CHARACTERISTICS OF MAGNETIC FIELD FLUCTUATIONS AS OBSERVED IN THE MAGNETOSHEATH

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***Abstract*:** Magnetic data obtained by the ISEE-1 and -2 satellites during twelve months from July to December, 1978 and 1979, are analyzed to clarify characteristics of low-frequency hydromagnetic fluctuations near the bow shock in the magnetosheath. Characteristics of the magnetic field fluctuations are examined by means of the spectral MEM and the minimum variance methods. The dynamic spectrum indicates that the spectral peaks appear in the frequency range from 0.01 to 0.05 Hz. The spectral power of the component parallel to the average magnetic field tends to be larger than those perpendicular to the field. The angles between the wave normal vector and the average magnetic field are almost restricted within 60°–90°, *i.e.*, the wave normal vector is directed nearly perpendicular to the magnetic field. Therefore, these characteristics strongly signify that the magnetic field fluctuations in the magnetosheath tend to be compressional mode.

1. Introduction

Dayside magnetic pulsations in the Pc 3–5 range observed on the ground and in space have been regarded to be closely related to the solar wind parameters (GREENSTADT *et al.*, 1970; SINGER *et al.*, 1977; OLSON and ROSTOKER, 1978; GREENSTADT *et al.*, 1979). A source of shorter-period magnetic pulsations in the Pc 3–4 range has been proposed in connection with upstream waves generated at the bow shock. The waves have been reported to be related to the shock structure, *i.e.*, a quasi-parallel shock is accompanied more frequently by the upstream waves (GREENSTADT, 1973). The interplanetary magnetic field (IMF) has been also examined in connection with controlling Pc 3–4 activity. The appropriate orientation of the IMF has been positively correlated when $\theta_{XB}<50°$, where θ_{XB} is the angle between the IMF direction and the sun-earth line (X-axis) (GREENSTADT and OLSON, 1977; GREENSTADT *et al.*, 1979; SAITO *et al.*, 1979).

The source of longer-period magnetic pulsations in the Pc 4–5 range is believed to the surface waves driven by the solar wind at the magnetopause. These waves are proposed to be generated through the Kelvin-Helmholtz type instabilities (SOUTHWOOD, 1968; YUMOTO and SAITO, 1980; MIURA and PRITCHETT, 1982).

In situ observations of the magnetic field in space, *i.e.*, the interplanetary space, the magnetosheath and the magnetosphere have recently clarified many important characteristics of low-frequency hydromagnetic waves and provided clear evidences of source waves of the magnetic pulsations on the ground.

The magnetosheath has been considered to be an important region as an interface between the interplanetary space and the magnetosphere. Although the general configuration of magnetic field in the magnetosheath has been relatively well understood, the time variations are not yet sufficiently characterized. One such study has been made by FAIRFIELD and NESS (1970) using the Imp 4 (Explorer 34) satellite. They demonstrated that spectral peaks of the magnetic field fluctuations in the magnetosheath are dominant around 0.06 Hz in frequency, and compressional fluctuations tend to become larger than transverse ones. Another study has done by KAUFMANN *et al.* (1970) using data from the Explorer 12 spacecraft. They also showed that the fluctuations occur in the frequency range from 0.01 to 0.1 Hz and exhibit characteristics of magnetoacoustic wave.

In order to determine more detailed properties of magnetic field fluctuations in the magnetosheath, it is necessary to examine wave modes and dominant frequencies using a lot of *in situ* magnetic field data obtained by the ISEE-1 and -2 satellites. The purpose of the present paper is to describe more clear properties of fluctuations in the magnetosheath near the bow shock.

2. Data Acquisition and Analysis Procedure

The data used in the present study are arranged in the format of magnetogram. The magnetograms consisting of three magnetic field components observed by the ISEE-1 and -2 were expanded and digitized with the semi-automatic digitizer with a sampling period of 4 s. Each data-point is plotted in the satellite coordinate. The digitized magnetograms in the GSE coordinate system were then transformed into magnetic field line coordinate system as illustrated in Fig. 1. Hereafter, the magnetic

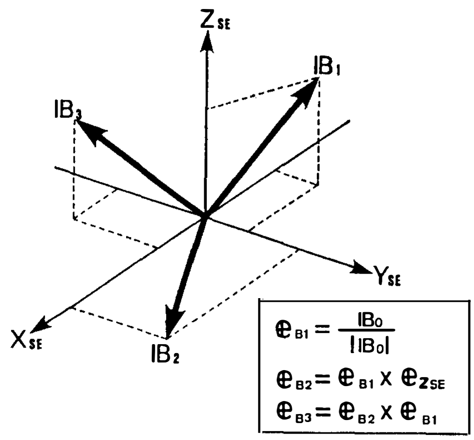

Fig. 1. A relation between geocentric solar ecliptic (X_{SE}, Y_{SE}, Z_{SE}) and magnetic field line (B1, B2, B3) coordinates systems. B1-axis is parallel to the average magnetic field, B2-axis normal to B1-Z_{SE} plane, and B3-axis is defined by $e_{B3}=e_{B2}\times e_{B1}$.

field line coordinate is abbreviated to FL coordinate in the present paper. In the FL coordinate ($B1$, $B2$, $B3$), the $B1$-axis is taken parallel to the average geomagnetic field, the $B2$-axis perpendicular to the plane including the $B1$-axis and Z_{SE}-axis, and $B3$-axis is defined as $e_{B3}=e_{B2}\times e_{B1}$. The transformed data in the ($B1$, $B2$, $B3$)-coordinate system are utilized to make a power spectral analysis.

The power spectra are calculated by means of the maximum entropy method (MEM) with the thirtieth order prediction error filter and are examined in the frequency range from 0.001 Hz to 0.1 Hz with logarithmically equal intervals. The dynamic spectra are calculated with a time window of ten minutes which is successively shifted with two minutes. In order to emphasize spectral peaks in the dynamic spectrum, we remove a background power by fitting a second-order polynomial to the average slope of the power spectrum, and then the dynamic spectra are displayed with a five-step gray code corresponding to the relative power to the background level. In this display the white and darkest areas correspond to the power density less than 1 dB and more 10 dB greater than that of the background, respectively.

3. Analyzed Results

3.1. Power spectral characteristics

Figure 2 shows the satellite trajectories in the magnetosheath projected on both the X_{SE}–Y_{SE} and Y_{SE}–Z_{SE} planes in the GSE coordinate. The longitudinal extent of the trajectory in the ecliptic plane covers from the noon to the dusk, while the latitudinal one is restricted only 35° from 0° to 35°N. All the cases examined here are 11 events, in which the satellite was located in the magnetosheath near the bow shock.

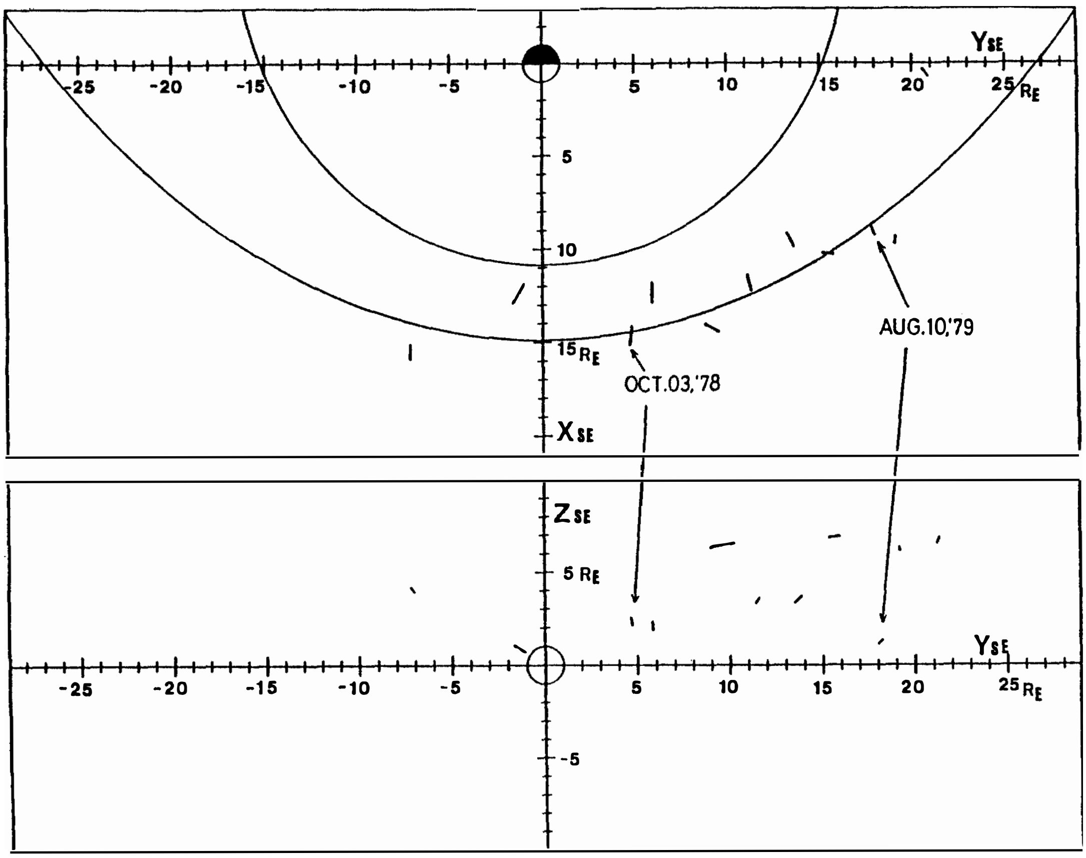

Fig. 2. Satellite trajectories of the bow shock and magnetopause boundary crossings projected on the $X_{SE}-Y_{SE}$ and $Y_{SE}-Z_{SE}$ planes, respectively. Typical locations of the bow shock and the magnetopause boundary are indicated with solid curves based on the conic section model.

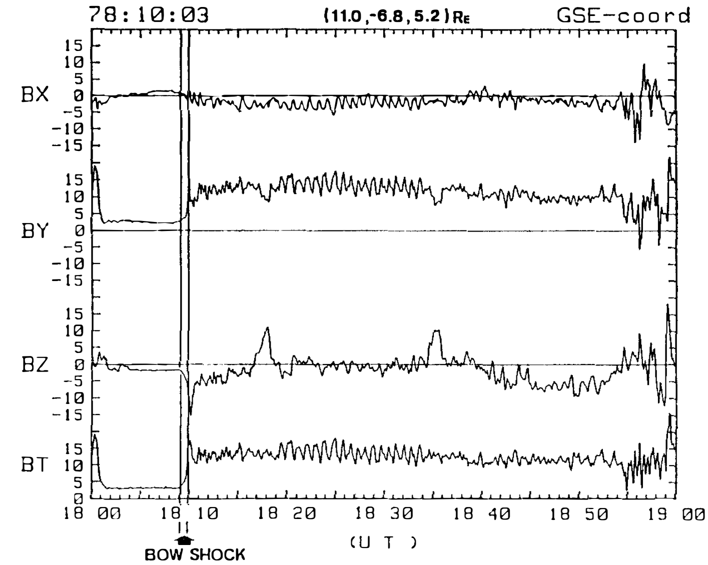

Fig. 3. A typical example of the magnetic field fluctuations in the magnetosheath near the bow shock at (11.0, -6.8, 5.2) R_E in the GSE coordinate observed by the ISEE-1 satellite on October 3, 1978. Note that clear oscillations are seen in the BX and BY components within the interval from 1820 to 1835 UT.

The following two events are typical examples of the magnetic field fluctuations in the magnetosheath near the bow shock. Figure 3 illustrates the magnetic field fluctuations observed on October 3, 1978. The ISEE-1 satellite was located in the post-noon side at (11.0, -6.8, 5.2) R_E in the GSE coordinate and passed into the magnetosheath through the bow shock at 1810 UT. The quasi-monochromatic magnetic field fluctuations were observed during the interval from 1820 to 1853 UT. The amplitude and the period of the fluctuations are about 5 nT and 50 s, respectively. The dynamic spectra of the three components of the fluctuations are shown in Fig. 4. It is noteworthy that the frequencies corresponding to those spectral peaks appear in the range of frequency higher than 0.01 Hz, especially from 0.01 to 0.05 Hz, but any remarkable peak power cannot be seen in the lower frequency range. Figures 5A and 5B illustrate the spectral powers for each component of the magnetic field fluctuations in the GSE coordinate (BX, BY, BZ) and the FL coordinate ($B1$, $B2$, $B3$), respectively. The spectral peak can be clearly seen at 0.02 Hz (50 s) in the BX and BY components, and $B1$ and $B2$ components in each coordinate. The average magnetic field is directed almost along the Y_{SE}-axis, since the unit vector of the field is indicated as (-0.16, 0.99, 0.04) in the GSE coordinate. Consequently it is clarified that the spectral power of the $B1$ component parallel to the average magnetic field exhibits the strongest power as shown in Fig. 5B.

Another example of the magnetic fluctuations in the magnetosheath observed by the ISEE-1 satellite on August 10, 1979, is shown in Fig. 6. As shown in Fig. 2, the satellite was located near the dusk side at (9.0, 18.0, 1.2) R_E in the GSE coordinate and passed into the magnetosheath through the bow shock at 0401 UT. Although any definite fluctuations are not seen in the figure, the small amplitude fluctuations of 2 nT appear persistently throughout the traverse. The dynamic spectra are displayed

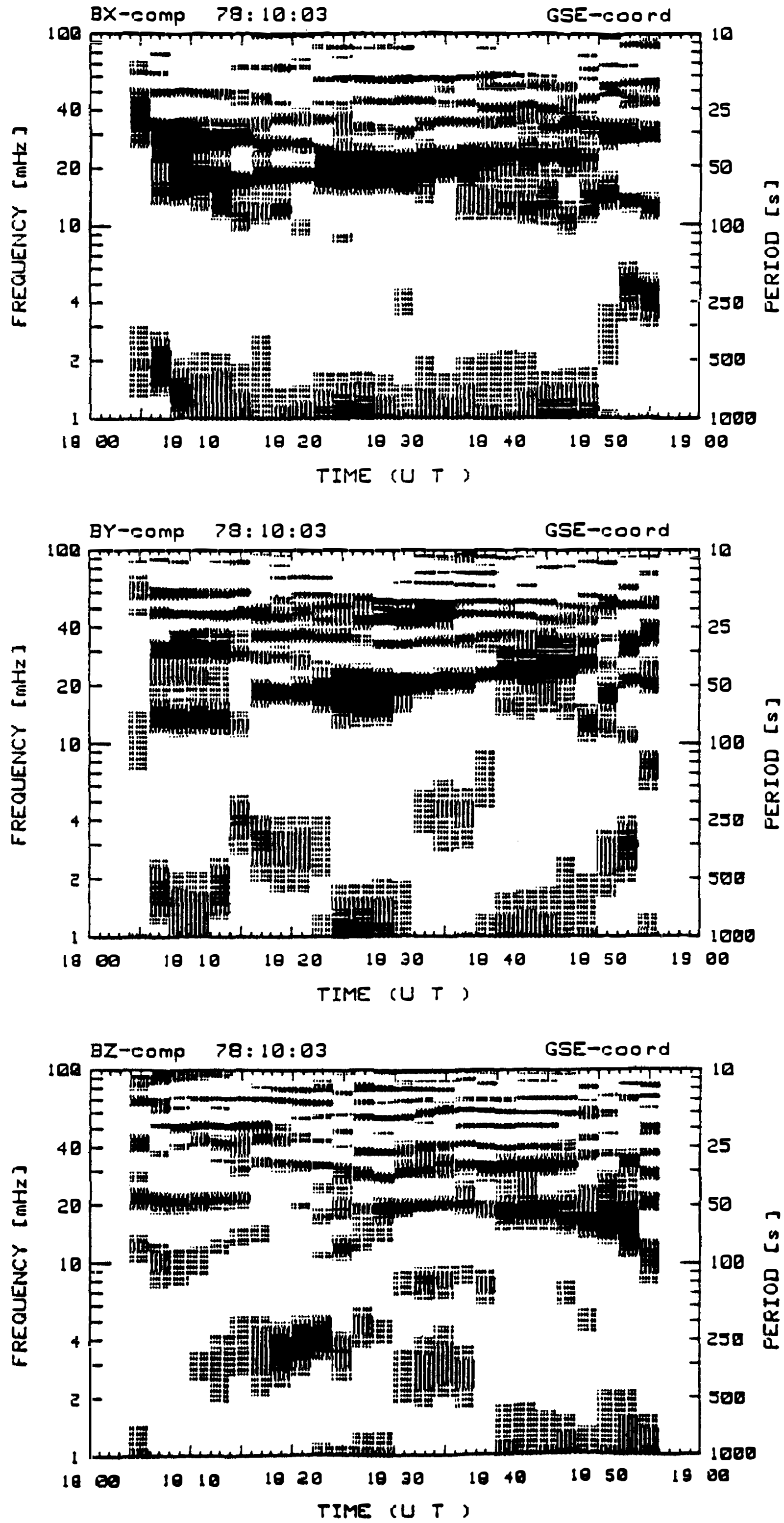

Fig. 4. Dynamic spectra of the magnetic field fluctuations as shown in Fig. 3. The top to bottom panels show the BX, BY and BZ components of the magnetic field. The dominant spectral peaks are clearly seen in the range of frequency higher than 0.01 Hz, especially from 0.01 to 0.05 Hz. Any remarkable peaks are not recognized in the frequency lower than 0.01 Hz.

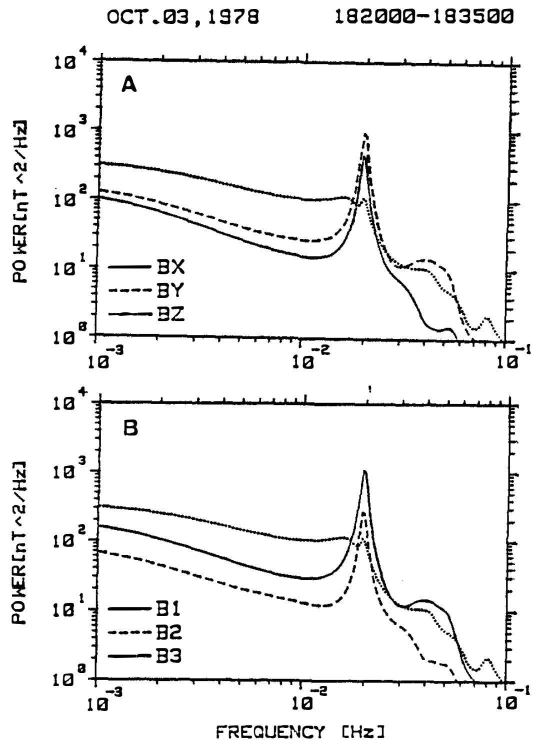

Fig. 5. Power spectra calculated from the data measured during the interval 1820–1835 UT. Solid, dashed and dotted curves represent BX, BY and BZ components in the GSE coordinate (A), and B1, B2 and B3 components in the magnetic field line coordinate (B), respectively. The dominant spectral peaks at 50 seconds are seen in all components in the both coordinate systems, especially in BY and B1 components. Note that the fluctuation parallel to the average magnetic field is greater than those perpendicular to the field.

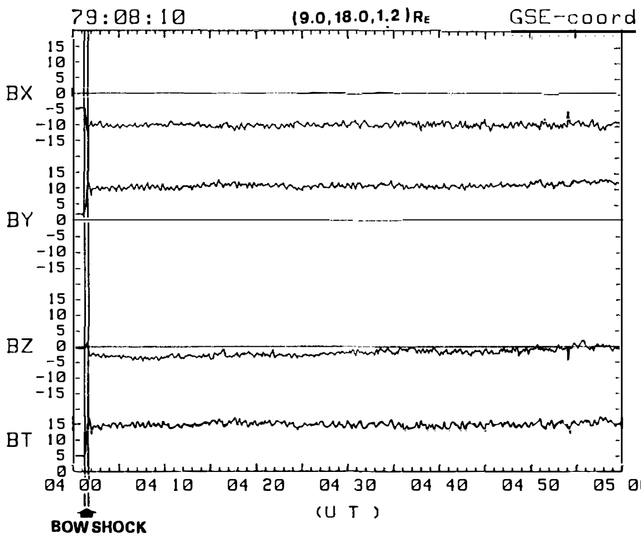

Fig. 6. A typical example of the magnetic field fluctuations in the magnetosheath near the bow shock at (9.0, 18.0, 1.2) R_E in the GSE coordinate observed by the ISEE-1 satellite on August 10, 1979. Note that the small amplitude ($\simeq$2 nT) fluctuations are seen in all components.

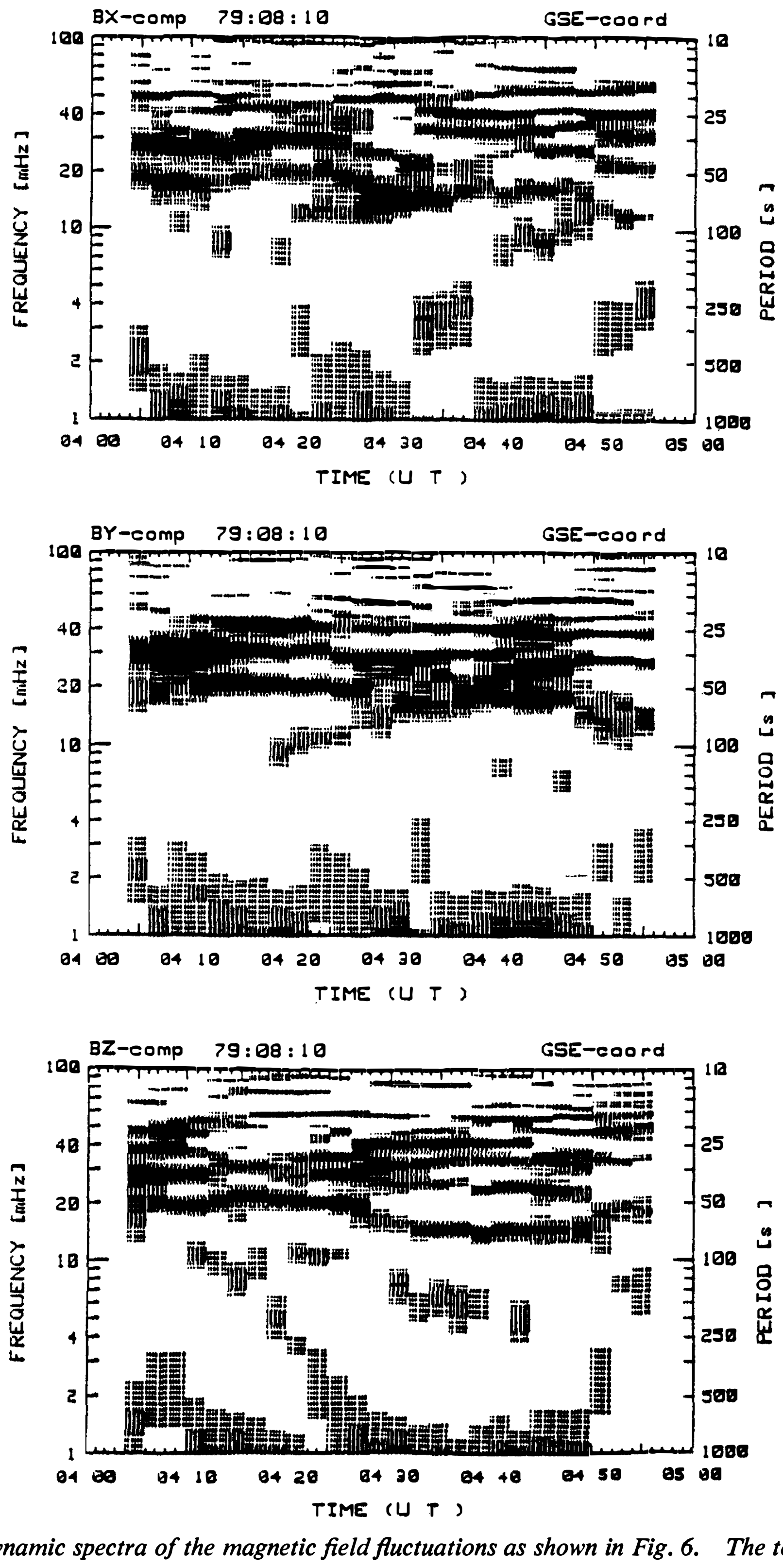

Fig. 7. Dynamic spectra of the magnetic field fluctuations as shown in Fig. 6. The top to bottom panels show the BX, BY and BZ components of the magnetic field. As shown in Fig. 5, the spectral peaks are restricted with the range of frequency higher than 0.01 Hz. Any remarkable peaks are not recognized in the range of lower frequency.

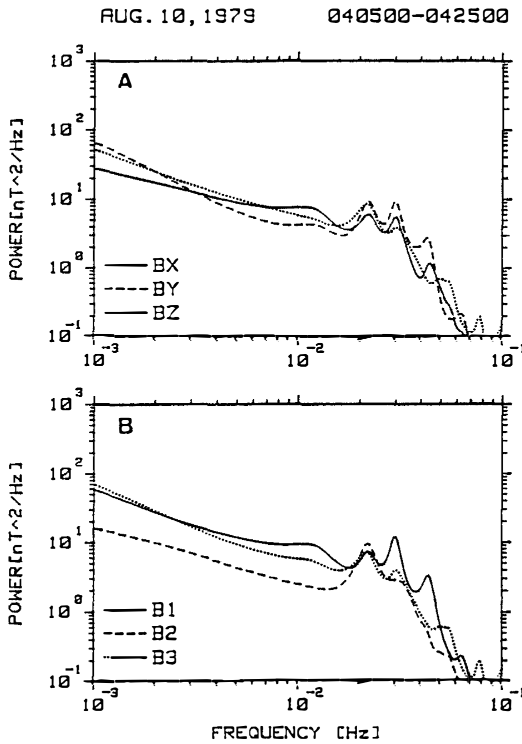

Fig. 8. Power spectra calculated from the data during the interval from 0405 to 0425 UT. Solid, dashed and dotted curves represent BX, BY and BZ in the GSE coordinate (A) and B1, B2 and B3 in the magnetic field line coordinate (B). The spectral peaks appear at 20.3 mHz in all components, at 29.4 mHz in BX, BY, B1 and B2 components, and at 35.7 mHz in BX, BY and B1 components. Note that the spectral power of the fluctuations parallel to the average magnetic field tends to be larger than those of the other components, which is clearly seen at 29.4 and 35.7 mHz.

in Fig. 7. The spectral peaks clearly appear in the range of frequency higher than 0.01 Hz, and are especially restricted within the frequency range from 0.01 to 0.05 Hz. Any remarkable spectral peak does not appear in the lower frequency range as similar to Fig. 4. Figures 8A and 8B show the power spectrum for each component of the magnetic field fluctuations taken in the GSE coordinate (BX, BY, BZ) and in the FL coordinate ($B1$, $B2$, $B3$), during the interval from 0405 to 0425 UT. In the GSE coordinate as shown in Figs. 7 and 8A, the spectral peak can be seen at 20.3 mHz (48 s), 29.4 mHz (34 s) and 35 mHz (28 s). The strong spectral power appears at 48 s in both BX and BY components, and at 34 and 28 s in the BY component. In this interval the average magnetic field is directed about 45° to X-axis (sun-earth line), since the unit vector of the field is calculated as (−0.68, 0.71, −0.20) in the GSE coordinate. In Fig. 8B it is noted that the spectral peaks appear at 34 and 28 s in the $B1$ component, expect at 48 s in the $B2$ component.

As described in Figs. 4, 5, 7 and 8, the spectral peaks appeared mainly in the frequency range from 0.01 to 0.05 Hz. To make clearer the frequency distribution of the spectral peaks, we examined all remaining events. In order to obtain the frequency distribution of the spectral peak, the spectra are divided into ten frequency intervals with a frequency width of Δf=0.01 Hz. The frequency of occurrence of the spectral

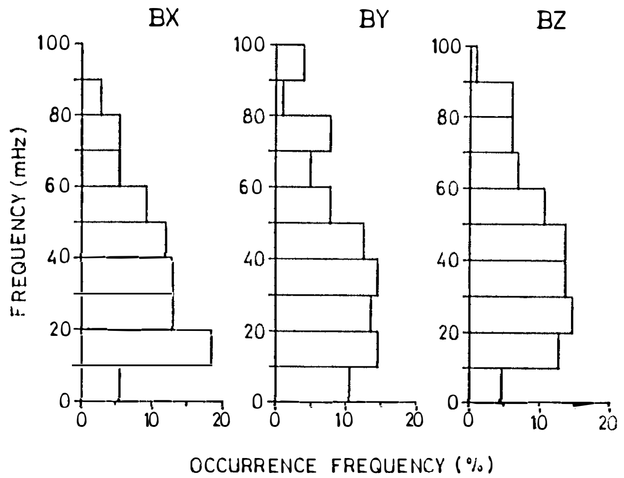

Fig. 9. Frequency of occurrence of spectral peak of the magnetic field fluctuations in the GSE coordinate versus wave frequency. Note that spectral peaks are distributed in the frequency range from 0.01 to 0.05 Hz.

peak is obtained and shown against the wave frequency in Fig. 9. The frequency of the occurrence of the interval from 0.01 to 0.05 Hz exceeds 10% in the whole interval from 0.001 to 0.1 Hz.

The results indicate that the magnetic field fluctuations in the magnetosheath near the bow shock occur in the frequency range from 0.01 to 0.05 Hz. Our results are consistent with the previous results obtained by FAIRFIELD and NESS (1970) and FAIRFIELD (1976). Using the Imp 4 (Explorer 34) satellite measurement, FAIRFIELD and NESS (1970) demonstrated that spectral peaks of the magnetic field fluctuations in the magnetosheath are dominant around 0.06 Hz in frequency. FAIRFIELD (1976) also presented using data from the Imp 6 spacecraft that the spectral power of the magnetic field variations was stronger in the parallel component than those of the perpendicular components to the average field direction.

3.2. *Wave mode characteristics*

In this section, we will examine the mode of the magnetic fluctuations in the magnetosheath by means of the minimum variance method. The wave mode is well recognized with an examination about wave normal vector of the magnetic field. In order to obtain the wave normal vector, we use the minimum variance method and make calculations of the auto- and cross-variances of the magnetic field during the period of interest. We then solve eigenvalue problems and determine eigenvectors which correspond to the principal axes of the variance ellipsoid. This technique has been developed by SONNERUP and CAHILL (1967) for an application to identify the normal vector of the magnetopause. Applying this method, the eigenvector for the minimum variance corresponds to the wave normal vector ($\boldsymbol{k}$), when we assume plane waves. The angle between the wave normal vector and the average magnetic field indicates information about the wave mode.

As examined in the preceding section, the spectra have generally several spectral peaks in the frequency range from 0.01 to 0.05 Hz. The direction of wave normal vector ($\boldsymbol{k}$) is determined at each frequency corresponding to the spectral peak. In order to obtain the wave normal vector ($\boldsymbol{k}$) for each spectral peak, we have to assume a monochromatic wave corresponding to the frequency of each spectral peak. Usually a spectral peak has the bandwidth spreading around the center frequency. According to FOWLER *et al.* (1967), a quasi-monochromatic wave is defined when the bandwidth (Δf) of the wave is much less than the center frequency ($\bar{f}$), *i.e.*, $\Delta f \ll \bar{f}$. In this analysis, we determine the monochromatic wave as the bandwidth (Δf) to the center frequency ($\bar{f}$) is less than 0.5. We then divide the frequency range corresponding to the all spectral peaks of interest into four ranges, *i.e.*, 0.04–0.025 Hz (T=25–40 s), 0.025–0.017 Hz (T=40–60 s), 0.017–0.0125 Hz (T=60–80 s) and 0.0125–0.01 Hz (T=80–100 s). In these frequency ranges, the frequency of occurrence with respect to the angle between the wave normal vector and the average magnetic field is displayed in Fig. 10. In every frequency range, the frequency of the occurrence shows

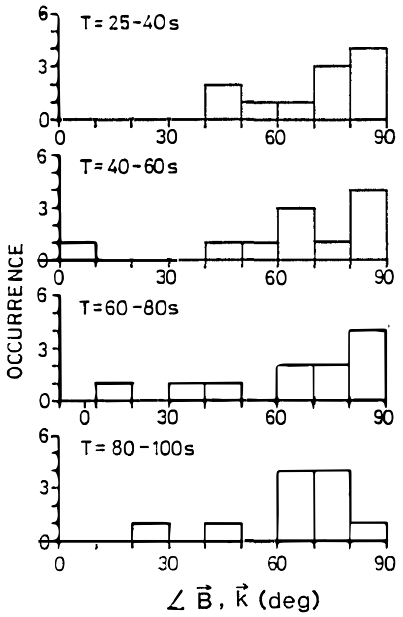

*Fig. 10. Frequency of occurrence of the angle between the wave normal vector (**k**) and the direction of the average magnetic field in the magnetosheath. The occurrence almost concentrates into angle larger than 60°, and magnetic field fluctuations in the magnetosheath tend to show compressional characteristic.*

a similar distribution against the angle and dominates at the angle larger than 60°. The result implies that the magnetic fluctuations in the magnetosheath tend to show compressional mode. This result is consistent with those obtained by FAIRFIELD and NESS (1970), KAUFMANN *et al.* (1970) and FAIRFIELD (1976). By using the Imp 4 satellite data in the magnetosheath, FAIRFIELD and NESS (1970) demonstrated that when the power spectra were computed in the frequency range below 0.2 Hz in a field-aligned coordinate, compressional fluctuations tend to be larger than transverse ones in the lower frequency (from 0.01 to 0.06 Hz), while in the higher frequency ($\simeq$0.1 Hz) transverse fluctuations dominate. KAUFMANN *et al.* (1970) obtained similar results on the mode of the magnetic fluctuations in the inner magnetosheath.

4. Summary and Discussion

This paper describes characteristics of the wave mode and dominant frequency of the low-frequency hydromagnetic waves in the magnetosheath based on the magnetic field data obtained by the ISEE-1 and -2 satellites during twelve months from July to December, 1978 and 1979. The observational characteristics are summarized as follows:

(1) In the magnetosheath the spectral peaks appear in the range of frequency higher than 0.01 Hz, but not in the lower frequency range. The spectral power is larger in the component parallel to the average magnetic field than those perpendicular to the field.

(2) The wave normal vector ($\boldsymbol{k}$) in the magnetosheath is directed almost perpendicular to the average magnetic field.

These properties strongly suggest that the fluctuations in the magnetosheath exhibit compressional mode in the range of frequency higher than 0.01 Hz, especially from 0.01 to 0.05 Hz. These results are consistent with the previous ones (FAIRFIELD and NESS, 1970; FAIRFIELD, 1976; GREENSTADT *et al.*, 1983).

It is revealed in the present study that the magnetic fluctuations in the magnetosheath exhibit the compressional mode, which must be the fast magnetoacoustic wave, since in the magnetosheath the sound speed generally exceeds the Alfvén speed. The magnitude of the wave vector in the magnetosheath may be $|\boldsymbol{k}|\simeq 10^{-5}$–$10^{-4}$ km^{-1}, if the phase velocity ($V_{\mathrm{ph}}=\omega/|\boldsymbol{k}|$) of the fluctuations in the magnetosheath is assumed to be equal to the velocity of the fast magnetoacoustic wave (the sound speed and the Alfvén speed have typically 235 and 157 km/s, respectivelly), since the angle between the wave normal vector ($\boldsymbol{k}$) and the average magnetic field was found to be nearly 90° and the frequency ranges from 0.01 to 0.05 Hz in the satellite frame. The Doppler-shifted frequency, ω_{s}, observed by the spacecraft can be written as

$$\omega_{\mathrm{s}}=\omega+\boldsymbol{k}\cdot V_{\mathrm{sw}} ,$$

where ω is the frequency in the plasma frame, $\boldsymbol{k}$ is the wave vector, and V_{sw} is the solar wind velocity ($\simeq$100–300 km/s). Defining α as the angle between $\boldsymbol{k}$ and V_{sw}, we may write the above equation as

$$\omega_{\mathrm{s}}=\omega[1+(V_{\mathrm{sw}}/V_{\mathrm{ph}}) \cos \alpha] .$$

Since $V_{\mathrm{ph}}\simeq V_{\mathrm{sw}}$, $\omega_{\mathrm{s}}\simeq\omega[1+ \cos \alpha]$. Thus, if $\alpha=45°$, $\omega_{\mathrm{s}}=1.7\ \omega$. However, the results in the present study are not strongly influenced by the Doppler-shifted effect. WOLFE and KAUFMANN (1975) showed that the fast magnetosonic wave propagating with the incident angle of less than $\sim$10° from normal to the magnetopause could penetrate into the magnetosphere and slow waves were completely reflected at the magnetopause. They postulated also that the transmission was possible under the condition of the wave vector only with $|\boldsymbol{k}|\simeq 8\times 10^{-10}$ cm^{-1}. Our results are in agreement with the typical value of wave normal vector predicted by WOLFE and KAUFMANN (1975). The low-frequency fluctuations in the magnetosheath dealt with in the present study can penetrate into the magnetosphere through the magnetopause, which has been recently demonstrated by GREENSTADT *et al.* (1983).

Although the wave characteristics of magnetic fluctuations in the magnetosheath have not yet been well understood, the origin of the magnetic fluctuations in the magnetosheath has been proposed as follows;

(1) Transmission of interplanetary fluctuation through bow shock: The low-frequency (0.01 to 0.05 Hz) quasi-periodic waves have been recognized to exist in the upstream of the bow shock (FAIRFIELD, 1969; GREENSTADT *et al.*, 1970; SCARF *et al.*, 1970; HOPPE *et al.*, 1981; HOPPE and RUSSELL, 1983). It has been suggested that those waves are generated by ion cyclotron resonance with protons emanating from the bow shock (FAIRFIELD, 1969; BARNES, 1970; FREDRICKS, 1975; GOSLING *et al.*, 1978; PASCHMANN *et al.*, 1979; GARY *et al.*, 1981; SENTMANN *et al.*, 1981). This possibility has been well established with the observations of the ion distributions in the energy less than 3–4 keV, streaming back upstream along the interplanetary magnetic field from the direction of the bow shock (GOSLING *et al.*, 1978; PASCHMANN *et al.*, 1979; HOPPE *et al.*, 1981; GREEN *et al.*, 1983; TSURUTANI, 1983). The theory of transmission of those waves generated in the upstream region through the bow shock has been investigated by MCKENZIE and WESTPHAL (1969), WESTPHAL and MCKENZIE (1969), MCKENZIE (1970) and ASSÉO and BERTHOMIEU (1970). In the transmission of an Alfvén wave incident on a fast hydromagnetic shock, the transmitted wave has an amplitude approximately 3 times that of the incident wave (MCKENZIE and WESTPHAL, 1969). In the more complicated case of a magnetoacoustic wave incident on the bow shock, the incident wave is amplified by a factor of 4 (WESTPHAL and MCKENZIE, 1969). It seems reasonable that the transmission of the interplanetary fluctuations (especially the upstream waves) through the bow shock serves as an important source of the fluctuations in the magnetosheath (FAIRFIELD and NESS, 1970; GREENSTADT, 1973; FAIRFIELD, 1976).

(2) Discontinuities: Interplanetary tangential discontinuities incident on the bow shock are convected through the shock, but may be modified by the interaction process. In addition, secondary discontinuities may be generated by this interaction with various waves, all of which contribute to magnetosheath fluctuations (JAGGI and WOLF, 1971; VOLK and AUER, 1974). JAGGI and WOLF (1971) have studied the generation of magnetosonic waves in the magnetosheath by the weak tangential discontinuities incident on the bow shock. Experimental work on discontinuities in the magnetosheath has not proceeded. Although interplanetary discontinuities probably contribute to magnetosheath fluctuation, a significant portion of the fluctuation that is continually present in the magnetosheath cannot be explained.

(3) Shock generation: One of the other sources of fluctuations in the magnetosheath is believed to be closely related to bow shock (TIDMAN and KRALL, 1972; HOLZER *et al.*, 1972; KAN and SWIFT, 1983). HOLZER *et al.* (1972) showed that from the magnetic field observation of the bow shock crossing, the high-frequency (1.5 Hz) waves in the upstream region were right-handed polarized whistler mode waves propagating away from the shock, and the lower-frequency (0.3 Hz) downstream waves were observed to be left-handed polarized. Recently, KAN and SWIFT (1983) performed a simulation of stability of the quasi-parallel bow shock. They showed that in the supercritical regime ($M_A>3$, where M_A is Alfvén mach number), the right-hand polarized whistler waves were generated in the upstream side, and the right-hand polarized whistler ($\omega>\Omega_i$) and fast magnetosonic waves ($\omega<\Omega_i$) were generated in the downstream side. Any distinction between shock generation and upstream origin of the magnetosheath waves is probably difficult at least from the observational point

of view.

(4) Magnetopause origin: Possible source of the magnetosheath fluctuation is magnetopause. Many authors have discussed the possible Kelvin-Helmholtz type instability at the magnetopause caused by the velocity shear between the magnetosheath and magnetosphere (SOUTHWOOD, 1968; YUMOTO and SAITO, 1980; MIURA and PRITCHETT, 1982). Even if the waves are generated by the Kelvin-Helmholtz instability over a significant region of the magnetopause, there remains the question of whether the waves can propagate to locations in the outer portion of the magnetosheath. However, even if the propagation to distance locations in the magnetosheath is not always possible, this source may have a significant effect on the fluctuations occurring near the magnetopause.

(5) Magnetosheath origin: Generation of fluctuations in the magnetosheath is a relatively unexplored area. One such suggestion for generating waves in the magnetosheath has been given by KAUFMANN *et al.* (1970) and CROOKER and SISCOE (1977). They suggested that the mirror instability might be responsible for the observed large-amplitude waves in the frequency from 0.01 to 0.1 Hz. Instabilities in the magnetosheath may generate various waves, but neither theory nor experiment has been investigated on this possibility to any great extent.

The fluctuations in the magnetosheath probably originate in a variety of ways, but the relative importance of various sources is not clear. Our results suggest that the major source of the magnetosheath fluctuations is the transmission of the interplanetary fluctuations through the bow shock, because the frequency range of the fluctuations observed in the magnetosheath is similar to that in the upstream region, and moreover the compressional waves can propagate into the inner magnetosheath.

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