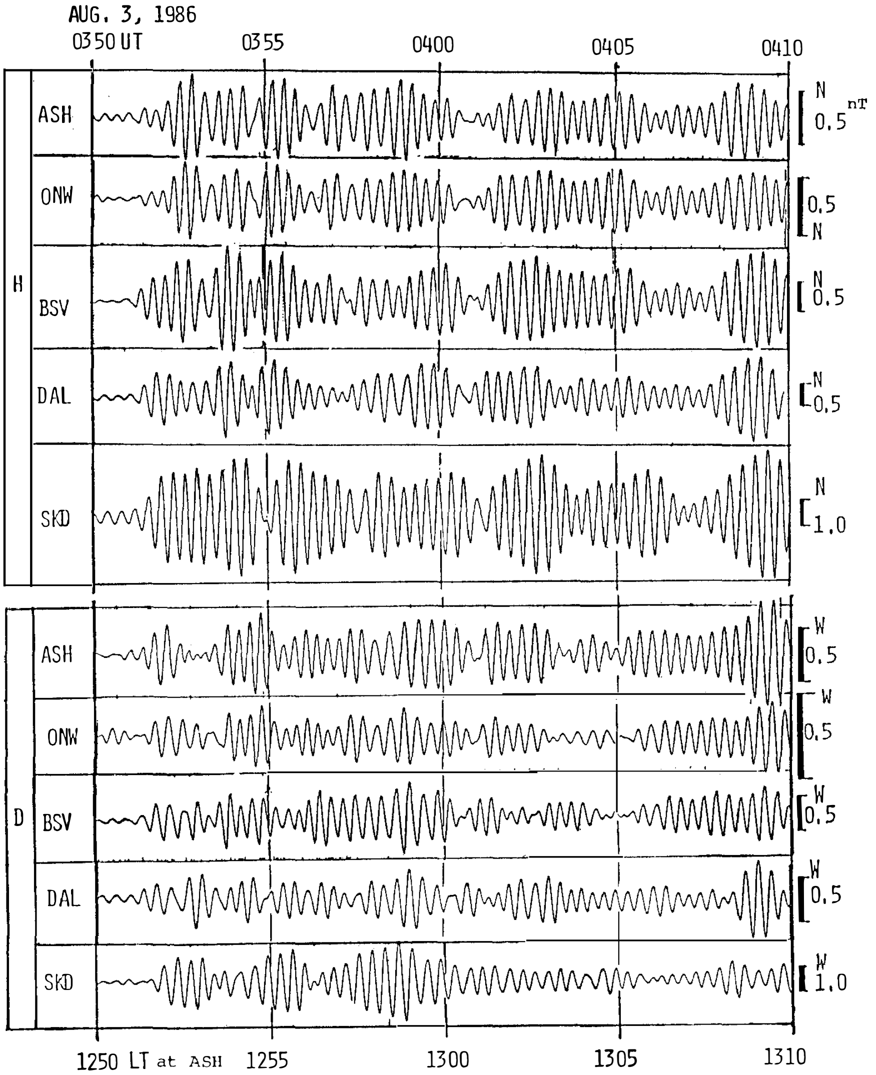

Fig. 3. An example of expanded time-amplitude records of H and D components of low-latitude Pc 3 pulsations having dominant frequency of 45 mHz.

The maximum amplitude ranges (peak-to-peak amplitude) of Pc 3 pulsations for 20 min segments in the H and D component at ASH, BSV, SKD, and DAL are plotted in Fig. 4 as a function of each local time. The time interval of the 20-min segments for Pc 3 events was habitually determined (*cf.* YUMOTO *et al.*, 1985b). Solid curves in each panel indicate averages of the Pc 3 amplitude ranges during from July 25 to August 5, 1986. In order to elucidate relations among Pc 3 activities at the four stations, the averages of Pc 3 amplitudes are represented for the same meridian stations (ASH, BSV, SKD; left panel in Fig. 5) and for the same latitude (BSV, DAL; right one of the figure). The solid thick lines from 0750 to 2140 UT at SKD, from 0800 to 2130 UT at BSV, from 0710 to 2040 UT at DAL, and from 0930 to 1920 UT at ASH, indicate night hours on the basis of f_oE plots of the ionospheric data (*cf.* YUMOTO *et al.*, 1985b). The D-component averages of Pc 3 amplitudes at low latitudes (L=1.5–2.1) are smaller than those in the H component. Especially, simultaneous

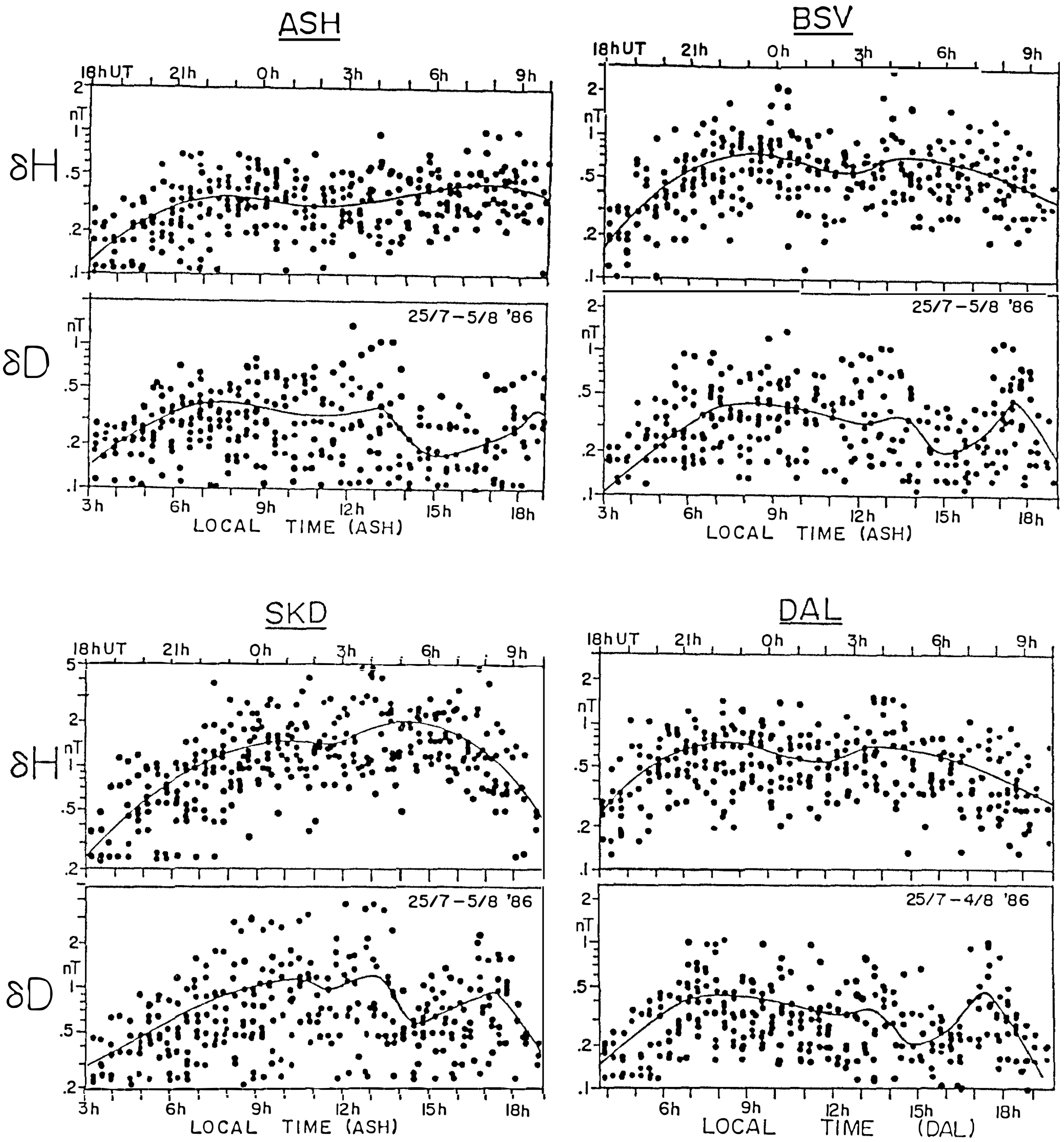

Fig. 4. Diurnal variations of H- and D-component amplitude of low-latitude Pc 3's simultaneously observed in the conjugate area around L=1.3–2.1. The solid curves are the average of the Pc 3 amplitude ranges at each station.

depressions in the D component at the four stations are found to appear in the afternoon sector from ~1300 to ~1700 LT. The Pc 3 amplitudes at SKD (L=2.11), which is believed to be located near a foot point of standing field-line oscillation in the Pc 3 frequency range at L=1.7–2.6 (see YUMOTO, 1986), are approximately 2.5 times of those at BSV (1.55). It is also noteworthy that the Pc 3 amplitude ranges in the H component at BSV in the winter hemisphere are larger than those at ASH in the summer hemisphere, whereas the averaged amplitudes in the D component are comparable at the low-latitude conjugate stations. The northern and southern asymmetry of Pc 3 activities in the H component at ASH and BSV (L=1.55) is a new finding.

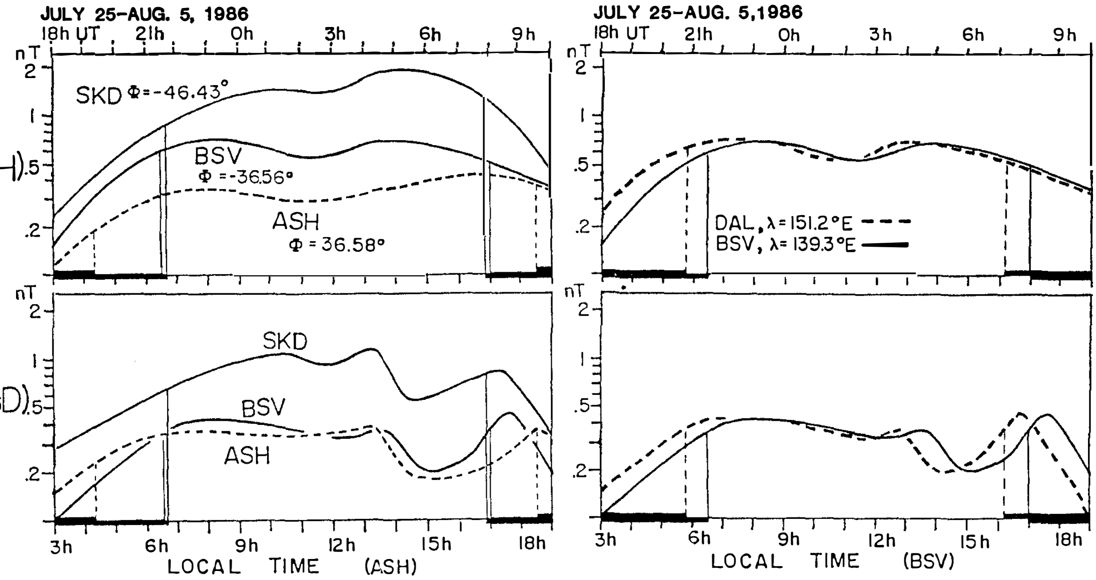

Fig. 5. Diurnal variations of the averaged Pc 3 amplitudes obtained in Fig. 4 near the same meridian (ASH, BSV, SKD; left panel) and at the same magnetic latitude (BSV, DAL; right panel). Solid thick lines in the abscissa indicate night time in the ionosphere with respect to the ionospheric f_0E data.

Although more statistical studies with respect to the seasonal and solar cycle dependences of the ionospheric conductivity are required to establish the results as shown in Fig. 5, we can explain the observational fact by using the asymmetry of the ionospheric conductivity in the summer and winter hemisphere. The details of theoretical discussions will be the subject of a later paper. Local time dependence of the averaged Pc 3 amplitudes at the same magnetic latitude (BSV, DAL) is illustrated in the right panel of Fig. 5. The averaged Pc 3 amplitude at DAL (dotted line) which is located ~12° east of BSV is found to be quite similar to that at BSV (solid line), shifted about 50 min toward earlier local time. These facts indicate that Pc 3 activities observed on the ground at low latitudes (L=1.5–2.1) depend on the diurnal variation of ionospheric conductivities above each station.

4. Pc 3 Polarizations at Low-Latitude Conjugate Stations

In order to clarify statistical and sequential characteristics of Pc 3 polarizations observed simultaneously at the low-latitude five stations (see Fig. 1), we analyzed magnetic pulsation data during the period from July 25 to August 5, 1986.

Figure 6 shows statistics of Pc 3 polarizations in the H-D plane at ASH, ONW, BSV, DAL, and SKD, as a function of each local time. Open, shaded, dotted, and solid areas indicate left-hand, linear, mixed, and right-hand polarization, respectively, from a view looking down onto the earth in each hemisphere. Statistically, the Pc 3 polarizations at the northern (southern) station at L=1.30–2.11 are left-handed (right-handed) in the local morning hours and right-handed (left-handed) in the local evening hours, which is consistent with the previous studies on Pc 3 polarizations both at low latitudes (L=1.5–2.7) (*cf.* LANZEROTTI *et al.*, 1981; FRASER and ANSARI, 1985; YUMOTO

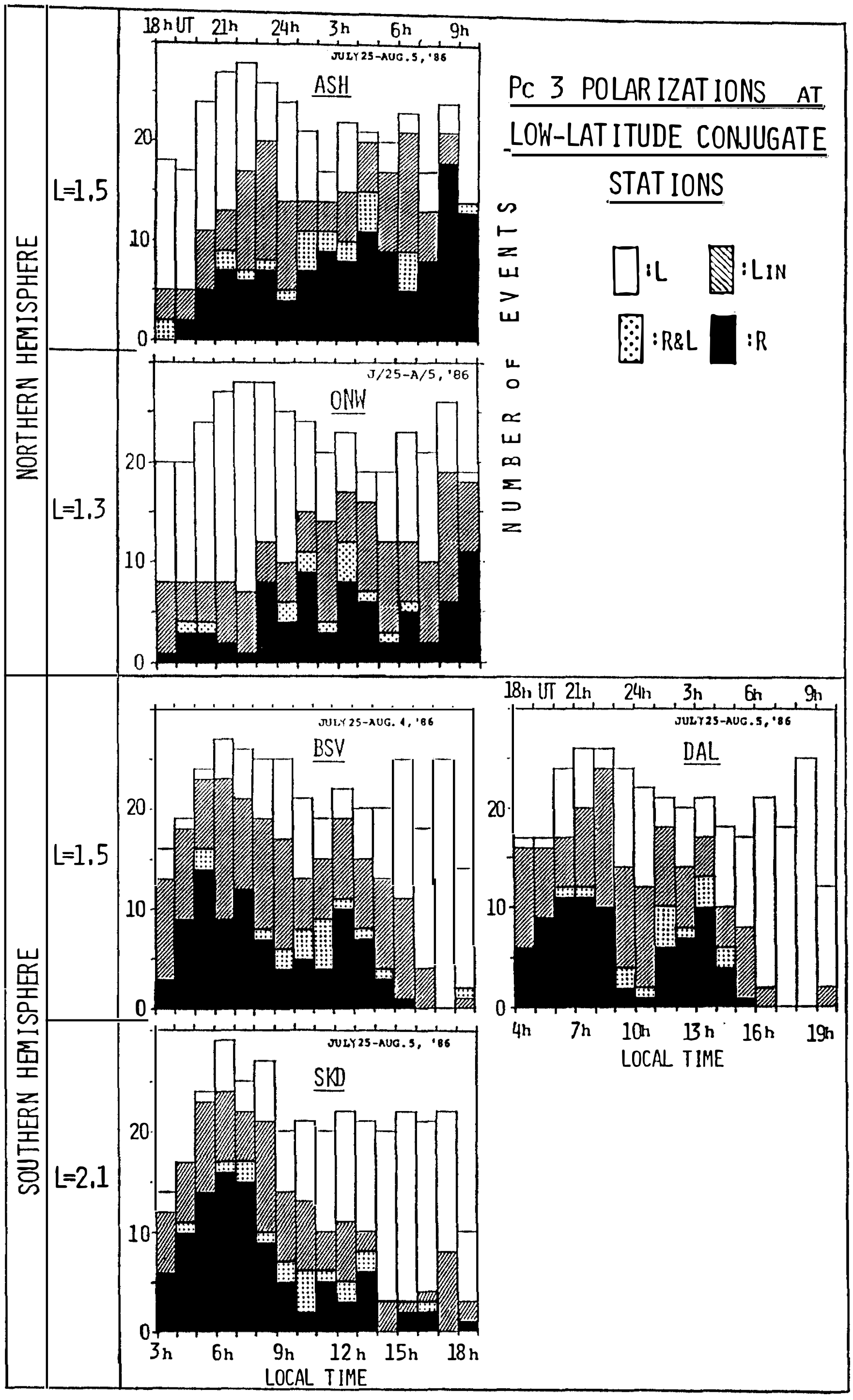

Fig. 6. Statistical, diurnal variations of low-latitude Pc 3 polarizations in the H-D plane in the conjugate area around L=1.3–2.1. Open, shaded, dotted, and solid areas indicate left-haud, linear, mixed, and right-hand polarizations when looking down onto the earth in each hemisphere, respectively.

et al., 1985b) and at high latitudes (L=3.2–4.4) (LANZEROTTI *et al.*, 1976). The Pc 3 polarization characteristics at L=1.3–2.1 (Fig. 6) and the larger amplitudes (Fig. 5) of Pc 3 pulsations at the higher latitude station (SKD) suggest that a hydromagnetic wave resonance in the Pc 3 frequency range occur at $L>2.1$. It is also noteworthy that the low-latitude Pc 3 polarizations tend to be more complicated with decreasing the L value. At SKD of $L=2.11$ a primary peak in the number of R-H events can be seen at ~0600 LT, whereas two peaks appear at lower-latitude stations, *e.g.*, ~0600 and 1200 LT at BSV, ~0700 and ~1300 LT at DAL ($L=1.55$), and ~1000 and ~1800 LT at ONW ($L=1.30$). It is believed that Pc 3 magnetic pulsations at SKD are associated mainly with a standing field-line oscillation at situated $L>2.1$, while those at lower latitudes of $L\sim1.5$ consist both contributions from the standing field-line oscillation and a compressional Pc 3 component directly propagating from the outer magnetosphere (*cf.* YUMOTO, 1986).

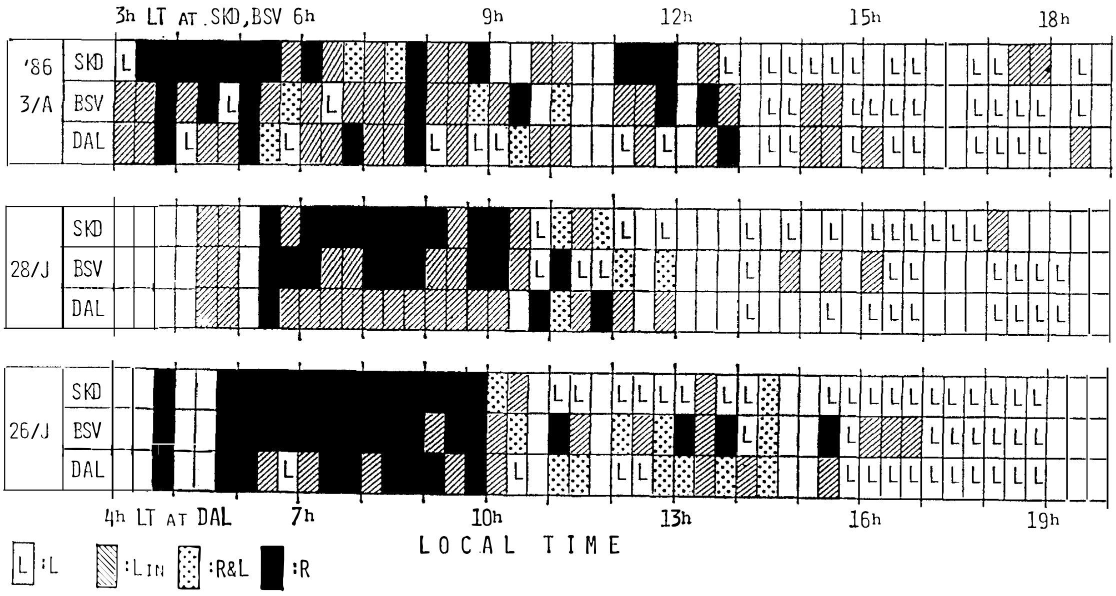

Fig. 7. Diurnal variations of low-latitude Pc 3 polarizations at SKD, BSV, and DAL stations in the southern hemisphere. Open indicates no event, and the rest are the same polarizations as denoted in Fig. 6, respectively.

Although the statistics of Pc 3 polarizations at each of the five stations behave in a reasonably systematic fashion during the local daytime, close inspections of the data show that the polarization varies with time, revealing occasional shifts in the polarization throughout a given hour and a given day. Representations obtained at the southern stations (SKD, BSV, DAL) for 16 hour intervals on July 26, 28, and August 3, 1986, are plotted in Fig. 7, where open, L, shaded, dotted, and solid ones indicate no event, left-hand, linear, mixed, and right-hand polarization, respectively. The Pc 3 polarizations at SKD ($L=2.11$) are predominantly right-handed in the local morning and left-handed in the afternoon sector, confirming the statistics of Fig. 6. However, there are intervals of one or several 20-min segments where the polarization senses at the lower stations (BSV, DAL) are more complicated, linear, and mixed ones in the daytime from ~1000 to ~1500 LT.

The data from the conjugate stations (ASH, BSV) can exclude latitudinal and longitudinal differences of Pc 3 polarizations and a propagation effect of Pc 3 source

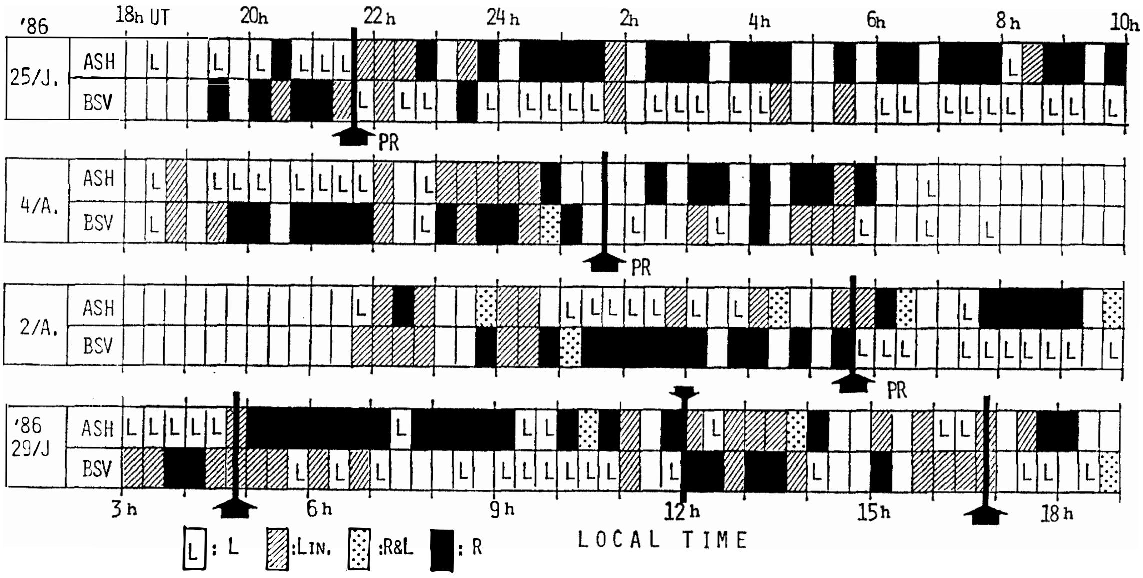

Fig. 8. Diurnal variations of low-latitude Pc 3 polarizations at the conjugate stations (ASH, BSV; L=1.55). The notation is the same as Fig. 7. The solid arrows indicate the local time of polarization reversal.

waves, therefore, are useful to clarify when and/or where the switch from L-H (R-H) to R-H (L-H) polarization occurs at $L=1.55$ in the northern (southern) hemisphere. The Pc 3 polarizations at SKD ($L=2.11$) statistically switched in the restricted interval from ~0900 to ~1200 LT (see Figs. 6 and 7), whereas the polarization reversal at ASH and BSV (1.55) is found to be not always occurring near local noon, and to sometimes appear at ~0700 LT (on July 25) and ~1500 LT (on August 2, 1986) as shown in Fig. 8. These are a quite surprising discovery. On 29 July 1986, transitions from L-H (R-H) to R-H (L-H) polarization at conjugate northern (southern) stations occurred two times at ~0500 LT and ~1700 LT (the bottom panel in the figure). A change in the polarization is generally interpreted by a switch in sign of the azimuthal wave propagation direction. The statistical average of Pc 3 polarizations at the low-latitude stations as shown in Fig. 6 can be explained by the switch in sign of wave propagation direction of Pc 3 source waves around local noon. This had been considered in the past as evidence for a solar wind control, with a change in the azimuthal propagation direction being produced by the separation of solar wind flow around the nose of the noon magnetopause (*e.g.*, ATKINSON and WATANABE, 1966). However, the polarization changes at the conjugate points of $L=1.55$ in the local morning (~ 0500 LT) and in the evening (~ 1700 LT) sector are difficult to be interpreted by the solar wind driven Kelvin-Helmholtz type instability on the magnetospheric boundary.

Finally, orientation angles of major axes of the Pc 3 polarization ellipses on the same meridian are plotted in Fig. 9. The orientation angle from the H axis can be approximately expressed by $\tan^{-1}(\delta D/\delta H)$. In the NE-SW and NW-SE quadrants the angles are positive and negative, respectively. The bold solid lines in the abscissa from 1650 to 0640 LT at SKD, from 1700 to 0630 LT at BSV, and from 1830 to 0420 LT on ONW and ASH stand for night time on the basis of f_0E plots of the ionospheric

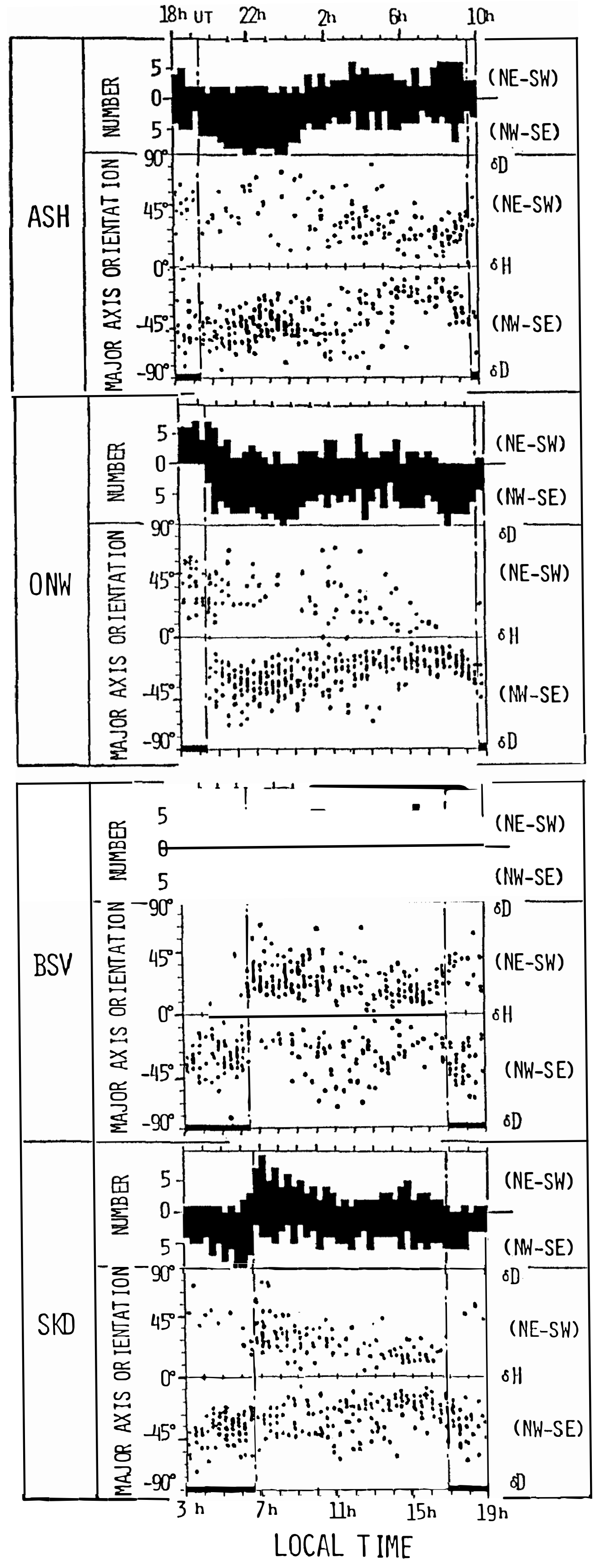

Fig. 9. Diurnal variations of the major axis orientation of low-latitude Pc 3 polarization ellipses in the H-D plane near the same meridian around L= 1.3–2.1. The solid thick lines indicate the night-time ionosphere. The orientation angle of the major axis measured from the H axis toward the NE-SW (NW-SE) quadrant is taken positive (negative).

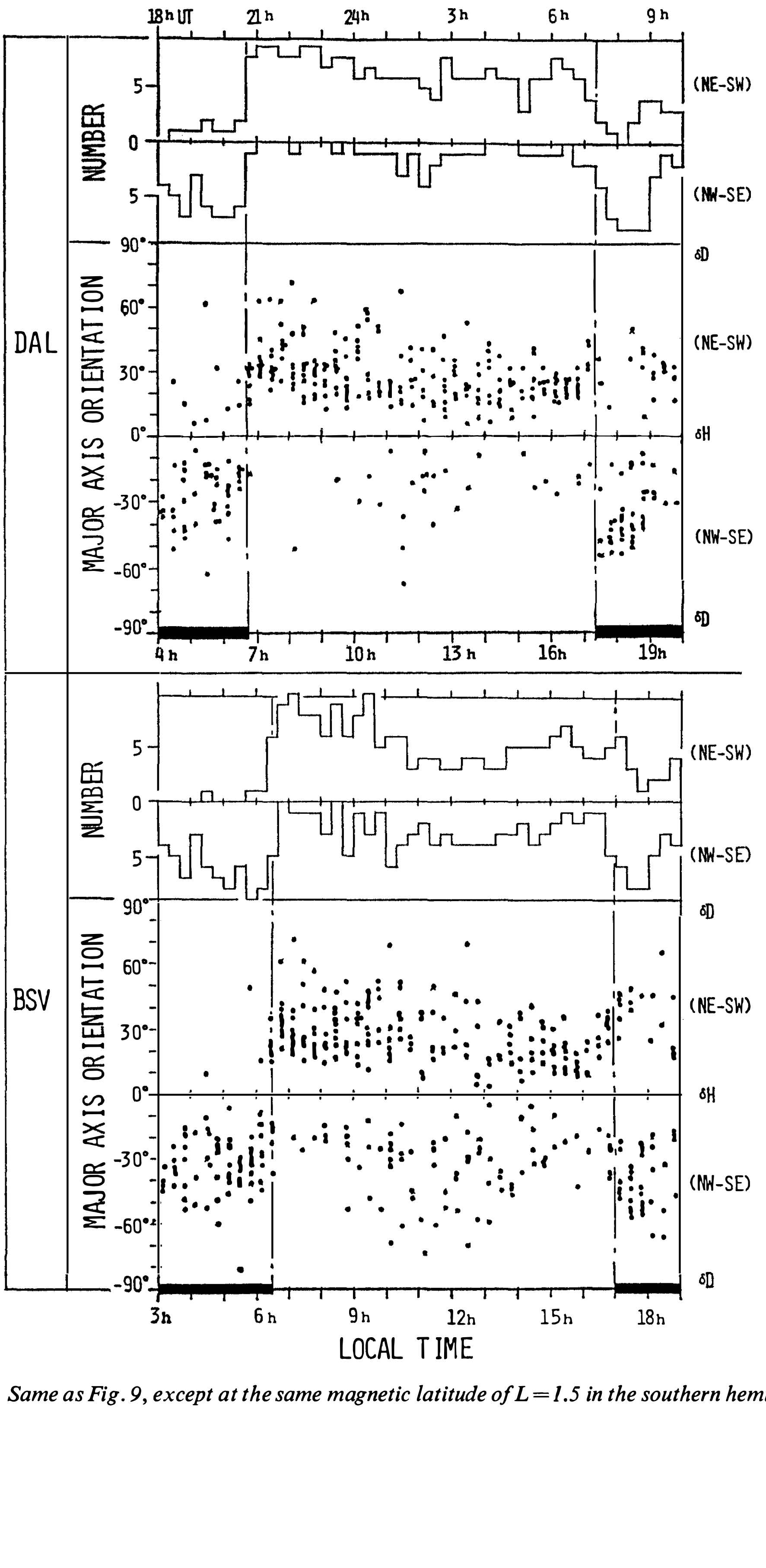

Fig. 10. Same as Fig. 9, except at the same magnetic latitude of L = 1.5 in the southern hemisphere.

data. It is noteworthy that at lower latitudes more clearer abrupt changes in the Pc 3 polarization ellipse orientations from NW-SE (NE-SW) to NE-SW (NW-SE) and from NE-SW to NW-SE occur at local sunrise and sunset times, respectively, in the southern (northern) hemisphere. In the daytime between sunrise and sunset, the ellipse orientations at ONW and ASH (BSV; $L \sim 1.5$) in the northern (southern) hemisphere maintain a primarily NW-SE (NE-SW) in the local morning and mixed and/or NW-SE (NE-SW) in the local afternoon sector (*i.e.*, and/or a primarily NW-SE (NE-SW) orientation throughout all local daytime hours). The orientations at SKD ($L=2.1$) in the southern winter hemisphere show a complicated, however, a weak evidence for a change from NE-SW quadrant in the prenoon to NW-SE one in the afternoon sector, which is consistent with the observational results for higher latitudes ($L \sim 4$), reported by RASPOPOV and LANZEROTTI (1976), except for the sunrise and sunset effect. The more complicated ellipse orientation of the low-latitude Pc 3's during each local daytime would arise from either geological effects of electric currents flowing below the observation sites or propagation of Pc 3 source waves in the inner magnetosphere. Figure 10 shows a difference between the major axis angle of Pc 3 polarization ellipses observed at the same latitude (DAL, BSV) in the southern hemisphere. The solid thick lines indicate night-time ionosphere at each station. It is interesting to note that the difference of local times of abrupt changes of the Pc 3 orientation angles between DAL and BSV is consistent with the longitudinal difference between the separated stations.

These longitudinal (Fig. 10) and latitudinal (Fig. 9) behaviors suggest that the abrupt changes of major axis orientation of the Pc 3 polarization ellipses appear to coincide with the *E*-layer ionization enhancement and depression associated with local sunrise and sunset, respectively.

5. Summary and Conclusion

The results of the analysis of Pc 3 pulsations at the low-latitude conjugate stations (ASH, ONW, BSV, DAL, SKD; $L=1.3$–2.1) during July 25 to August 5, 1986, can be summarized as follows.

(1) The Pc 3 amplitudes at SKD ($L=2.1$) are approximately 2.5 times of those at BSV (1.55) (Fig. 5).

(2) The *D*-component averages of Pc 3 amplitudes at $L=1.55$–2.11 are smaller than those in the *H* component. Especially, simultaneous depressions in the *D* component are found to appear in the afternoon sector from $\sim$ 1300 to $\sim$ 1700 LT (Fig. 5).

(3) The Pc 3 amplitudes in the *H* component at BSV in the winter hemisphere are larger than those at ASH in the summer hemisphere, whereas the averaged amplitudes in the *D* component are comparable at the low-latitude conjugate stations (left panel of Fig. 5).

(4) The averaged Pc 3 amplitudes at DAL, located $\sim 12°$ east of BSV, are quite similar to those of BSV shifted about 50 min toward earlier local time (right panel of Fig. 5).

(5) Statistically, the Pc 3 polarizations at the northern (southern) station at $L=$

1.3–2.1 are left-handed (right-handed) in the local morning and right-handed (left-handed) in the local evening. However, the Pc 3 polarizations at lower latitude of $L \lesssim 1.5$ are more complicated than those at $L=2.1$ as shown in Figs. 6 and 7.

(6) The polarization changes at the low-latitude conjugate stations (ASH, BSV) do not always occur near local noon, but sometimes appear at ~0500 and ~1700 LT (Fig. 8).

(7) The abrupt changes of major axis orientations of the Pc 3 polarization ellipses at lower latitudes appear to coincide with the *E*-layer ionization enhancement and depression associated with local sunrise and sunset, respectively (Figs. 9 and 10).

On the basis of the observational relationships of the solar wind parameters with pulsation parameters, YUMOTO (1986) concluded that the magnetosonic upstream waves in the earth' foreshock are transmitted into the magnetosphere without significant changes in spectra, and can be a main source of low-latitude Pc 3 pulsations at $L \sim 1.5$–3.0. (*cf.* WOLFE *et al.*, 1985; YUMOTO *et al.*, 1985a). These transmitted compressional waves can propagate across the ambient magnetic field into the inner plasmasphere, and then can excite a standing field-line oscillation in the Pc 3 frequency range at $L=1.7$–2.6 (YUMOTO and SAITO, 1983). Pc 3 magnetic variations around $L=1.5$–3.0 are believed to be caused mainly by an ionospheric eddy Hall current associated with the standing field-line oscillation at $L \sim 2.0$ and by an ionospheric Pedersen eddy current induced by the compressional source waves (see YUMOTO *et al.*, 1987).

The observational results (1) and (5) suggest that a HM resonance occurs at higher latitude than SKD site, *i.e.*, $L>2.1$. The pre- and postnoon asymmetry of *D*-component Pc 3 activity (2) at $L=1.5$–2.1 may be associated with an asymmetry of horizontal wavenumber, which controls the effectiveness in the bouncing of HM waves between both the hemispheres along the field line (*cf.* YUMOTO *et al.*, 1985b). However, further studies are required to clarify why and how *D*-component Pc 3 pulsations are depressed in the afternoon sector. The *H*-amplitude asymmetry (3) at the conjugate points and the abrupt changes of major axes (7) at sunrise and sunset at lower latitude can be explained by a transmission of compressional Pc 3 mode into the lower ionosphere. The longitudinal and latitudinal behaviors of the averaged amplitude and the major axis orientation of Pc 3 polarization ellipses (4 and 7) also suggest that magnetic variations in the Pc 3 frequency range at lower latitudes are more effectively controlled by changes of the ionospheric conductivity. The detailed discussion of the ionospheric conductivity effect on the compressional component at lower latitudes will be the subject of a later paper. The polarization changes of Pc 3 pulsations at the conjugate points (ASH, BSV) in the local morning (~ 0500 LT) and in the evening (~ 1700 LT) (6) cannot be interpreted by the solar wind driven Kelvin-Helmholtz type instability on the magnetospheric boundary. The meridian where the polarization reversal occurs may be related to the longitudinal distance from the subsolar point to a region in the magnetosheath where upstream waves could be most intense near the streamline of θ_{BN} (angle between the IMF and shock normal)$=0°$.

The characteristics of Pc 3 pulsations in conjugate area around $L=1.3$–2.1, clarified in this paper, are concluded not to be disagreement with the possible interpretation that Pc 3 magnetic variations at lower latitudes consist both of contributions from a standing field-line oscillation at $L>2.1$ and compressional Pc 3 waves originating from upstream waves in the earth's foreshock.

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