TAO, Vol. 9, No. 1, 1-14, March 1998

ULF Field Fluctuations in a "Quiet" Subsolar Magnetosheath

K. Liou* and C. A. Lin[1]

(Manuscript received 17 September 1996, in final form 27 June 1997)

ABSTRACT

We present the analysis of plasma and field data acquired from the AMPTE/IRM satellite for ULF wave fluctuations in the subsolar magnetosheath under a "quiet" condition. A total of seven magnetosheath crossings, representing twelve hours of observations, were selected for statistical analysis. The statistical analysis results indicated that mirror-like compressional fluctuations are typical of the quiet-state subsolar magnetosheath. It is also found that mirror-like fluctuations with typical frequencies between 10 mHz and 80 mHz (or $0.02 f_{H^+} \leq f \leq 0.2 f_{H^+}$, where f is the wave frequency and f_{H^+} the local proton gyro frequency) are associated with $0.1 \leq (T_\perp / T_\parallel - 1) \leq 0.6$ and $1 \leq \beta_p \leq 10$ magnetopause plasma, where β_p is the proton beta and $T_\perp$ and $T_\parallel$ are the perpendicular and parallel proton temperature, respectively. We also found that the condition for mirror instability, $T_\perp / T_\parallel > 1 + \beta_\perp^{-1}$, is generally not satisfied in the entire region of the magnetosheath, especially near the magnetopause. This may indicate that temperature anisotropy is reduced due to the development of mirror waves as suggested by *Price et al.* [1986] and *Lee et al.* [1988].

(Key words: ULF fluctuations, Magnetosheath, Temperature anisotropy)

1. INTRODUCTION

It has long been suggested that magnetic Pc 3-4 pulsations observed in the magnetosphere are influenced by solar wind parameters, such as the solar wind velocity and the orientation and magnitude of the interplanetary magnetic field (IMF)[Fairfield, 1969]. A comparison of ULF fluctuations in the solar wind, the magnetosheath, and the dayside magnetosphere using simultaneous data from ISEE 1 and 2 in the upstream solar wind, AMPTE/IRM in the subsolar magnetosheath, and AMPTE/CCE in the dayside magnetosphere [Engebretson *et al.*, 1991] showed that dayside magnetospheric Pc 3-4 pulsation activities are associated with low IMF cone angles and increased turbulence in the subsolar magnetosheath magnetic field, and with increased and highly variable levels of energetic magnetosheath particles. In a related paper, Lin *et al.* [1991] found that the thermal beta and the perturbation energy increase greatly as the

*Now at The Johns Hopkins University, Applied Physics Laboratory,Laurel, MD 20723, USA
[1]Institute of Space Science, National Central University, Chung-Li, Taiwan 320, ROC

magnetosheath region becomes more disturbed, and the total pressure of the subsolar magnetosheath region decreases as the region becomes more disturbed. They also found that the changes in magnitude of the plasma bulk velocity in the subsolar magnetosheath have little effect on the occurrence of Pc 3-4 waves in the outer magnetosphere.

Although the solar wind and interplanetary magnetic field (IMF) ultimately control geomagnetic activity, it is the magnetic field and plasma in the magnetosheath which impinge directly on the magnetopause [Anderson and Fuselier, 1993]. Hence the processes responsible for transferring solar wind energy into the magnetosphere and the features of the magnetosheath are of great interest and are one of the most debated issues in space physics.

Magnetic field fluctuations in the magnetosheath associated with ion cyclotron and mirror instabilities have long been identified. Fairfield [1976]first attributed the observed field fluctuations of around 1 Hz, below the local proton cyclotron frequency with a left-hand polarization, in the magnetosheath near the magnetopause, to ion cyclotron waves. Large-amplitude compressional fluctuations, $\delta B/B \sim 0.5$, were also observed in the magnetosheath and were attributed to the mirror instability [Tsurutani *et al.*, 1982]. Numerical simulation of mirror waves at the earth's magnetosheath has been studied by Price *et al.* [1986]. Lee *et al.* [1988] found that the mirror instability provides a mechanism for the isotropization of the ion temperature downstream of the shock. A number of studies have also examined the magnetic fluctuation characteristics of the magnetosheath near the magnetopause [Song *et al.*, 1990, 1993; Anderson *et al.* 1991; Anderson and Fuselier, 1993]. By using the AMPTE/CCE satellite data, Anderson *et al.* [1991] and Anderson and Fuselier [1993] found close correlation between the wave magnetic fluctuations and plasma properties. They found that cyclotron waves occurred for reduced plasma density and increased magnetic field strength (low β). Their observations also suggested that magnetosheath ion anisotropies may be ordered by the ion anisotropy mode that is most unstable. Anderson and Fuselier [1994] studied the plasma properties associated with different spectral features of 0.1-4.0 Hz magnetic fluctuations in the magnetosheath and found that mirror waves are associated with $\beta_p > 5$ and $T_\perp/T_\parallel \sim 1.5$, where β_p is the proton beta, and $T_\perp$ and $T_\parallel$ are the perpendicular and parallel temperature, respectively.

Phan *et al.* [1994] studied 38 low-latitude, dayside (0800-1600 LT) magnetopause crossings by the AMPTE/IRM satellite and found that the structures of the key parameters, magnetic field and the dynamics of plasma flows, in the magnetosheath region depend strongly on the magneticshear across the magnetopause. They concluded that when the magnetic shear is low ($\leq 30°$), a magnetosheath transition layer, also called the "plasma depletion layer,'' of 10-min average width exists where the magnetosheath magnetic field piles up against the magnetopause. In this region the plasma density and plasma β , as well as the proton and electron temperatures, are lower than in the magnetosheath proper. They also found that the condition for the onset of the mirror instability is generally not met in the magnetosheath transition layer, where the plasma β often falls below 1, while it is marginally satisfied in the magnetosheath proper, where usually $\beta > 1$. When the magnetic shear across the magnetopause is high ($> 60°$), the near-magnetopause magnetosheath is more disturbed. The magnetic field in this case does not pile up in the immediate vicinity of the magnetopause, and no systematic variations in the plasma parameters are observed in this region until the encounter of the magnetopause current layer; that is, there is no magnetosheath transition layer. Also, in contrast to the low-shear case, the mirror instability threshold is marginally satisfied throughout the magnetosheath.

The study of relative high frequency (0.1-4 Hz) and high solar wind dynamic pressure in the magnetosheath has been reported by Anderson and Fuselier [1994]. To our knowledge, however, there is no report concerning the PC 3-4 range fluctuations (< 0.1 Hz) in the magnetosheath, which may be directly associated with the PC 3-4 pulsations observed in the magnetosheath. In the present paper we will use AMPTE/IRM measurements to study the wave characteristics in a frequency range below 0.1 Hz and their associated plasma properties in a "quiet" magnetosheath under normal solar wind dynamic pressure. A "quiet" magnetosheath can be distinguished from a "disturbed" one by the presence of energetic ions of 3-40 keV [Asbridge *et al.*, 1978].

The organization of the report is as follows. In section 2 we present data analysis using a case study with emphasis on wave characteristics and mode identification. Section 3 presents the statistical analysis on background plasma parameters. Since this research is only preliminary, we will not try to make any conclusion but a short discussion will be given in section 4.

2. DATA ANALYSIS

The AMPTE/IRM satellite was launched on August 16, 1984, into near equatorial highly elliptical orbits. Plasma parameters are sampled every 4.5 s and the magnetic field data are averaged over the plasma sampling time from the original sample rate of 32 s^{-1}. A detailed discussion of the magnetometer and the plasma instruments on board the APMTE/IRM can be found in the reports of Lühr *et al.* [1985] and Paschmann *et al.* [1985], respectively.

During the entire mission of the AMPTE/IRM between 1984 and 1986, a total of 68 passes through the daytime (0800-1600 LT) low-latitude magnetopause have been identified. A preliminary study indicated that highly structured magnetic field fluctuations (< 60 mHz) were often seen during the near noon magnetosheath passes. In order to study these waves, we only select cases in which the AMPTE/IRM made a near noon equatorial pass (< 15° LMT). Under this restriction, only 7 such passes are found to be appropriate. In this study, we will present a typical event to study the waves in the ULF frequency range (< 0.1 Hz).

To identify the structured field fluctuations, we will use a simple parameter, R, introduced by Lin *et al.* [1991]. The R parameter is defined by

$$R = \frac{1}{N}\left| \sum_{i=1}^{N} \frac{\mathbf{B}_i}{|\mathbf{B}|} \right| \qquad (0 \le R \le 1) \qquad (1)$$

where N is the number of measurements of the vector **B** in a time interval. The R parameter gives the information about the concentration level of vectors [Mardia, 1972]. If the vectors are randomly distributed in direction, R is zero and if the vectors all point toward the same direction, R is equal to 1. For scattered vectors, R will fall between 0 and 1.The variation of R indicates both the fluctuation level of the field and plasma flow, and, as pointed out by Lin *et al.* [1991], that R is sensitive to the transverse variation of the vector but is unaffected by the compressional component of the vector. This means that R is a good indicator of direction changes but not of magnitude changes. In this study, we will use the R parameter to separate the "quiet" state magnetosheath from the "disturbed" state magnetosheath. The "quiet" state is defined by a low fluctuation in the level of magnetosheath plasma, and the field parameter (large R). A preliminary study of the seven selected events indicated that in each case magnetosheath magnetic fluctuations intensified when R was lower than 0.8. Therefore, only data with R > 0.8 will be used for statistical analysis.

In this study, each R parameter is evaluated using 55 samples (about 5 min.). Data are shifted 12 samples (about 1 min.) for calculating the next R value. It should be noted that the choice of the time interval and the shift length are not unique. Generally, a smaller time segment results in a more detailed time variation for R.

Case study event: 1000-1200 UT August 30, 1984 (day 213)

Figure 1 shows an outbound near noon magnetosheath pass. The AMPTE/IRM satellite entered the magnetosheath at about 10:05 UT from the magnetosphere. Data from the top panel to the bottom panel of Figure 1 are respectively, the plasma flow velocity, plasma density, three components of magnetic field in GSE coordinates, the total magnetic fields, the proton parallel and perpendicular temperature, and the electron parallel and perpendicular temperature. After the encounter of the magnetosheath plasma (> 1005 UT), the AMPTE/IRM observed a highly structured magnetic field fluctuation as can be seen in Figure 1. The wave structure of the magnetic field, with an amplitude (δB/B) decreasing from ~0.5 to ~0.1, appeared throughout the magnetosheath. The R parameter shown in the bottom panel of Figure 4 indicates that the field vectors are highly concentrated (R~1). By using the minimum variance analysis, we found that the wave vectors are mainly pointing in the x direction (not shown).

The dynamic power spectra of the waves from 1015-1145 UT are shown in Figure 2. The time window is about 5 minutes and data are shifted such that the total number of data segment (about 200) across the entire time range is fixed. The power density (in unit of nT^2/Hz) is scaled using 16 tones of gray. From top to bottom, the panels in Figure 2 show the total, the Z, the Y, and the X components of the magnetic fields on GSE coordinates. One can see that the wave power is mainly in the range 10 mHz to 80 mHz (or $0.02 f_{H^+} \leq f \leq 0.2 f_{H^+}$, where f is the wave frequency and f_{H^+} the local proton gyro frequency). The wave frequencies tend to be increasing with the distance from the magnetopause for the first 30 minutes. They then remain steady, but weaker in power, in the range 40 to 80 mHz throughout the rest of the magnetosheath region. It is interesting to note that the highly similarity between the B_y and the B_t power spectra densities indicates that wave fluctuations were mainly in the y direction. This can also be justified by the low power density in the z direction for frequencies above 10 mHz. Since the wave vectors were approximately in the x direction and the local magnetic fields were roughly in the y direction (see Figure 1), we conclude that these are compressional waves.

Large-amplitude compressional fluctuations in the magnetosheath have long been attributed to mirror instability [Tsurutani *et al.*, 1982]. Previous theoretical study has also shown that compressional fluctuations are consistent with the mirror mode [Gary *et al.*, 1993]. To identify the wave mode of the observed compressional fluctuations, a simple and useful method

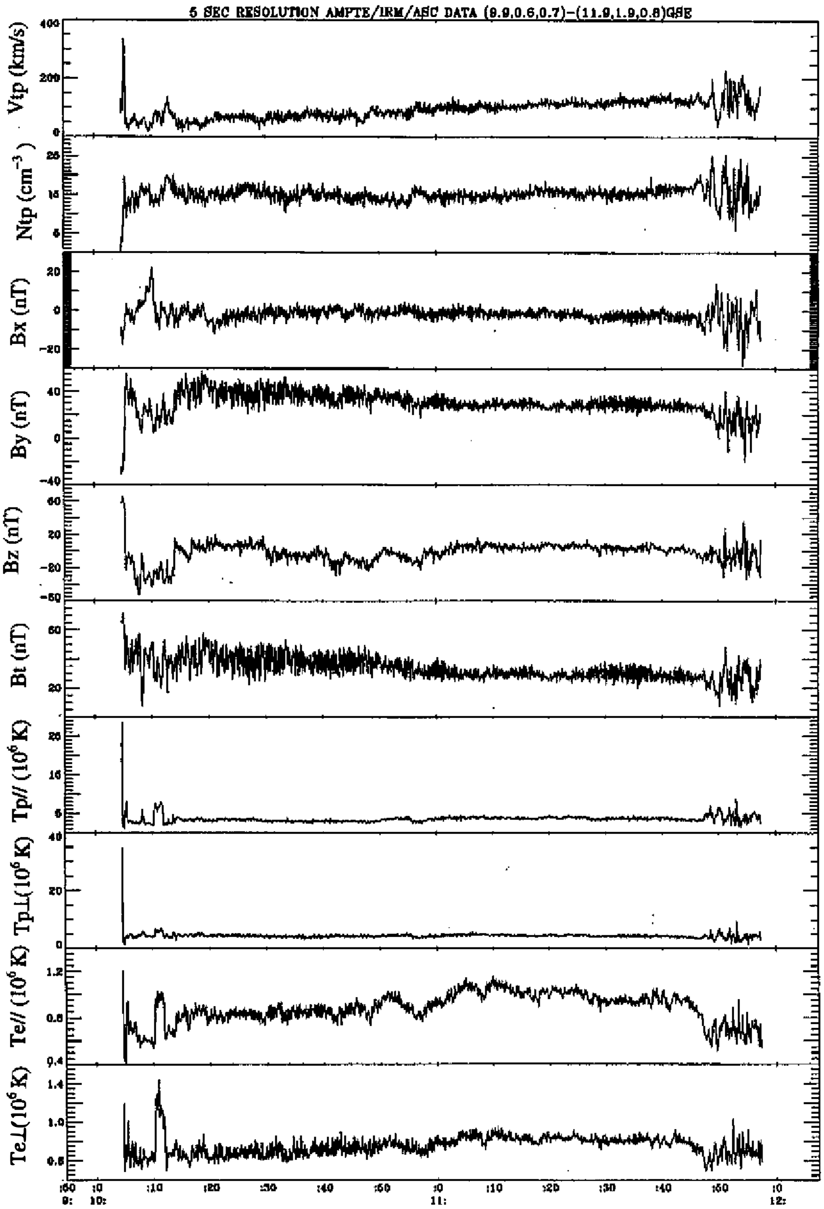

Fig. 1. Plasma and magnetic field data for the magnetosheath interval of August 30, 1984. From top to bottom, the figure shows the plasma flow speed (V_{tp}), the plasma density (N_{tp}), three components of magnetic field (Bx,By,Bz) on GSE coordinates, the total magnetic field (Bt), the proton parallel ($T_{p\parallel}$) and perpendicular temperature ($T_{p\perp}$), and the electron parallel ($T_{e\parallel}$) and perpendicular temperature ($T_{e\perp}$), respectively. The start and end positions of the AMPTE/IRM are shown next to the main title on the right in Earth radii (R_e).

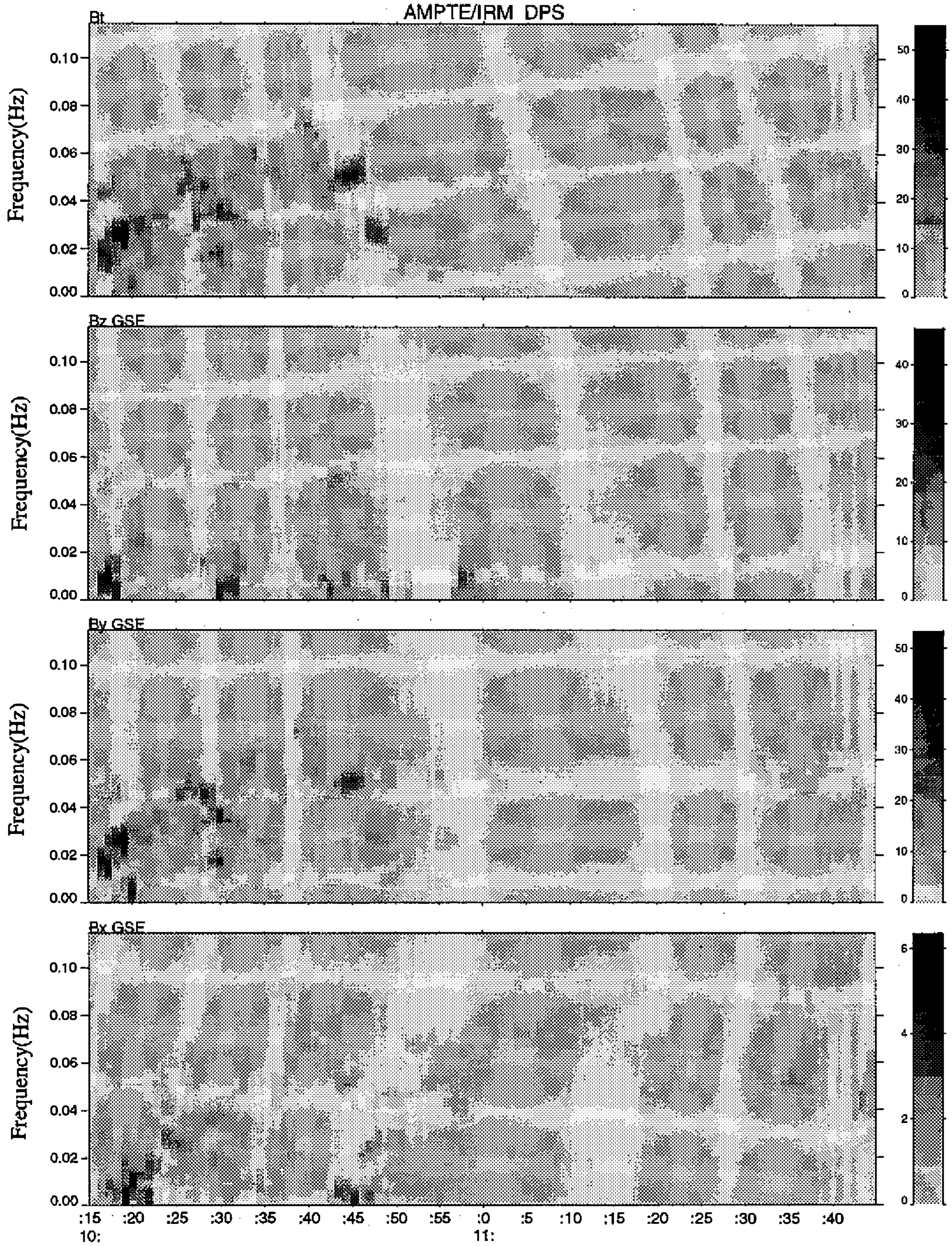

Fig. 2. Dynamic power spectral density of the magnetic field for the 1015-1145 UT interval of August 30, 1984. From top to bottom, the figure shows the dynamic spectra of the total, the Z, the Y, and the X components of the field in GSE coordinates.

will be used. Although fast, slow, and mirror modes can all be predominantly compressional, the phase relation between the density variation δn and the field variation δB is different. For the fast mode, δn and δB are in phase, but they are in antiphase for the slow and mirror modes. The mirror and slow modes may be distinguished according to the ratio of $|\delta n/n|$ to $|\delta B/B|$: magnetic field perturbations predominate in the mirror mode [Gary, 1992], $|\delta B/B|>|\delta n/n|$; whereas density perturbations predominate in the slow mode [Gary and Winske, 1992], $|\delta n/n|>|\delta B/B|$.

To identify the observed wave mode, we plot a small time segment from 1015 UT to 1025 UT of the normalized variations of plasma density, $\delta n/n$, and magnetic field, $\delta B/B$, in Figure 3. The plasma density variations are calculated using proton density rather than electron density as an approximation. In a typical magnetosheath plasma, the concentration of He^{+2} is about 5%. It is easy to estimate that the error introduced by our underestimation of the plasma density is less than 10%. The variation of the plasma density and field are obtained from high-pass filtering of the observed data at 1 mHz. One can see from Figure 3 that $\delta B/B$ (dotted line) predominates $\delta n/n$ (solid line) and that they are anticorrelated, indicating a mirror wave.

The plasma parameters for this event from 1015-1145UT are evaluated and plotted in Figure 4. From top to bottom, the panels show the mirror instability parameter, $T_\perp/T_{\parallel}-1-\beta_\perp^{-1}$, the proton temperature anisotropy, $T_\perp/T_{\parallel}$ - 1, the electron beta, β_e, the proton beta, β_p, the perpendicular proton pressure, $P_\perp$, the parallel proton pressure, $P_{\parallel}$, the dynamic pressure, P_D, the magnetic pressure, $B^2/8\pi$, and the R parameter. The dynamic pressure is defined as 0.881 $N_p M_p V_n^2$ [Spreiter *et al.*, 1966], where N_p and M_p are the proton density and mass, respectively, and V_n is the velocity component normal to the magnetopause. For simplicity, we will approximate V_n to V_x because this event was a subsolar measurement. The magnetic pressure generally decreases with the distance from the magnetopause, where as the plasma thermal pressure and dynamic pressure increase with the distance from the magnetopause. Consequently, the proton beta and electron beta increase with the distance from the magnetopause. The proton temperature anisotropy is enhanced in the high

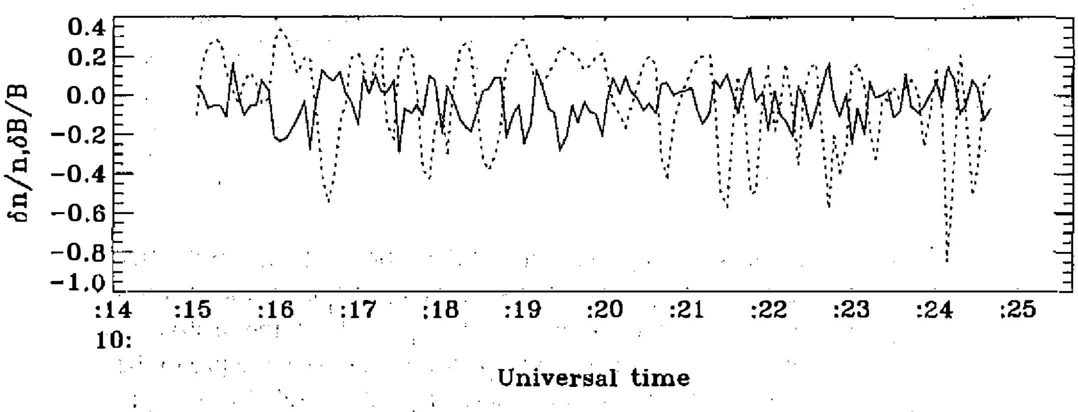

Fig. 3. Normalized plasma density (solid line) and magnetic field (dotted line) fluctuations for the 1015-1025 UT interval of August 30, 1984.

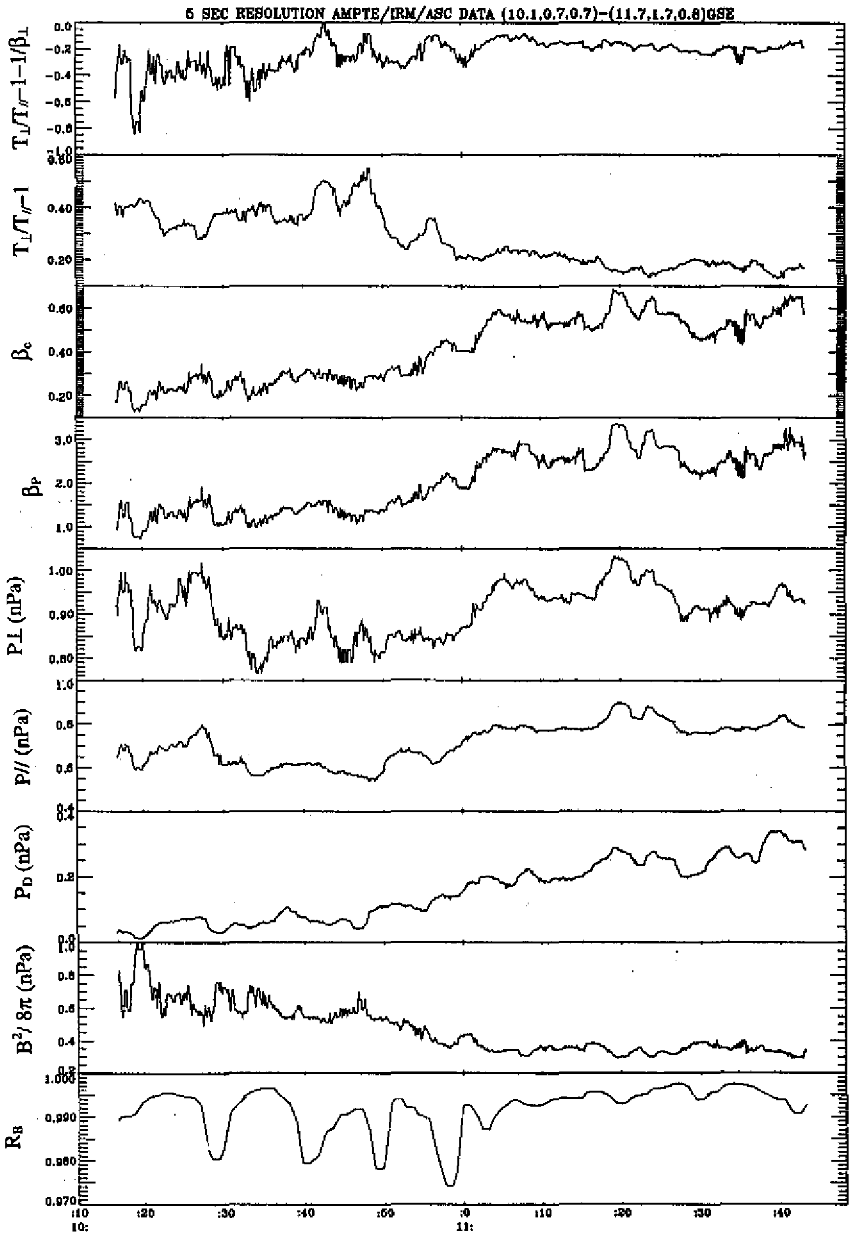

Fig. 4. Parameters calculated using data from AMPTE/IRM satellite for the 1015-1145 UT interval of August 30, 1984. From top to bottom the panels are the mirror instability parameter ($T_\perp / T_{\parallel} - 1 - 1/\beta_\perp$), the proton temperature anisotropy ($T_\perp / T_{\parallel}$ -1), the electron beta (β_e), the proton beta (β_p), the perpendicular proton pressure ($P_\perp$), the parallel proton pressure ($P_{\parallel}$), the dynamic pressure (P_D), the magnetic pressure ($B^2/8\pi$), and the R parameter.

field, low-β region. This is because of a comparatively large decrease in parallel temperature. One should note from the top panel in Figure 4 that the condition for mirror instability is not satisfied for the entire magnetosheath region. Since mirror instability provides a mechanism for the isotropization of the ion temperature [Lee *et al.*, 1988], this may indicate that mirror waves have developed, leading to a decrease in $T_\perp/T_\parallel$ to below the instability condition.

3. STATISTICAL ANALYSIS

The example shown in the previous section is one of typical "quiet" state magnetosheath observations near the subsolar point. In this section, we will address two questions raised from the previous case study. The first is whether the mirror mode predominates the ULF waves in a "quiet" state magnetosheath near the subsolar region, and the second is what the mechanism responsible for the generation of the observed wave fluctuations is.

There were 7 magnetosheath passes which fall within our interests. In addition to the case study event of August 30, 1984, the other 6 events are 1305-1445 UT of August 28, 1984, 0630-1000 UT of September 1, 1984, 0900-1045 UT of September 12, 1984, 1240-1400 UT of October, 1984, 1300-1500 UT of September 12, 1985, and 1130-1300 UT of November 17, 1985.

To answer the first question, we take each measurement of density and field variation over all the surveyed events (about 12 hours or around 8700 samples) and $\delta n/n$ versus $\delta B/B$ in Figure 5. It should be noted that in Figure 5 a single dot corresponds to a single measurement. One can see that the anticorrelation between the density and field variations is obvious with $|\delta n/n| < |\delta B/B|$, indicating a mirror mode. The correlation coefficient is high at -0.8. Therefore mirror mode may be the typical wave which predominates the field fluctuations in the ULF range in a "quiet" state subsolar magnetosheath.

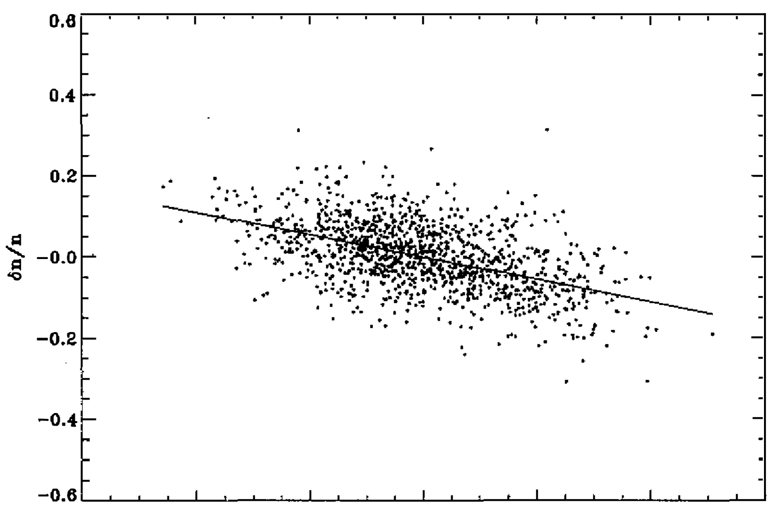

Fig. 5. Plot of normalized plasma density variation versus normalized magnetic field variation for all events.

In order to determine what physical parameters control the wave activity observed by AMPTE/IRM in the subsolar magnetosheath, we have studied the relation between the sheath parameters for all events. The magnetosheath parameters include proton parallel thermal pressure, P_{ll}, proton perpendicular thermal pressure, $P_{\perp}$, proton beta, β_p, electron beta, β_e, plasma dynamic pressure, P_D, magnetic pressure, $B^2/8\pi$, proton temperature anisotropy, $T_{\perp}/T_{ll}$ - 1, and the mirror instability parameter, $T_{\perp}/T_{ll} - 1 - \beta_{\perp}^{-1}$. The background sheath parameters are an average of 55 point (~5 minutes), and a total of 158 points was obtained for each parameter. The results are shown in Figure 6. Figure 6(a) shows the relation between the proton parallel and perpendicular pressure or temperature. Under the "quiet" state condition, the proton perpendicular temperature is linearly dependent on the proton parallel temperature with $P_{ll} \sim P_{\perp}$ - 0.5 nPa. Figure 6(b) shows the relation between the electron parallel and perpendicular beta or temperature. One can see that the temperature ratio, $T_{ell}/T_{e\perp}$ is equal to 1 over a wide range of electron beta. The electron beta, for most of the measurements, falls between 0 and 2. The isotropy feature in electron temperature may be useful for identifying a quiet state magnetosheath.

According to kinetic theory, the condition for mirror instability is $T_{\perp}/T_{ll} > 1 + \beta_{\perp}^{-1}$. Since we have identified the observed compressional fluctuations as a mirror mode, we expect that this condition must be satisfied for all events. However, this is not consistent with the observational result. In Figure 7, the mirror instability parameter is plotted versus proton beta. One can clearly see that the value of this parameter falls between -0.5 and 0.3. It should be noted that mirror instability occurs for a positive value of this parameter. The mirror condition is satisfied, but only marginally, for $\beta_p \geq 2$. However, it is not satisfied for $\beta_p \leq 2$.

Linear Valsov theory predicts that magnetosheath ion temperature anisotropy with $T_{\perp} > T_{ll}$ can give rise to three different growing modes in a homogeneous plasma. From the condition under which a mirror wave can grow, *i.e.*, $T_{\perp}/T_{ll} - 1 - \beta_{\perp}^{-1} > 0$, a high beta plasma becoming unstable is more probable at a low level of anisotropy than at a low beta plasma. The

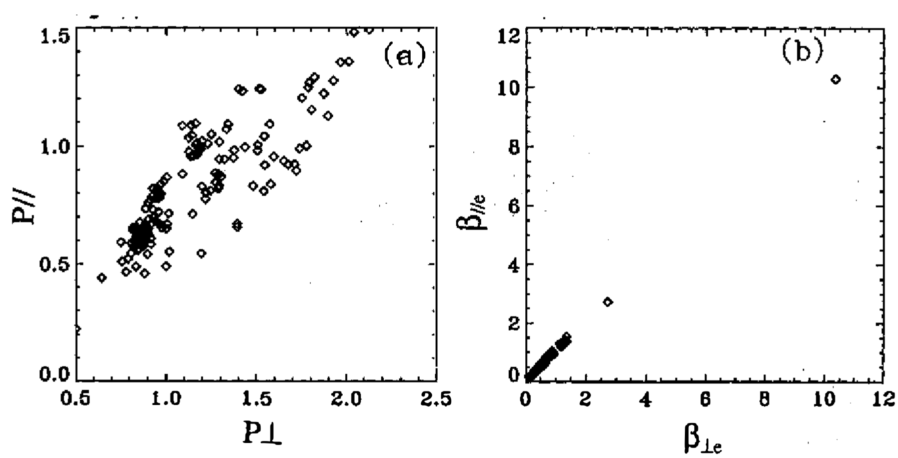

Fig. 6. Relation of parallel and perpendicular proton pressures (left panel) and parallel and perpendicular electron beta (right panel) for all mirror mode intervals.

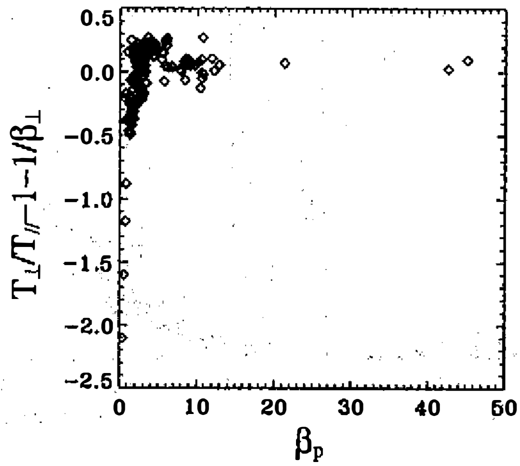

Fig. 7. The mirror instability parameter as a function of β_p for all mirror mode intervals.

result shown in Figure 8(a) is consistent with this theory. The relation between ($T_\perp/T_\parallel$ - 1)and $B^2/8\pi$ is roughly linear correlation, *i.e.*, the proton temperature anisotropy increases with the increase in the magnetic pressure (see Figure 8(b)), where as the temperature anisotropy increases with the decrease in proton pressure and dynamic pressure (see Figure 8(c) and 8(d)). It should be noted that the temperature condition, ($T_\perp/T_\parallel$ - 1) < 0.5, accounts for more than two-thirds of our surveyed measurements, indicating a low level of temperature anisotropy under a "quiet" state magnetosheath condition.

4. DISCUSSION AND CONCLUSION

In this study we have shown that compressional mirror-like field perturbations predominate the ULF band fluctuation in the equatorial magnetosheath under a "quiet" sheath condition. The mirror-like fluctuations found in this study have frequencies in the range of 10 mHz - 80 mHz ($0.02\, f_H + \leq f \leq 0.2 f_H +$) throughout the magnetosheath. However, the peak of the wave spectrum shifts from low frequency near the magnetopause to high frequency near the bow shock, and the wave power, in general, increases with the distance from the magnetopause.

Statistical analysis of seven surveyed magnetosheath crossings indicates that mirror-like field fluctuations were observed throughout the magnetosheath under different plasma conditions. In general, the plasma conditions under which the mirror-like fluctuations occurred can be summarized as follows.

(1) Electron temperature is isotropic for all measurements (from Figure 1).

(2)The condition for mirror instability to occur is generally satisfied for $\beta_p \geq 2$ (from Figure 7).

(3)The mirror-like fluctuation occurs when ($T_\perp/T_\parallel$ - 1) < 1.5 and $\beta_p \geq 1$. We also found that $0.1 \leq$ ($T_\perp/T_\parallel$ - 1) ≤ 0.6 and $10 \geq \beta_p \geq 1$ account for over two-thirds of the measurements (see Figure 8a).

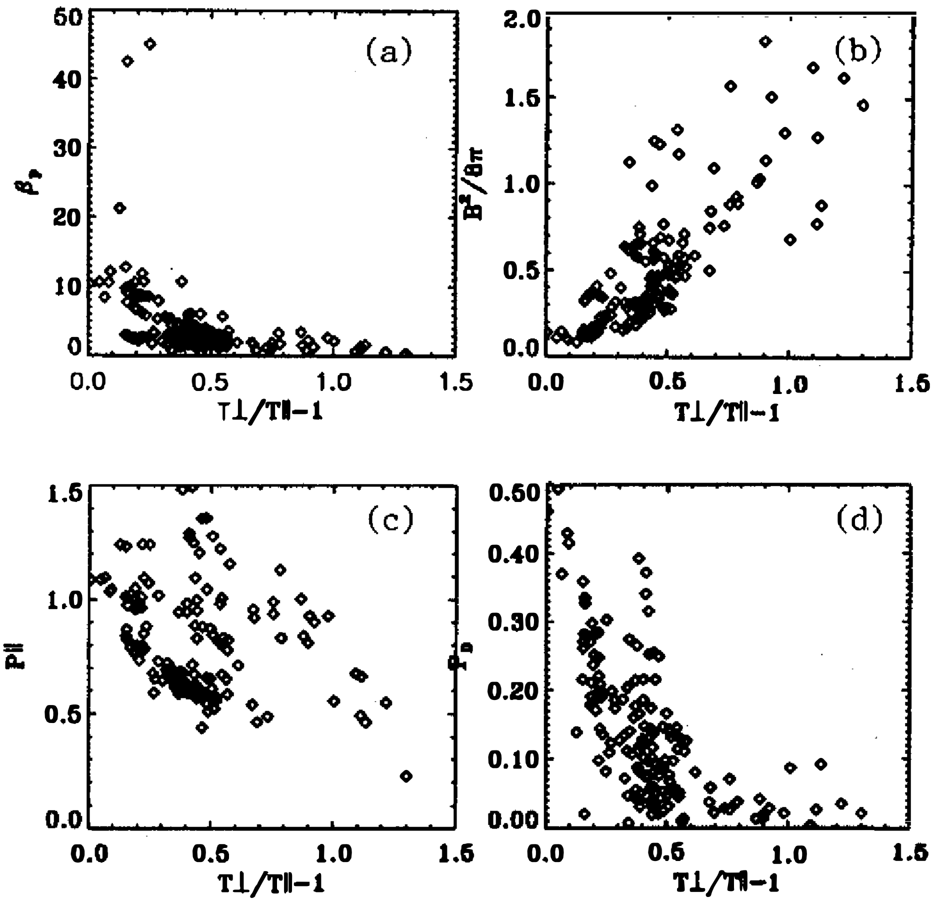

Fig. 8. Plot of the proton beta (panel a), the magnetic pressure (panel b), the parallel proton thermal pressure (panel c), and the dynamic pressure (panel d) versus the proton temperature anisotropy.

The identification of the compressional fluctuations as the mirror mode is based on the criterion given by Gary [1992] that magnetic field perturbations predominate the density perturbations in the mirror mode and the antiphase relation between δn and δB. Our result is reasonably consistent with that of Anderson and Fuselier [1993] who found that compressional mirror waves with $f < 0.2 f_{H+}$ are associated with $\beta_p > 5$ and $(T_\perp/T_\parallel - 1) = 0.5$. However, we do find that mirror-like fluctuations might occur for $\beta_p < 5$, and mirror instability is generally not met near the magnetopause where the most intense mirror-like compressional fluctuations were observed. This might indicate that the mirror wave may have developed, leading to a decrease of $T_\perp/T_\parallel$ below the instability condition.

Acknowledgments This work was supported by the National Science Council of the ROC under contracts NSC-85-2612-M008-004 and NSC-211-M-008-011-AP8.We'd like to thank

Dr. G. Paschmann and Dr. H. Lühr who provided AMPTE/IRM data for this study and Space Data Center of Institute of Space Science, NCU.

REFERENCES

Anderson, B. J., S. A. Fuselier, and D. Murr, 1991: Electromagnetic ion cyclotron waves observed in the plasma depletion layer. *Geophys. Res. Lett.*, **18**, 1955-1958.

Anderson, B. J., and S. A. Fuselier, 1993: Magnetic pulsations from 0.1 to 4.0 Hz and associated plasma properties in the Earth's subsolar magnetosheath and plasma depletion layer. *J. Geophys. Res.*, **98**, 1461-1479.

Anderson, B. J., S. A. Fuselier, S. P. Gary, and R. E. Denton, 1994: Magnetic spectral signatures in the Earth's magnetosheath and plasma depletion layer. *J. Geophys. Res.*, **99**, 5877-5891.

Asbridge, J. R., S. J. Bame, J. T. Gosling, G. Paschmann, and N. Sckopke, 1978: Energetic plasma ions within the Earth's magnetosheath. *Geophys. Res. Lett.*, **5**, 953.

Denton, R. E., S. P. Gary, B. J. Anderson, S. A. Fuselier, and M. K. Hudson, 1994: Low-frequency magnetic fluctuation spectra in the magnetosheath and plasma depletion layer. *J. Geophys. Res.*, **99**, 5893-5901.

Engebretson, M. J., N. Lin, W. Baumjohhann, H. Luehhr, B. J. Anderson, L. J. Zanetti, T. A. Potemra, R. L. McPherron, and M. G. Kivelson, 1991: A comparison of ULF fluctuations in the solar wind, magnetosheath, and dayside magnetosphere 1. Magnetosheath morphology. *J. Geophys. Res.*, **96**, 3441-3454.

Fairfield, D. H., 1969: Bow shock associated waves observed in the far upstream interplanetary medium. *J. Geophys. Res.*, **74**, 3541.

Fairfield, D. H., 1976: Magnetic fields of the magnetosheath. *Rev. Geophys.*, **14**, 117-134.

Gary, S. P.,1992: The mirror and cyclotron instabilities. *J. Geophys. Res.*, **97**, 8519-8529.

Gary, S. P., and D. Winske, 1992: Correlation fluctuation ratios and the identification of space plasma instabilities. *J. Geophys. Res.*, **97**, 3103.

Gary, S. P., S. A. Fuselier, and B. J. Anderson, 1993: Ion anisotropy instabilities in the magnetosheath. *J. Geophys. Res.*, **98**, 1481-1488.

Lee, L. C., C. P. Price, C. S. Wu, and M. E. Mandt, 1988: A study of mirror waves generated downstream of a quasi-perpendicular shock. *J. Geophys. Res.*, **93**, 247-250.

Lin, N., M. J. Engebretson, R. L. McPherron, M. G. Kivelson, W. Baumjohann, H. Luehhr, T. A. Potemra, B. J. Anderson, and L. J. Zanetti, 1991: A comparison of ULF fluctuations in the solar wind, magnetosheath, and dayside magnetosphere 2. Field and plasma conditions in the magnetosheath. *J. Geophys. Res.*, **96**, 3455-3464.

Lühr, H., N. Klöcker, W. Oelschlägel, B. Häusler, and M. Acuña, 1985: The IRM fluxgate magnetometer. *ISEE Trans. Geosci. Remote Sens.*, **GE-23**, 259-261.

Mardia, K. V., 1972: Statistics of Directional Data, Academic, San Diego, Calif..

Paschmann, G., H. Loidl, P. Obermauer, M. Ertl, R. Laborenz, N. Sckopke, W. Baumjohann, C. E. Carlson, and D. W. Curtis, 1985: The plasma instrument for AMPTE/IRM. *IEEE Trans. Geosci. Remote Sens.*, **GE-23**, 262-266.

Phan, T.-D, G. Paschmann, W. Baumjohhann, N. Sckopke, and H. Lühr, 1994: The magnetosheath region adjacent to the dayside magnetopause: AMPTE/IRM observations. *J. Geophys. Res.*, **99**, 121-141.

Price, C. P., D. W. Swift, and L. C. Lee, 1986: Numerical simulation of non-oscillatory mirror waves at the earth's magnetosheath, *J. Geophys. Res.*, **91**, 101-112.

Song, P., C. T. Russel, R. J. Strangeway, J. R. Wygant, C. A. Cattel, R. J. Fitzenreiter, and R. R. Anderson, 1993: PC 3-4 energy coupling for northward interplanetary magnetic field. *J. Geophys. Res.*, **98**, 187-196.

Spreiter, J. R., A. L. Summers, and A. Y. Alksne, 1966: Hydromagnetic flow around the magnetosphere, *Planet. Space Sci.*, **14**, 223.

Tsurutani, B. T., E. J. Smith, R. R. Anderson, K. W. Ogilvie, J. D. Scudder, D. N. Baker, and S. J. Bame, 1982: Lion roars and non-oscillatory drift mirror waves in the magnetosheath. *J. Geophys. Res.*, **87**, 6060-6072.