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WAVES IN THE VICINITY OF THE MAGNETOPAUSE

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D. H. FAIRFIELD

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GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

ABSTRACT

IMP 6 magnetic field measurements demonstrate that the magnetopause is a complex variable boundary with few specific characteristics that persist from orbit to orbit. The appearance of the local magnetopause is determined largely by the boundary conditions imposed by the interplanetary field and the geomagnetic dipole. Magnitude changes across the magnetopause are frequently absent, and if concurrently the magnetosheath and magnetosphere fields also happen to be aligned, then the Chapman-Ferraro current sheet is absent. Ion cyclotron waves are identified in the magnetosheath near the magnetopause. Similar waves near the proton gyrofrequency are frequently seen in the current sheet associated with a large angle change at the boundary. Such waves may be important in the transfer of particles and momentum into the magnetosphere. Tailward propagating waves on the magnetopause boundary are found to be responsible for multiple crossings of the tail boundary at $32R_E$. Monochromatic waves are occasionally seen in the magnetosphere at frequencies slightly below the proton gyrofrequency.

1. INTRODUCTION

The earth's magnetopause remains one of the most important, yet least understood, features of the magnetosphere. It is important since the physical processes at the magnetopause control the entry of energy into the magnetosphere and the formation of the geomagnetic tail. The subject is not well understood theoretically because the relevant physical processes span both hydromagnetic and kinetic regimes and include many of the most difficult problems of plasma physics. Also, many theories depend critically on boundary conditions which experiments have not clearly delineated. Experimental difficulties arise primarily from the inability of some experiments to provide sufficient time resolution within the thin boundary region.

Existing theories of the magnetopause can be roughly categorized according to three different points of view:

1. Hydromagnetic continumm theory assumes that the magnetopause is a tangential discontinuity. This theory is able to predict the location of the magnetopause and study its stability with respect to processes such as the Kelvin-Helmholtz instability. Some of these theories hypothesize a viscosity (Cassen and Szabo, 1970) to describe the magnetosphere-magnetosheath interaction.

2. Reconnection theory (see review by Vasyliunas, 1975) avoids the assumption of a tangential discontinuity. This theory attaches great importance to a particular point or line on the magnetopause where the field components in a plane perpendicular to the local boundary are zero.

3. Kinetic theory investigates the incidence of plasma on a uniform field representing the magnetosphere (see review by Willis, 1971). Many theories in this class are deficient in that they neglect the magnetosheath field.

Experimental studies can similarly be classified as attempts to comment on the predictions of these three types of theories. Category one studies have found surprisingly good agreement with the hydromagnetic predictions of the magnetopause location (e.g. Fairfield, 1971) and there is a growing body of evidence in support of the Kelvin-Helmholtz instability (e.g. Dungey and Southwood, 1970; Ledley, 1971; Aubry et al. 1971; Wolfe and Kaufmann, 1975). Category two theories have stimulated a number of searches for a field component normal to the magnetopause surface (e.g. Sonnerup and Ledley, 1974 and references therein). The presence or absence of this normal component was supposed to differentiate between open magnetospheric models characterized by field lines crossing the magnetopause and closed models characterized by a boundary which is a tangential discontinuity. During recent years, considerable indirect evidence has been gathered for the existence of an open magnetosphere, but the direct evidence for the normal field component is quite limited. Category three studies of the microscale structure, on the other hand, have not stimulated extensive experimental study. Only a few examples of high time resolution data have been presented (Aubry et al. 1971; Ogilvie et al. 1971; Neugebauer et al., 1974; Sonnerup and Ledley, 1974) and the presence of waves near the proton gyrofrequency has been only briefly noted.

This paper uses magnetic field data from the IMP 6 spacecraft, sampled at a rate of 12.5 vectors $(\sec)^{-1}$ (See Fairfield, 1974, for experimental details), in an attempt to further clarify the magnetic field microstructure of the magnetopause. After discussing the problems in identifying the magnetopause in Section 2, and the difficulties in determining normal components in Section 3, the presence of waves in the vicinity of the magnetopause is discussed in Section 4. Section 5 considers the downstream magnetopause and demonstrates the presence of surface waves on the tail boundary.

2. IDENTIFYING THE MAGNETOPAUSE

The magnetopause is identified by locating a discontinuity in the magnetic field, plasma or particles. The position of discontinuities seen by different experiments on the same spacecraft generally agrees fairly well, at least on the time scale of the slowest sampling experiment (generally a few minutes). The present study has primarily used magnetic field data in identifying magnetopause crossings, although IMP 6 energetic particle data has been supplied by Anderson and Meng (private communication) and has been useful in confirming certain identifications.

The early publication of Cahill and Amazeen (1963) and the success of hydromagnetic theory has led to the popular notion that the subsolar magnetopause is characterized by weak magnetosheath fields relative to strong magnetosphere fields. In fact, the magnetosheath field is often equal to or greater than the magnetosphere field (Heppner et al, 1967). This more usual situation is displayed in Figure 1, where 15.36 second averages of the field magnitude B, standard deviation SD, and solar magnetospheric latitude angle θ and longitude angle ϕ are plotted for a time interval beginning outside the shock (located at 4h 36m) and ending after the magnetopause (located at 7h 19m) on May 2, 1971. Note that the field increases gradually as the spacecraft approaches the magnetopause. The magnetopause is characterized by the sudden angle change and the termination of field fluctuations as reflected in the standard deviation. On certain days the interplanetary field may happen to be oriented such that the magnetosheath is aligned with the magnetosphere field. Under these conditions there is no angular change and, when magnetic field data alone are available, only the termination of high frequency ($T \leqslant 60s$) fluctuations identifies the boundary. Except for the fluctuations in such cases, there is a uniform field across the magnetopause implying $\underset{\sim}{j} = \nabla \times \underset{\sim}{B} = 0$ and an absence of the conventional, thin Chapman-Ferraro current layer which is frequently assumed to characterize the magnetopause. The termination of magnetosheath fluctuations is usually adequate to identify the magnetopause with an accuracy of ten minutes ($\sim 0.2R_E$) and hence has sufficient precision for statistical work where orbit to orbit variations are much larger. These cases with little or no angle change cannot be properly studied without plasma data and will be largely ignored in the present study.

3. NORMAL COMPONENTS

The search for a field component along the magnetopause normal has been a subject of prime interest in many magnetopause studies. Although careful searches have revealed a few examples of such normal components (Sonnerup, 1971; Sonnerup and Ledley, 1974), it is clear (see also Aubry 1971; Ledley, 1971) that any identifiable normal component is small or lacking most of the time.

The present study has approached this problem by plotting the magnetopause data for some 30 traversals (mostly in the noon to dawn region) in a coordinate system where one axis is the direction of a model magnetopause normal (Fairfield, 1971). Since this field component generally shows little change across the magnetopause, the model normal is apparently a good approximation to the actual normal.

Furthermore, the magnitude of this component is invariably small ($B_n/B \leq .05$), thus confirming the results of earlier studies. Refinements in determining the correct normal have been attempted, but this report will concentrate on demonstrating the difficulties involved rather than reporting any new quantitative results.

The search for improved normals has employed two conventional methods. The first (hereafter called Method 1), the technique usually used in magnetopause studies (Sonnerup and Cahill, 1968), selects the direction $\hat{n}$ that minimizes the quantity $\sum_i (\underset{\sim}{B}_i - \bar{\underset{\sim}{B}} \cdot \hat{n}$ where $\underset{\sim}{B}_i$ are the vector measurements made throughout the magnetopause region and $\bar{\underset{\sim}{B}}$ is the average over the interval. The second method (Method 2) has been used on interplanetary discontinuities, and in a similar manner it minimizes the quantity $\underset{\sim}{B}_i \cdot \hat{n}$. (Siscoe et al., 1968). Clearly, for an idealized tangential discontinuity, there will be a direction of zero field and zero variation and both methods will yield this direction. In an actual "quasi-tangential discontinuity" such as the magnetopause, fluctuations along $\hat{n}$ can lead Method 1 to select a direction other than that in which the B_n is constant across the discontinuity. On the other hand, Method 2 selects a direction which is "most perpendicular" to the collection of vectors and hence discriminates against rotational discontinuities. The use of Method 2 can be justified a priori when a tangential discontinuity is found, whereas the component along

"$\hat{n}$" determined from a rotational discontinuity should display a characteristic variation across the boundary. Whether the average component across a discontinuity of 30 seconds width is meaningful or whether one should talk about variations on a time scale of seconds (Aubry et al., 1971) is not completely clear. It should be recalled that a time scale of seconds is approaching the proton gyrofrequency which is the limit of the hydromagnetic discontinuity theory.

4. ION CYCLOTRON WAVES

Figure 2 illustrates five minutes of detailed data for a magnetopause crossing on a geomagnetically disturbed day (April 18, 1972) when the AE index was continually greater than 200γ. The crossing point was located near the noon meridian but at southerly latitudes (X_{SE} = 8.9, Y_{SE} = 1.4, Z_{SE} = -6.0). Three components and the field magnitude are shown in a coordinate system where Z is the $\hat{n}$ direction computed by Method 2 over the interval shown. The two axes perpendicular to Z are oriented by choosing Y along the average magnetosphere field. The crossing is identified by a large angle change (123°) which occurs primarily during an interval of 10s beginning at 21h 33m 15s. The ten minute period prior to the interval shown is similar to the interval 30m 0s-31m 30s and the interval after that shown is characterized by even fewer high frequency fluctuations than seen from 34m-35m.

Power spectra of the interval 30m-31m are shown in Figure 3 in a coordinate system where Z is the average field direction and X and Y are perpendicular to Z. The spectra are characterized by considerable transverse power below the proton gyrofrequency (indicated by an arrow at .91 hz in Figure 3) and an abrupt cutoff in the power at this frequency. The waves are highly coherent, left hand polarized, and are propagating very nearly along the field direction. Near the cutoff frequency the waves are approximately circular (a ratio of minor to major axes of the polarization ellipse = .9) but at a lower frequency, such as 0.4 hz, the waves are much more elliptical (ratio $\sim$0.1). The direction of the perturbation vector of the elliptical waves (obtained by diagonalizing the real part of the spectral matrix, (see Fairfield and Behannon, 1975) is perpendicular to the magnetopause normal. The more circular waves at higher frequencies have perturbation vectors both along and perpendicular to the normal. This behavior can be seen in Figure 2 by the fact that waves with a period of a few seconds are clearly present in the X and Y components, but only higher frequency waves appear in the Z component. Such waves are frequently present near the magnetopause having 1) left hand polarization, 2) a cutoff at the proton gyrofrequency, and 3) ellipticity as a function of frequency invariably the same as described above. All these observed features are characteristics of the ion cylotron mode of wave propagation (Stix, 1962, p. 36). Since doppler shifting due to plasma flow should be minimal in this location, this identification of the wave mode is made with some confidence.

The region in Figure 2 between 21h 31m 30s and 21h 33m 30s that is neither clearly magnetosheath nor clearly magnetosphere is also characterized by large amplitude waves. Between 31m 30s and 33m 15s there appe to be two cycles of a wave with a period of about one minute as the field begins to slowly change direction. Superposed on these waves are large amplitude higher frequency waves of ion cyclotron-type frequencies. Three cycles of these waves that occur during the abrupt angle change have a frequency of .44hz (half the proton gyro-frequency) and peak to peak amplitudes of at least 20γ along the magnetopause normal. These higher frequency waves are a common feature of magnetopause crossings characterized by a large angle change. It is interesting to speculate that such waves may be the current driven electromagnetic ion cyclotron waves described by Kindel and Forslund (1972).

Figure 4 is an example from a relatively quiet interval on the very geomagnetically disturbed day of May 6, 1971. The spacecraft is at 8.9 R_E near the subsolar point and the interplanetary field is northward, so there is little angle change at the magnetopause. High fluxes of

> 20 kev trapped electrons are present before 11:51 and after 11:53, but they decrease three orders of magnitude between these times and help identify a pair of magnetopause crossings near these times. The waves present between approximately 11:51 and 11:53 are clearly ion cyclotron waves and are confined primarily to the magnetosheath and perhaps, to the extent it can be identified, the magnetopause. Note that the magnetosheath field is actually 20γ (20%) larger than the magnetosphere field at this time.

On rare occasions, highly coherent wave packets can be seen inside the magnetopause. Figure 5 illustrates an example seen at 9.0 R_E (X_{SE} = 8.3 Y_{SE} = 3.4 Z_{SE} = -0.8) about 40 minutes after the inbound magnetopause was seen at 9.8 R_E on April 3, 1971. Geomagnetic conditions were disturbed with the AE index decreasing from a value of 450γ an hour before the measurements to a value of 250γ at the time of the measurements. Three four-minute intervals (with 2 minutes missing between them) are shown with the m, l and k directions for each interval corresponding to the directions of maximum, intermediate, and minimum fluctuations respectively for the three segments indicated by bars. For all three time segments the direction of minimum fluctuation (the propagation direction of the waves) is very nearly the average field direction. For the first interval, the waves are confined primarily to one axis, indicating highly elliptical polarization. In the other two cases, the waves are also seen along the direction of intermediate variance, indicating more circular polarization. Spectral analysis confirms these facts and also indicates that the dominant polarization for these intervals is left handed. Examination of hodograms does, however, reveal individual cycles with right hand polarization. The major axis of the polarization ellipse changes with time as can be seen by comparing the m direction computed for each of the three intervals or by noting how the waves shift from the m to the 1 axis between 15m 45s and 17m 10s.

The frequency of the waves in each case is .34 hz (.36 Ωp where Ωp is the proton gyrofrequency) and the packets reappear at intervals of approximately 6 minutes. This is true not only of the three packets shown, but for two prior intervals not shown in Figure 5. Similar waves have been seen on a few other orbits, but they are not a common feature of the outer magnetosphere. The periodic occurrence of the packets has only been observed for the case discussed above.

Waves in this frequency range have been measured on the surface of the earth, where they are known as Pc1 micropulsations, but Figure 5 constitutes the first report of such waves observed beyond the synchronous orbit. Such waves undoubtedly participate in wave-particle interactions in the outer magnetosphere.

5. THE DOWNSTREAM MAGNETOPAUSE

Boundary crossings further downstream were studied by selecting an orbit when the spacecraft apogee of $32.4R_E$ was located near the boundary of the geomagnetic tail. This situation occurred on August 28, 1971, when a total of 36 boundary crossings were seen between 00h and 20h. Twenty-one of these crossings occurred during the 7.5h-interval shown in Figure 6. Geomagnetic conditions were quiet ($AE<100$) until $\sim$ 15:00 when a substorm occurred. The interplanetary field measured by the IMP 5 spacecraft had a small northward component prior to 10:20 and then a small southward component most of the time, until the field turned very southward an hour before the substorm. This behavior is duplicated by the IMP 6 data in the magnetosheath as can be seen in the θ component of Figure 6. The tail intervals in Figure 6 stand out as high field regions and are indicated by vertical lines over the magnitude.

This set of boundary crossings was studied by using the variance analysis to determine a boundary normal (Method 2 was used although Method 1 gave very similar results for most cases). The orientation of the boundary normals is seen in Figure 7 which displays the distribution of the angles between the normal and the earth-sun line. Crossings from the tail to the magnetosheath are separated from those in the reverse order. The median of the whole data set is 84.2 degrees which is a very reasonable value corresponding to the tail flaring away from the earth-sun line at an angle of 5.8°. Tail-magnetosheath crossings have significantly lower angles (median 81.6°) than magnetosheath-tail crossings (median 87.4°). This result is similar to that seen by Aubry et al. (1971) and Ledley (1971) near the subsolar magnetopause and can be interpreted, as these authors did, in terms of surface waves propagating in a tailward direction (see also Kaufmann and Konradi, 1969). This interpretation is illustrated schematically by the sketch in Figure 7, where normal vectors have been drawn at the median angles for corssings in the two directions. Waves propagating in a tailward direction will create tail to magnetosheath crossings with a smaller angle between $\hat{n}$ and the earth-sun line.

Other than the fact that the field magnitudes are smaller due to the more downstream location, no differences were noted between these crossings and those seen in the subsolar hemisphere. This fact is not surprising, however, in view of the great variety of the types of crossings seen in the subsolar hemisphere.

6. SUMMARY AND DISCUSSION

Study of high time resolution magnetic field data from passes of the IMP 6 spacecraft through the magnetopause region confirms earlier studies that have shown the magnetopause to be a very complex variable structure. This variability makes it particularly difficult to classify different structures and recognize features that are common to many orbits.

The boundary conditions imposed by the interplanetary field and the geomagnetic dipole are of considerable importance in determining the appearance of the magnetopause. When interplanetary fields with certain orientations are convected into the magnetosheath and draped over the magnetosphere (see review by Fairfield, 1975), the magnetosheath and magnetosphere fields may make a large angle, implying a strong current sheet. For other orientations, the magnetosphere and magnetosheath fields may happen to be aligned and no local current sheet is present. The net Chapman-Ferraro current on the surface of the magnetopause is then determined by the local boundary conditions at the various locations. These currents should be considered a function of the interplanetary field orientation rather than an invariant feature of the magnetopause.

Difficulties in accurately determining the magnetopause normal preclude any definitive statement about the existence of a small field component along the normal. In spite of these difficulties, the lack of a large component along the normal may be considered one of the few features to characterize all boundary crossings.

Rapid time variations of the field on time scales of 1-10's of seconds are another feature common to most orbits. These variations are probably due partly to waves and time varying structure and partly to irregular motion of a constant structure past the spacecraft whose velocity (~ 2 $km(sec)^{-1}$)must usually be small relative to the boundary velocity. The time scales of the crossings range from a few seconds to a few minutes, but the question of whether this variability is due to a changing thickness or a changing velocity remains unanswered.

Ion cyclotron waves have been identified in the magnetosheath near the magnetopause. These waves are propagating along the field, are left hand elliptically polarized with the major axis of the polarization ellipse tangent to the magnetopause and perpendicular to the normal. Similar frequency waves are often seen in the magnetopause current sheets associated with large angle changes, but these waves are not coherent enough to display the left hand polarization and sharp cutoff frequency that would absolutely confirm them as ion cyclotron waves. Whether the magnetosheath ion cyclotron waves have their origin at the magnetopause is not clear. Since they are propagating nearly along the field which is nearly tangent to the magnetopause, those waves observed at one location would have to have propagated from a more distant point on the magnetopause.

Eviatar and Wolf (1968) suggested that ion cyclotron waves in the magnetopause might be due to the two-stream cyclotron instabily associated with flow past the magnetopause. The waves reported in the present paper, however, are seen near the subsolar point where such flow should be small, and hence this suggestion would not appear to be applicable. An alternate possibility is that the waves are due to the current driven ion cyclotron instability (Kindel and Forslund, 1972). Once the waves are generated, the calculations of Eviatar and Wolf are applicable. These calculations show that ion cyclotron waves may be important in transferring particles and momentum to the magnetosphere.

The downstream magnetopause was studied using 36 crossings of the boundary which occurred on one day, while the spacecraft was at apogee at 32 R_E. Boundary normals at these times showed that the crossings were due primarily to tailward propagating waves on the tail boundary. Such waves are probably the tailward extension of a similar phenomenon seen closer to the subsolar point, and are probably due to the Kelvin-Helmholtz instability.

Monochromatic waves with frequencies 0.3 - 0.9 Ωp are occasionally seen in the magnetosphere. They are elliptically polarized and usually, but not always, left hand polarized. Such waves are probably the space analogue of Pc1 micropulsations observed on the ground. They undoubtedly participate in wave-particle interactions but do not necessarily have any relation to the magnetopause.

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FIGURE CAPTIONS

Figure 1 A typical inbound spacecraft pass through the magnetosheath illustrating the gradual increase in the field magnitude as the spacecraft approaches the magnetopause. The magnetopause occurs at 7h 19m and is characterized by a large change in the angles and a termination of field fluctuations.

Figure 2 Illustrating vector magnetic field data sampled every 80 milliseconds for a magnetopause crossing characterized by a large angle change. Although the average field component along the magnetopause normal (the Z direction) is small, large amplitude waves with frequencies below the proton gyrofrequency have perturbation vectors along this direction.

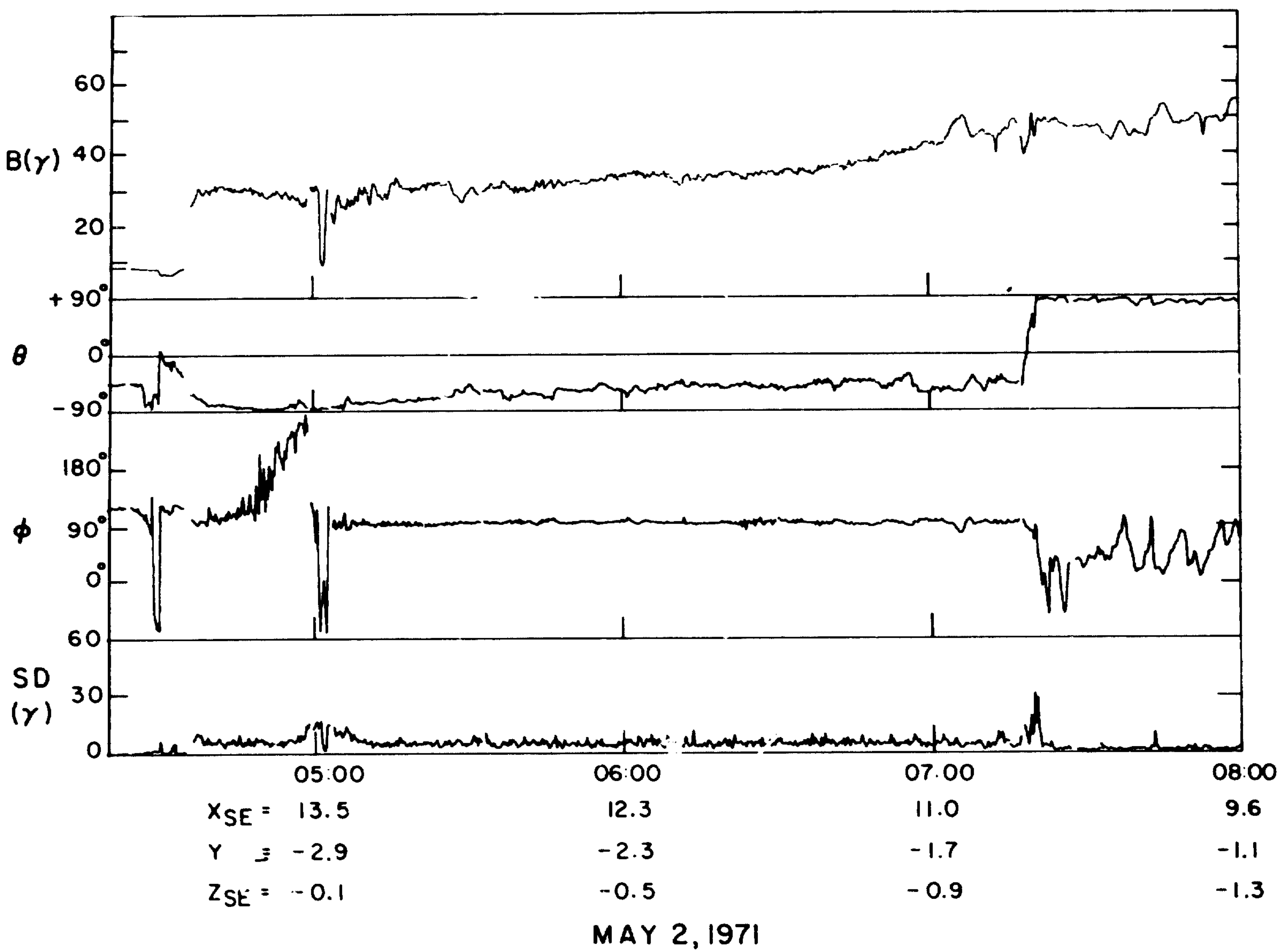
Figure 3 Magnetosheath power spectral density estimates for a time interval included in figure 2. The cutoff of the waves at the proton gyrofrequency, their left hand polarization, and the behavior of their ellipticity as a function of frequency serve to identify the waves as ion cyclotron mode waves.

Figure 4 Illustrating a pair of magnetopause crossings which occur at approximately 11h 51m and 11h 53m. The crossings were identified by the termination of high frequency fluctuations and a precipitous decrease in trapped electron flux.

Figure 5 An example of magnetosphere waves with frequency $\sim .36\ \Omega p$ which, for the example shown, occur in packets at intervals of 6 minutes.

Figure 6 Illustrating 21 crossings of the magnetotail boundary observed while the spacecraft was moving very slowly near apogee. Enhanced magnitudes characterize the magnetotail intervals whose boundaries have been marked by vertical lines.

Figure 7 The distribution of the angle between the normal to the tail boundary and the earth-sun line. Tail to magnetosheath crossings consistently have smaller angles, indicating tailward propagating waves on the boundary.



B(γ)
60
40
20
θ
+90°
0°
-90°
φ
180°
90°
0°
SD
(γ)
60
30
0
05:00
06:00
07:00
08:00
XSE = 13.5
12.3
11.0
9.6
Y -2.9
-2.3
-1.7
-1.1
ZSE = -0.1
-0.5
-0.9
-1.3
MAY 2, 1971

FIGURE 1

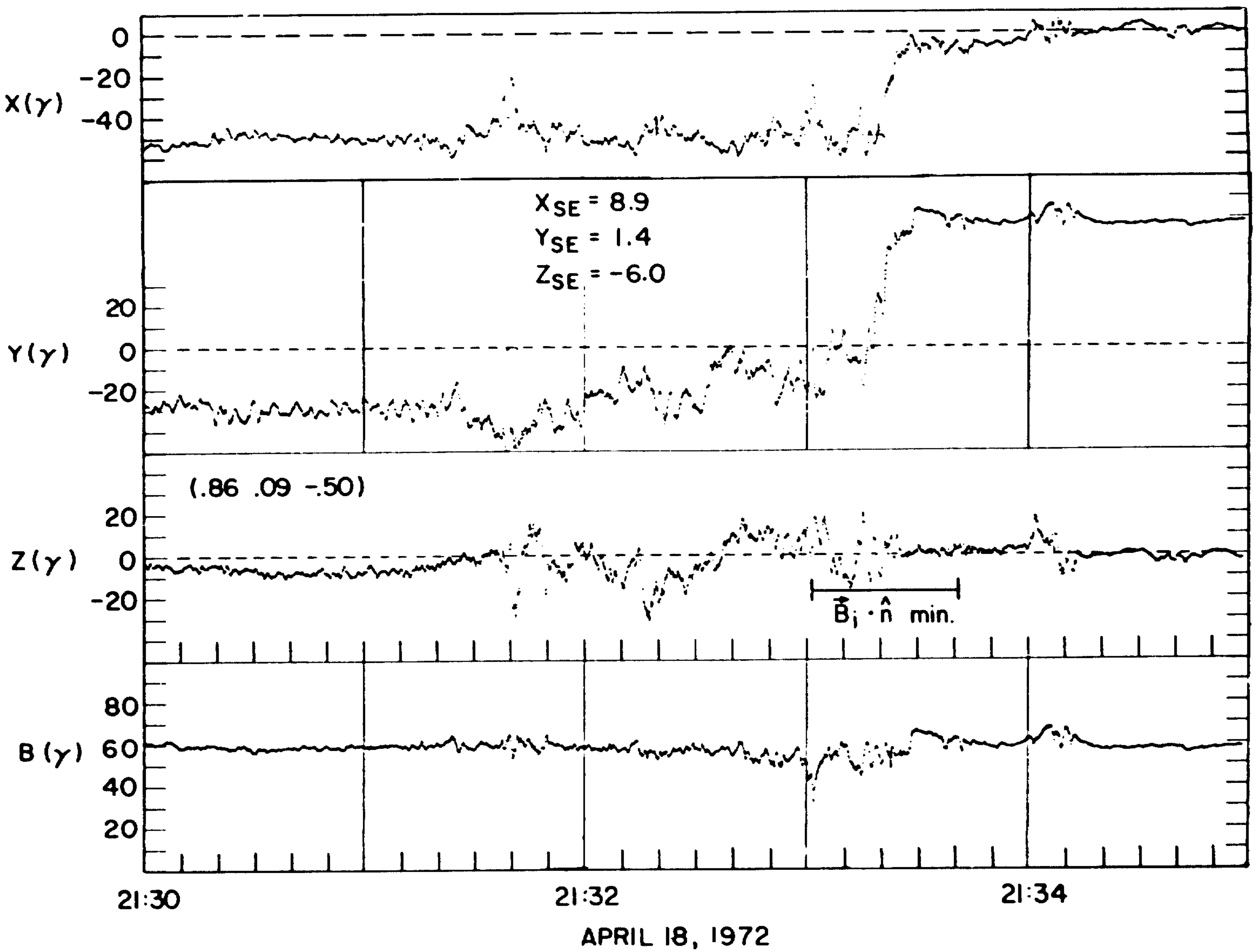

X(γ)
0
-20
-40
X_{SE} = 8.9
Y_{SE} = 1.4
Z_{SE} = -6.0
Y(γ)
20
0
-20
(.86 .09 -.50)
Z(γ)
20
0
-20
$\vec{B}_i \cdot \hat{n}$ min.
B(γ)
80
60
40
20
21:30
21:32
21:34
APRIL 18, 1972

FIGURE 2

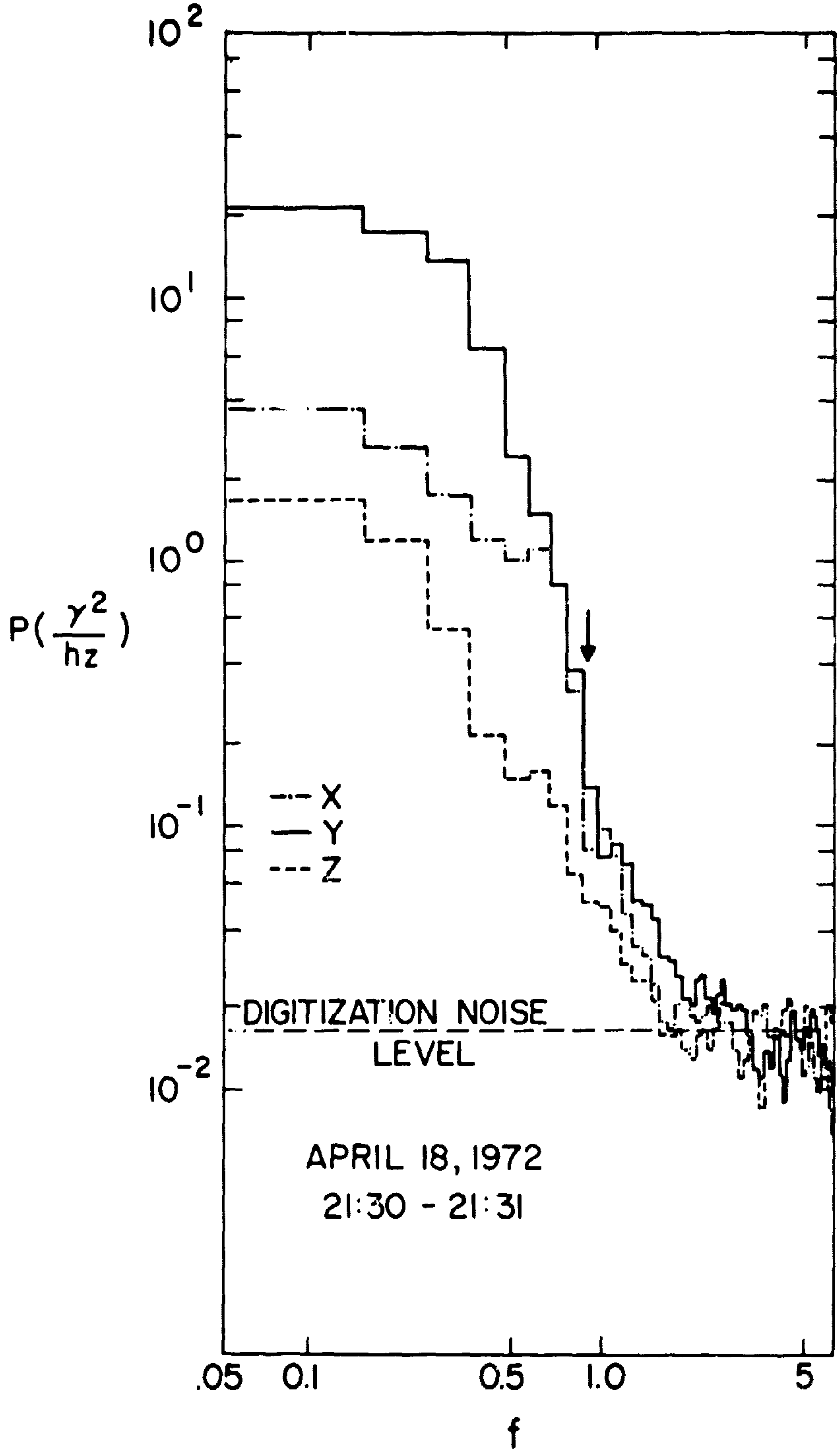
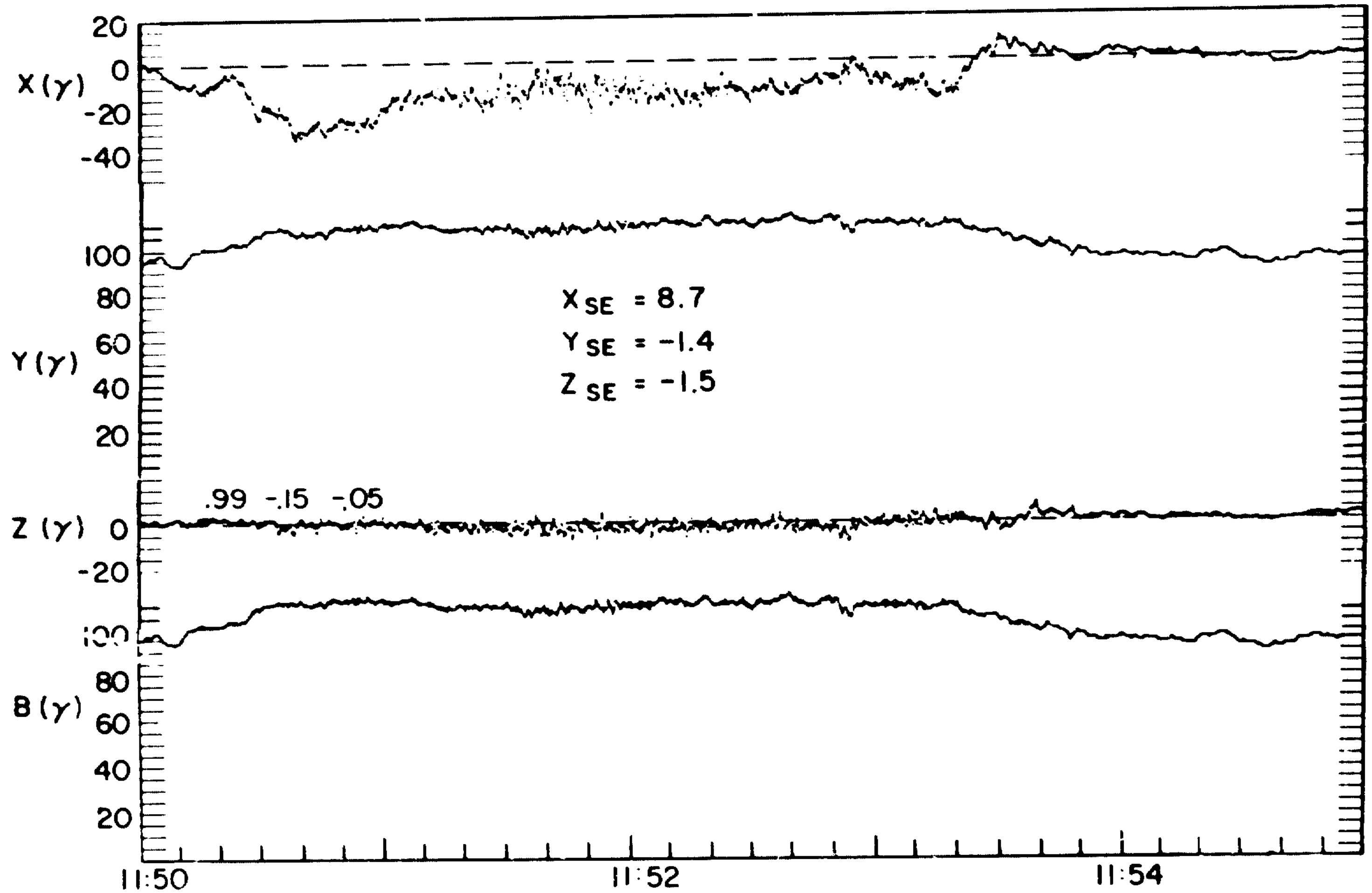

10^2
10^1
10^0
10^-1
10^-2
P(γ²/hz)
X
Y
Z
DIGITIZATION NOISE
LEVEL
APRIL 18, 1972
21:30 - 21:31
.05
0.1
0.5
1.0
5
f

FIGURE 3



MAY 6, 1971

FIGURE 4

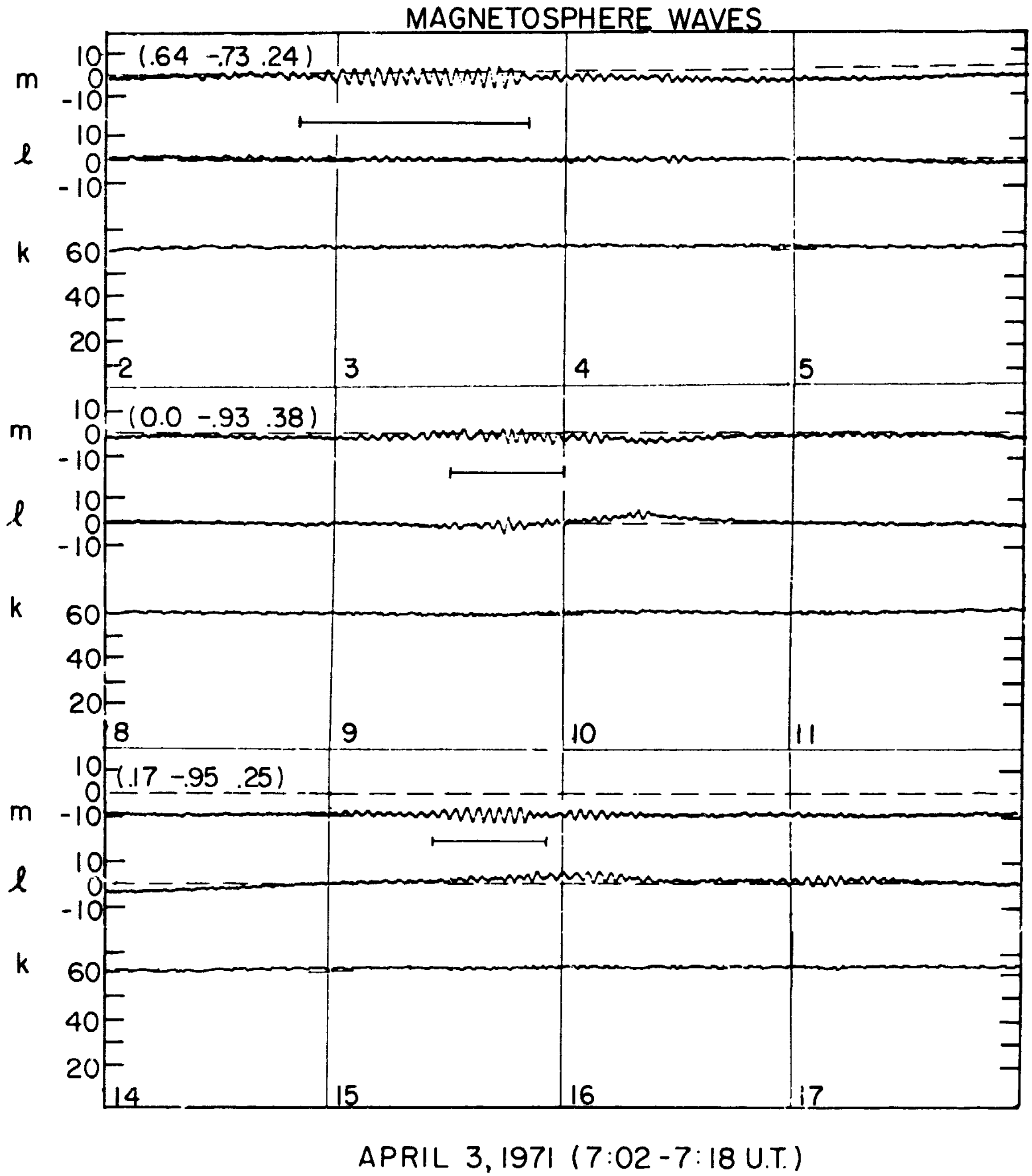
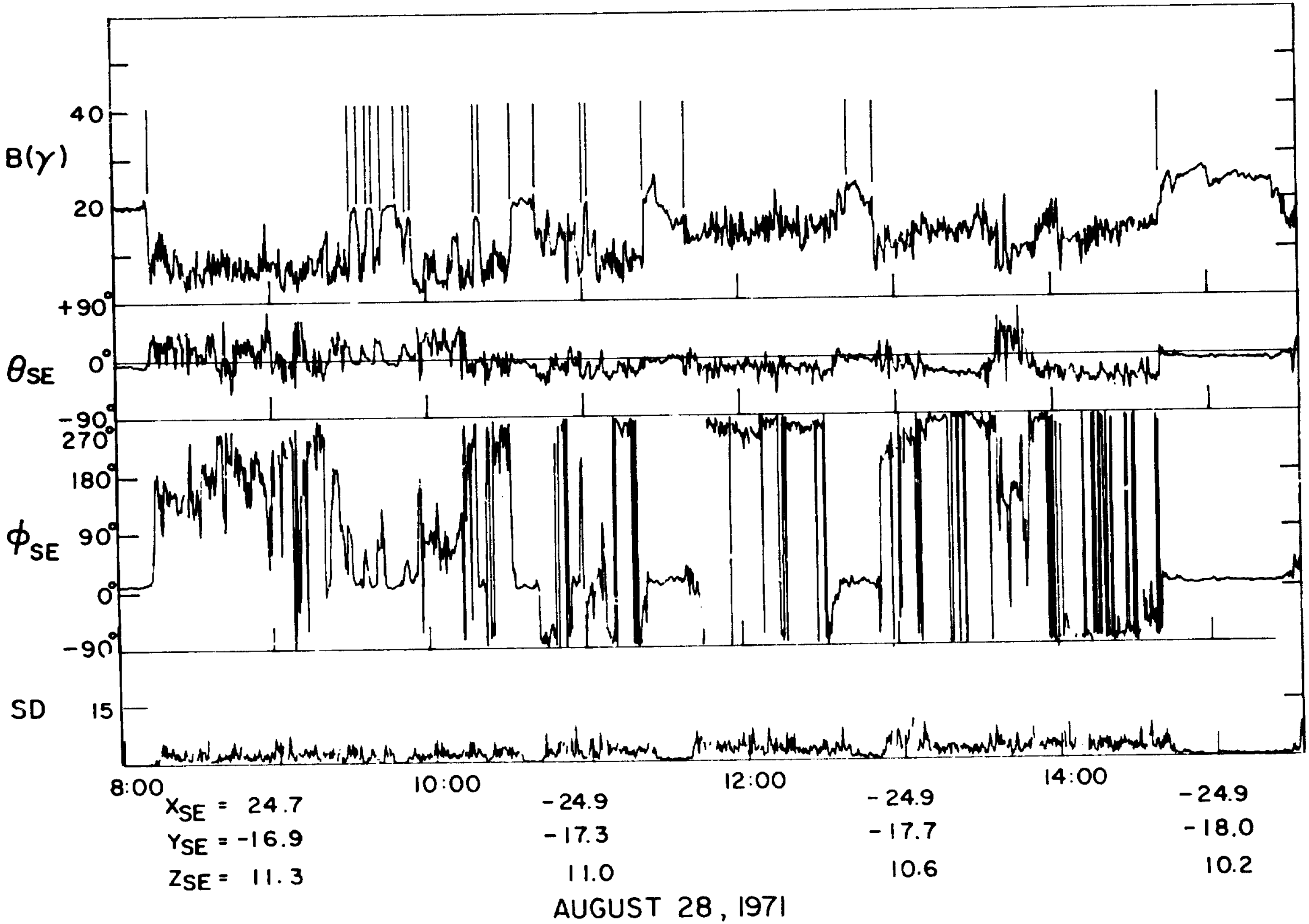

MAGNETOSPHERE WAVES
(.64 -.73 .24)
(0.0 -.93 .38)
(.17 -.95 .25)
m
ℓ
k
10
0
-10
60
40
20
2
3
4
5
8
9
10
11
14
15
16
17
APRIL 3, 1971 (7:02-7:18 U.T.)

FIGURE 5



B(γ)
40
20
+90°
θSE
0°
-90°
270°
180°
φSE
90°
0°
-90°
SD
15
8:00
10:00
12:00
14:00
XSE = 24.7
YSE = -16.9
ZSE = 11.3
-24.9
-17.3
11.0
-24.9
-17.7
10.6
-24.9
-18.0
10.2
AUGUST 28, 1971

FIGURE 6

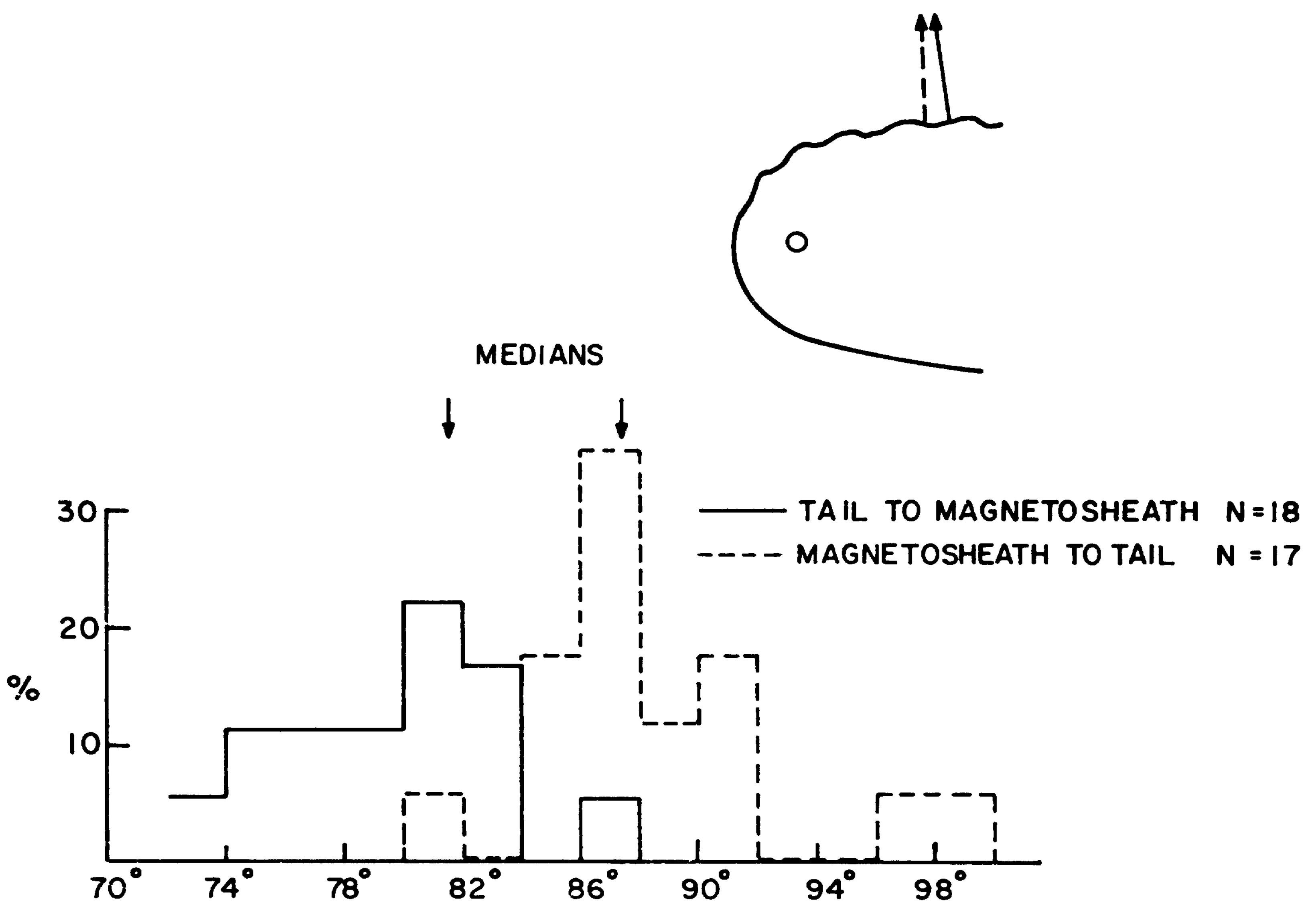

MEDIANS
TAIL TO MAGNETOSHEATH N=18
MAGNETOSHEATH TO TAIL N=17
%
30
20
10
70°
74°
78°
82°
86°
90°
94°
98°

FIGURE 7