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Abstract

IMP 4 measurements have been used to study magnetic field fluctuations in the sunward hemisphere of the magnetosheath. Power spectra have been computed in the frequency range below 0.2 Hz in a field-aligned coordinate system which allows the separation of transverse and longitudinal perturbations. Power levels on different passes through the magnetosheath typically vary by an order of magnitude or more and spectral peaks are frequently seen throughout the frequency range studied. Spatial variations of wave amplitudes are characterized by enhancements of the transverse mode near both the shock and the magnetopause but these variations tend to be smaller than the day to day variations. The dawn quadrant of the magnetosheath tends to exhibit a somewhat higher level of fluctuations. Transverse waves are often linearly polarized and they tend to have their disturbance vector aligned with the shock and magnetopause surfaces. Compressional fluctuations tend to be larger than transverse fluctuations at low frequencies but transverse amplitudes dominate at higher frequencies. On three unique orbits when the bow shock was located more than 9 R_E outside its average location the magnetosheath power levels were depressed by more than an order of magnitude below their normal lowest levels. Transverse fluctuations were dominant at these times. A weak positive correlation was found between magnetosheath fluctuations and geomagnetic activity.

Introduction

The distinctive magnetic field fluctuations of the earth's magnetosheath are characterized by wave amplitudes which are considerably larger than those of the adjacent magnetosphere and interplanetary regions. The fluctuations are of interest because of their probable relation to the bow shock and magnetopause and also because of the possibility that they may influence phenomena within the magnetosphere. Although the presence of fluctuations has been noted by all magnetic field experiments passing through the magnetosheath, detailed studies in the low-frequency high-power hydromagnetic regime have been limited to satellites making a single pass through the region (Sonett and Abrams, 1963; Coleman, 1964; Siscoe et al., 1967a and 1967b; Mariani et al., 1969) or rarely entering the region (Cummings and Coleman, 1968). This paper discusses measurements from the earth orbiting spacecraft IMP 4 (Explorer 34) which made approximately 200 passes through the sunward magnetosheath during its two year lifetime. Results confirm the single observations of transverse shock-aligned fields near the bow shock (Siscoe et al., 1967b) and longitudinal waves near the magnetopause (Siscoe et al., 1967a; Cummings and Coleman, 1968) and allow these results to be viewed in the perspective of what is typical and what is unusual. The spatial variations of power levels between the shock and magnetosheath are shown to be small relative to the day to day variations. These spatial variations consist primarily of an increase in transverse waves near the shock and magnetopause and a fluctuation enhancement in the dawn quadrant. Transverse waves are always larger than compressional waves near the shock. Very low power-levels are associated with the occasional occurrence of abnormally distant bow shock locations.

Experiment

The IMP 4 spacecraft was launched May 24, 1967 into an elliptical polar orbit with period 4.3 days and apogee near the ecliptic plane at 34.1 R_E near the dusk meridian. A 67.4° inclination meant that the plane of the orbit was closely aligned to a solar ecliptic meridian plane and for present purposes the trajectory can be considered a radial cut through the magnetosheath. On each of the first fifty orbits the spacecraft made two passes through the magnetosheath with durations which were typically 3-4 hours near the subsolar point. The spacecraft was spin stabilized with an initial period of 2.59 seconds which increased slowly to 2.63 seconds on orbit 50.

The IMP 4 experiment (see also Fairfield, 1969) consisted of a triaxial fluxgate magnetomer with $\pm 32\gamma$ and $\pm 128\gamma$ ranges ($\pm .16\gamma$ and $\pm .64\gamma$ digitization errors) which were switched automatically by ground command at predetermined times on each orbit. The three sensors were sampled sequentially within 160 milliseconds to yield vector samples every 2.556 seconds. In-flight determinations of the sensor zero levels were obtained with an accuracy estimated at $\pm .1\gamma$ and $.3\gamma$ for the sensors perpendicular and parallel to the spin axis respectively.

The sampling frequency on IMP 4 corresponds to a cutoff frequency of .20 Hz; whereas, the bandpass of the magnetometers was 0-10 Hz (0-60 Hz) in the low (high) range with a fall off of 20 db/decade in amplitude response beyond 10 Hz (60 Hz). This means that aliasing occurs and the unambiguous determination of the frequency of spectral peaks is not possible in theory. In practice, typical power densities determined by all magnetosheath magnetometer experiments decrease with increasing frequency fast enough ($\propto f^{-\alpha}$ where α = 1-3) so that aliasing is seldom apt to be a problem. Although it seems likely that most spectral peaks found in IMP 4 data appear at their true frequencies, this possibility of aliasing must be kept in mind.

Analysis and Observations

Magnetic field fluctuations were analyzed by computing power spectra for half-hour intervals when the spacecraft was in the magnetosheath. The magnitude and three orthogonal components were used in a coordinate system where Z is the field direction, X is in the solar ecliptic X-Z plane and Y completes the orthogonal system. In this manner magnetoacoustic wave modes affecting the field magnitude could be distinguished from transverse Alfven waves with perturbation vector perpendicular to the average field. More than 70 such spectra were computed on 15 different orbits. The primary criterion for selecting the intervals was that the average field be relatively constant over the intervals to allow definition of a meaningful field-oriented coordinate system. This constant field requirement also avoided including a contribution due to power contained in interplanetary discontinuities which are simply convected into the magnetosheath (Fairfield, 1967, 1968). The resulting power can then be attributed to processes involving the interaction of the solar wind with the geomagnetic field. Orbits where the interplanetary field remained relatively constant in direction during the magnetosheath pass were also given preference. Spectra were integrated from 0.011 Hz to the cutoff of 0.20 Hz to obtain a total power. Again the low frequency power was omitted since it was felt to be due primarily to normal low frequency interplanetary fluctuations convected into the magnetosheath.

Spectra were found to vary considerably from day to day and also at different times on the same pass through the magnetosheath. In Figure 1 the histogram type spectra on September 1, November 1, September 9 and August 23, 1967 represent relatively high and relatively low power spectra for the field magnitude, P_F, and the transverse component, P_Y. The peaks in the F spectra do not always occur but are not unusual. In order to compare these typical spectra levels with published data from other spacecraft, observations from Mariner 4, (Siscoe et al., 1967a) OGO-1 Holzer et al., 1966) and ATS-1 (Cummings and Coleman, 1968) have been superposed in Figure 1. The fact that Mariner 4 is relatively low is not surprising since Mariner was near the 0400 local time meridian whereas Explorer 34 measurements were made sunward of the dawn-dusk meridian plane. The fact that ATS measurements are relatively high is also not surprising since this spacecraft in synchronous orbit at 6.6 R_E enters the magnetosheath only under the very exceptional circumstances which compress the magnetopause inside this position. OGO-1 search coil magnetometer data (Holzer et al., 1966) for frequencies >.2 Hz is indicated by two arrows in Figure 1. These two magnetosheath intervals described as highly disturbed and less disturbed agree well with the IMP 4 data representing typical high and low levels.

The bottom spectra in each panel of Figure 1 represent very atypical magnetosheath spectra. These measurements were taken at a position X_{se} = 24.5, Y_{SE} = 19.2, Z_{SE} = 1.1 on July 31, 1967 on an orbit when the bow shock had been crossed at a position more than 16 R_E beyond its average position. Although location of the shock at such a distant position is very rare, comparably distant shocks were observed on 3 orbits during the IMP 4 lifetime and each was associated with extremely low magnetosheath power spectra. This finding is consistent with an observation by Heppner et al. (1967) of a shock crossing located several R_E beyond its average position at a time when the usual shock-associated fluctuations were not observed. In all of these unusual IMP 4 cases the transverse fluctuations were found to dominate over compressional fluctuations.

Variations of magnetosheath power levels and their relation to distance across the magnetosheath are shown in Figures 2 and 3. In these figures the ordinate represents the integral power in the frequency range 0.01 Hz - 0.20 Hz and the abscissa represents the relative position in the magnetosheath observed by using the observed crossings of the shock and the magnetopause. Each point represents a spectra and the lines connect data from the same pass. The circled points correspond to the top pair of spectra in Figure 1. Considerable variations occur from orbit to orbit and even at different times on the same orbit. These variations are more striking in the F spectra shown in Figure 2. Little spatial variation occurs across the magnetosheath although compressional P_F fluctuations may, on the average, be slightly higher towards the magnetopause and transverse P_Y fluctuations increase near both the shock and the magnetopause. The quiet magnetosheath spectra associated with distant shock locations were not included in Figures 2 and 3 since they are not representative of typical conditions. If included, many points would fall off scale at the bottom of the figure.

The spatial variations of the compressional magnetoacoustic mode relative to transverse mode is shown in Figure 4 where $P_F/P_\perp$ is plotted vs. position. A logarithmic scale has been used so that distance above and below the line at unity represents the dominance of P_F or $P_\perp$. There is a clear tendency for the transverse waves to dominate near the shock and a less obvious tendency for compressional fluctuations to be more important near the magnetopause. The result demonstrates that both the Mariner 4 observations of transverse waves near the shock and compressional waves nearer the magnetopause and the ATS measurements of compressional fluctuations near the compressed magnetopause can be considered representative of typical conditions.

Further information about the transverse waves was gained by studying the relation between the two transverse components. Since the average magnetosheath magnetic field is known to exhibit a tendency to align itself along the shock or magnetopause surface, (Fairfield, 1967) when one transverse component is oriented near the shock normal the other tends to be aligned parallel to the shock surface. In Figure 5 the ratio P_Y/P_X is plotted against the angle between the shock normal and the transverse X axis. When this angle is small, meaning X is aligned along the shock normal, the power tends to be in the shock-plane-aligned Y component. When the angle is large and X is shock-plane aligned, X contains most of the power. Computation of the coherence and phase lag between the two transverse components frequently shows evidence for linear polarization. Less frequently circular polarization is observed. The above results confirm the observations by Siscoe et al.

(1967b) of shock aligned oscillations near the bow shock and extends its region of applicability to the entire subsolar magnetosheath. The result is also consistent with Mariani et al. (1969) who found that the greatest power in the downstream magnetosheath is in the Z_{SE} component which is approximately boundary aligned at Pioneer locations. Shock-aligned is equivalent to magnetopause-aligned within the accuracy of the IMP 4 determination.

An illustration of how spectra can vary within one pass of a spacecraft through the magnetosheath is illustrated in Figure 6. Spectra on September 27, 1967 are plotted for two half hour intervals spaced 19 minutes apart. The X, Y, Z and F spectra in the field-aligned coordinate system are shown from top to bottom with each being offset by one decade. From 9:01-9:31 distinct peaks are present in the spectra; whereas, during the 9:50-10:20 interval the peaks have either disappeared or have shifted out of the observed frequency band. The average fields for these intervals differ by only 1.8γ in magnitude and 12° in direction. The spectra at the right is rather unique in that it is unusually flat and undoubtedly aliased.

The spectral peaks in the left hand portion of Figure 6 also illustrate how relative power in the various modes can be a function of frequency. For the two F peaks at .015 Hz and .065 Hz the compressional mode exceeds the X power by factors of 5 and 7 and the Y power by factors of 15 and 11 respectively. At a slightly higher frequency of .12 Hz, however, there is a peak in the transverse components where P_X and P_Y exceed P_F by factors of 3. This tendency for the compressional mode to dominate at low frequencies while the transverse mode dominates at higher frequencies is typical of many magnetosheath spectra and consistent with the data of Siscoe et al., (1967b). Power shifting in and out of the observed frequency band in response to changes in solar wind parameters might account for much of the scatter observed in Figure 4.

It has been suggested (Axford, 1964) that transmission of magnetosheath waves through the magnetopause might be an important means of energy transfer into the magnetosphere. Geomagnetic activity is a manifestation of increased magnetosphere energy transfer and it is of interest to compare magnetosheath fluctuations and Kp. As a measurement of the field fluctuations a 20 second (8 point) standard deviation

$$\delta = \frac{\delta X + \delta Y + \delta Z}{3}$$

where $$\delta X = \left[\sum_{i=1}^{8} \frac{(X_i - \overline{X})^2}{N} \right]^{\frac{1}{2}}$$

was calculated. A quantity of $\bar{\delta}$ was then obtained by averaging δ over an entire pass through the magnetosheath. Figure 7 shows $\bar{\delta}$ and the average Kp value during the magnetosheath pass plotted versus orbit number. The approximate confinement of an Explorer 34 orbit to a meridian plane means that orbit number is equivalent to solar ecliptic longitude. The orbits located near the dusk, noon and dawn meridians are marked in the figure. An apparent dawn-dusk asymmetry exists with fluctuations tending to be higher in the dawn hemisphere where spiral oriented interplanetary fields are frequently normal to the shock surface.

Some correlation between Kp and δ may be present but the relation is not very definite. The use of integral spectral powers and average geomagnetic AE values (Davis and Sugiura, 1966) produces a similar result: a probable positive correlation with numerous exceptions.

Discussion

The observations of hydromagnetic waves from IMP 4 and other experiments in the cislunar magnetosheath and from Pioneer 7 and 8 in the downstream magnetosheath may be summarized briefly as follows. Wave amplitudes are quite variable on a time scale of hours and days and sometimes minutes. The amplitudes (particularly for the transverse components) are slightly enhanced near the magnetopause and shock and in the dawn quadrant but these variations are small relative to the day to day variations. Amplitudes decrease exponentially with distance from the sun-earth-line in the downstream magnetosheath (Mariani et al., 1969). The transverse wave mode has greater amplitude than the compressional mode near the bow shock and downstream but either mode may dominate further into the magnetosheath. Transverse waves are sometimes circularly polarized but are more often lineraly polarized with their disturbance vector approximately tangent to the magnetopause or shock surfaces. Hydromagnetic wave amplitudes are very small on rare occasions when the bow shock is far out beyond its normal location. Fluctuations show a weak positive correlation with geomagnetic activity.

In interpreting these observations it should be kept in mind that the magnetosheath plasma containing a frozen-in magnetic field is flowing past the spacecraft with a velocity which is typically 100 to 300 km/sec in the region studied. Characteristic wave velocities in the plasma frame are comparable to those speeds and the wave normals can have various directions relative to the flow velocity. This means the observed fluctuations are Doppler shifted to higher or lower frequencies in a complicated manner which depends on the relative direction of the field, the flow and the propagation. In attempting to explain these observations four possible sources of magnetosheath field fluctuations should be considered:

1) transmission and possible amplification of existing interplanetary fluctuations at the bow shock;
2) generation at the magnetopause;
3) generation at the bow shock; and
4) generation within the magnetosheath.

Bow Shock Transmission. Transmission of existing interplanetary fluctuations through the bow shock is undoubtedly a source of magnetosheath fluctuations. The primary question is that of its relative importance. McKenzie and Westphal (1967) theoretically investigate this question and analyze the tractable special case where the wave vector lies in the shock plane. They conclude that wave amplitudes of transverse Alfven waves will be increased by a factor of the order of three on transmission through the shock and therefore the power will be increased by approximately an order of magnitude. Magnetoacoustic waves are probably amplified by a factor of approximately four in amplitude (McKenzie, 1969). The observation that the transverse mode is dominant in the magnetosheath near the shock is consistent with the transmission-amplification hypothesis since transverse modes are known to be dominant in the solar wind. It appears difficult, however, to explain the further observation that the magnetoacoustic mode can dominante further into the magnetosheath. If the magnetoacoustic mode fluctuations increased (but transverse fluctuations did not) in proportion to the total field strength which increases toward the magnetopause, this mechanism might still serve as the explanation.

In considering the transmission mechanism one must consider not only the transmission of fluctuations inherent in the ambient solar wind but also the possibility that effects of the bow shock are transmitted upstream and subsequently convected back downstream where they would be incident on the shock. In particular, it has been suggested (Fairfield, 1969) that the presence of large amplitude (several gamma) waves far upstream from the bow shock is due to their generation in the upstream region by a wave-particle interaction initiated by particles coming from the bow shock. If this explanation is correct the waves would be incident on the shock and should be an important contribution to fluctuations in the magnetosheath. The dawn-dusk asymmetry in the fluctuations seen in Figure 7 are consistent with this effect since the upstream waves appear on field lines which intersect the bow shock. This situation occurs more frequently in the dawn hemisphere where the interplanetary fields are often oriented along the spiral direction.

Although it might appear that simultaneous observations on either side of the bow shock might yield a transmission-amplification ratio this is not necessarily so. Waves standing on the bow shock or propagating upstream are not incident on the shock but can be measured in the upstream region. On one distant IMP 4 crossing there was actually more power in the upstream interplanetary region than in the downstream magnetosheath.

Magnetopause Generation. Generation of field fluctuations at the magnetopause by the Kelvin-Helmholtz instability is a possible source of field fluctuations which has been studied most recently by Southwood (1968). This author investigates the stability conditions and concludes that transverse waves can indeed be generated. Evidence for such waves has been detected in close proximity to the magnetopause (Dungey and Southwood, 1969), but it is not clear that these fluctuations will be important further out in the magnetosheath. This mechanism also leaves unexplained the high level of compressional fluctuations.

The radial motion of the magnetopause (Anderson et al., 1968) is a possible source of compressional fluctuations but the reported periods (3-15 minutes) are longer than the periods discussed in the present paper.

Eviatar and Wolf (1968) have suggested that a two stream instability in the magnetopause will generate magnetic fluctuations. Again the relevance of such a mechanism to the magnetosheath observations is not clear because of the unknown propagation characteristics.

Bow Shock Generation. Generation of fluctuations at the earth's bow shock will almost certainly occur but the frequency of the fluctuations and their relation to the present observations is less certain. In particular, the attenuation distances for various frequency waves are unknown and consequently their relevance to measurements deep in the magnetosheath is unclear. Heppner et al., (1967) and Olsen et al., (1969) have studied somewhat higher frequency waves near the shock which appear to damp rather rapidly. The finding by Heppner et al., of an absence of shock-associated waves on a distant shock crossing suggests that bow shock generation is suppressed by low Mach number and is responsible for the quiet magnetosheath.

Magnetosheath Generation. Generation of fluctuations by a plasma instability within the magnetosheath appears to be the remaining possibility. This internal generation might be attractive for explaining the sudden onset of fluctuation enhancements particularly if it is related to sudden increases of particle fluxes.

Conclusions

Evaluation of the relative importance of the various wave sources is difficult because of the unknown propagation directions and attenuation characteristics of the waves. Indeed several or even all of the above sources could be important in different locations and at different times depending on solar wind conditions. Still there are several observations that can be more readily explained by one mechanism than another.

The fact that waves may often have difficulty propagating upstream from the magnetopause, suggests that the magnetopause is probably not an important source near the shock. The great variability in the upstream magnetosheath might, however, be due to waves that are sometimes able and other times unable to propagate upstream to the satellite. The sudden changes of spectral characteristics that are often observed with no change of field orientation would argue against this idea. The linear polarization often observed does not agree with the large amplitude circularly polarized waves found upstream being transmitted, but circular polarizations are also sometimes observed in the magnetosheath. It is also possible that the upstream waves are simply standing on the shock or moving upstream and will not affect the magnetosheath.

The very quiet shock and magnetosheath conditions associated with the distant crossings support local generation at the bow shock over transmission unless the unique solar wind conditions responsible for the distant shock are also associated with an extremely quiet interplanetary field. The Explorer 34 plasma data of Ogilvie, Wilkerson and Burlaga (private communication) make it clear that these distant crossings are associated with unusually low Alfven Mach numbers and thus appear to be contrary to McKenzie and Westphal's (1969) prediction of increased amplification at low Alfven Mach numbers. Again quiet interplanetary fields associated with low Mach number could explain this apparent contradiction and there is evidence for such an association (Burlaga et al., 1969).

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FIGURE CAPTIONS

Figure 1 Power spectra computed for the total field magnitude P_F and a component transverse to the average field direction P_Y. The top pair of spectra for both P_F and P_Y are examples of relatively high and relatively low spectra under normal magnetosheath conditions. The bottom spectra for both P_F and P_Y were obtained at a time when the bow shock had been observed more the 16 R_E outside its normal location.

Figure 2 Integral power in the total field variations for the frequency range 0.01-0.20 Hz vs. relative position across the magnetosheath. Each point represents a half-hour interval spectra and lines connect spectra obtained on the same pass through the magnetosheath.

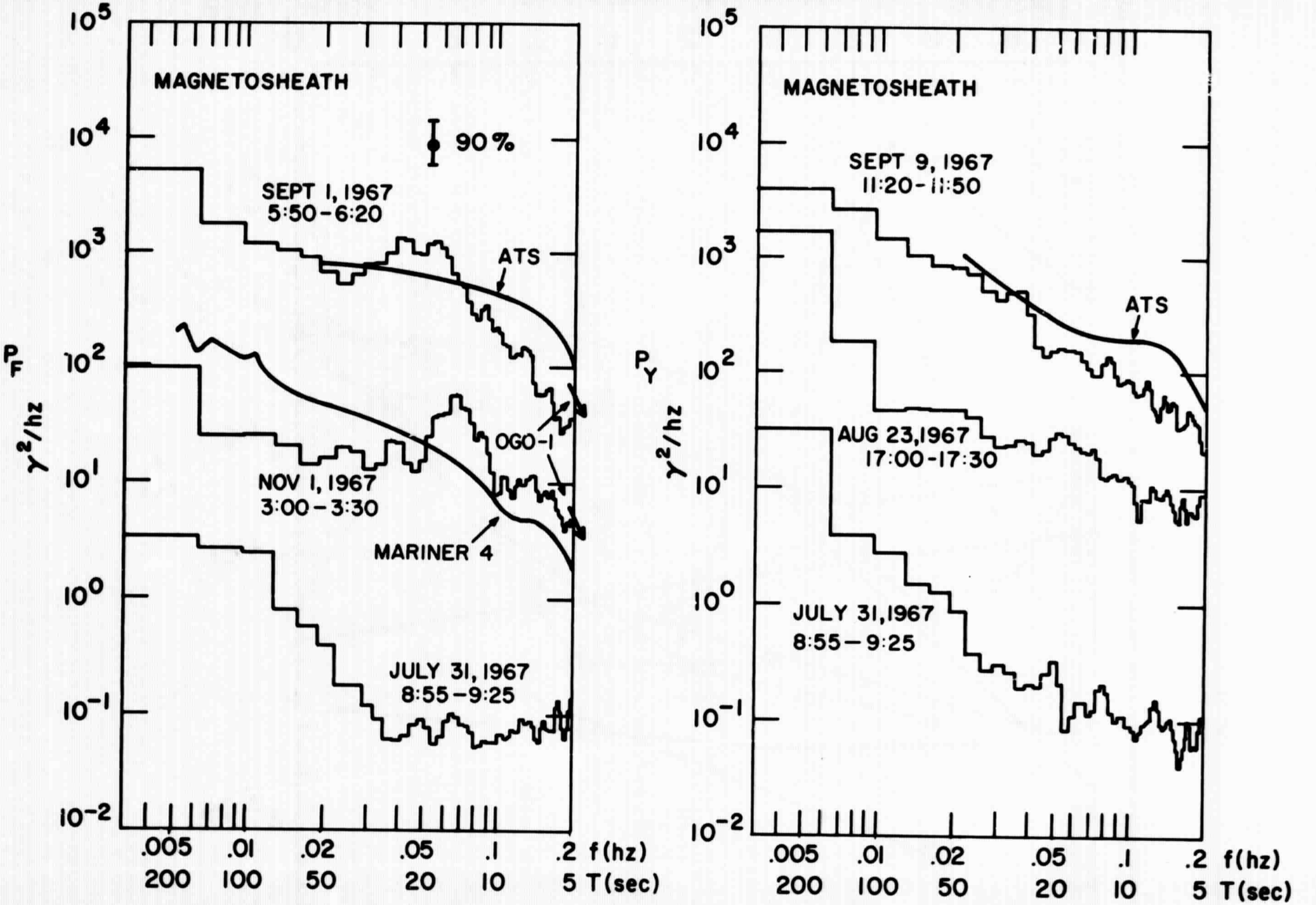
Figure 3 Same as for Figure 2 only using a field component transverse to the average field direction.

Figure 4 Relative importance of power in the compressional mode P_F and the transverse mode $P_\perp$ vs. relative position across the magnetosheath.

Figure 5 Relative power in the two transverse field components vs. the angle the X axis makes with a theoretical shock normal. When the angle is small and X is aligned near the shock normal there is considerably more power in the Y component which tends to be aligned with the shock surface.

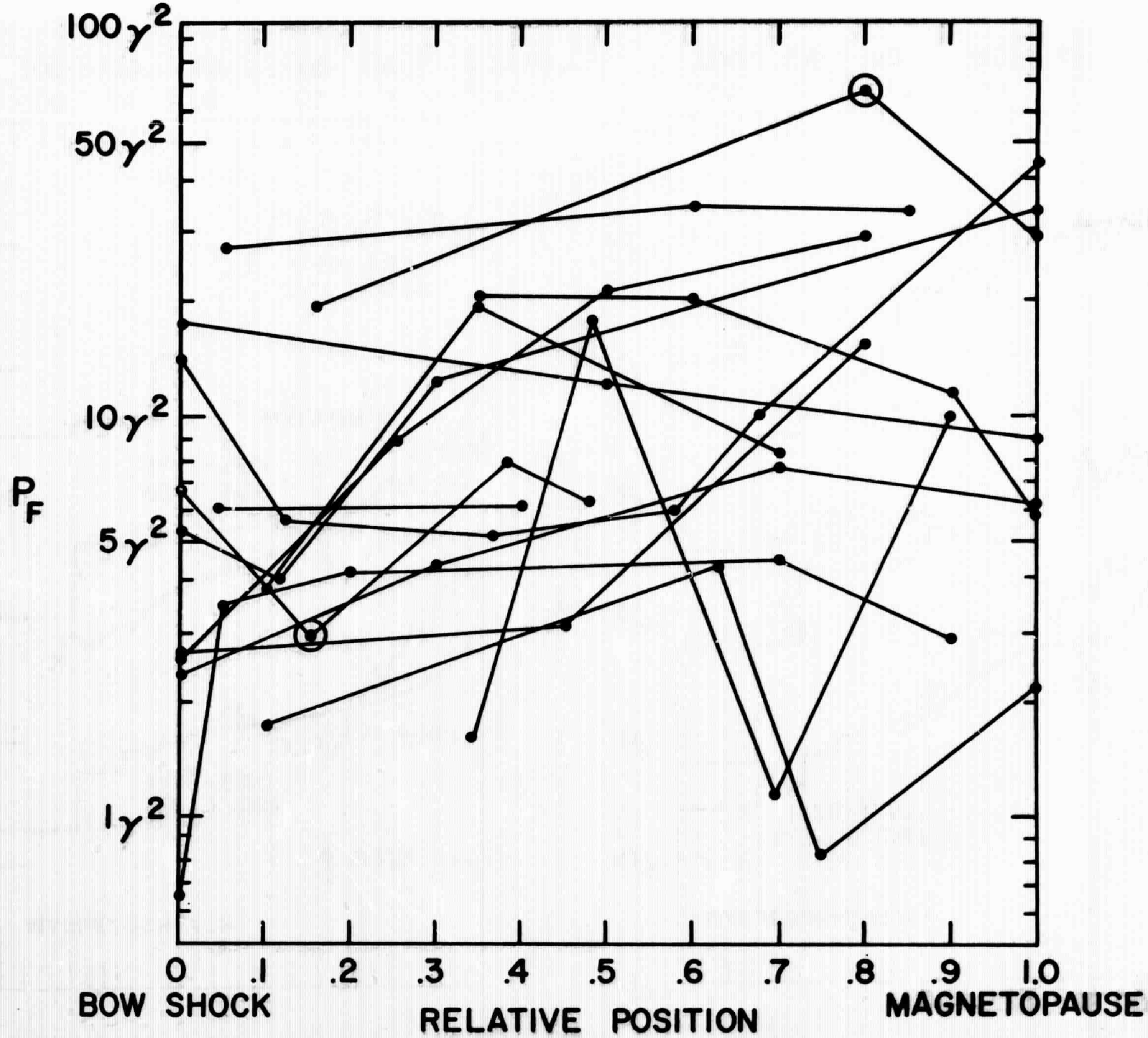
Figure 6 Spectra of the magnitude and three components for two intervals separated by 19 minutes. Each trace is offset by one decade in power.

Figure 7 Average standard deviation $\bar{\delta}$ on each magnetosheath pass and average Kp for the pass vs. orbit number or (equivalently) solar ecliptic longitude.



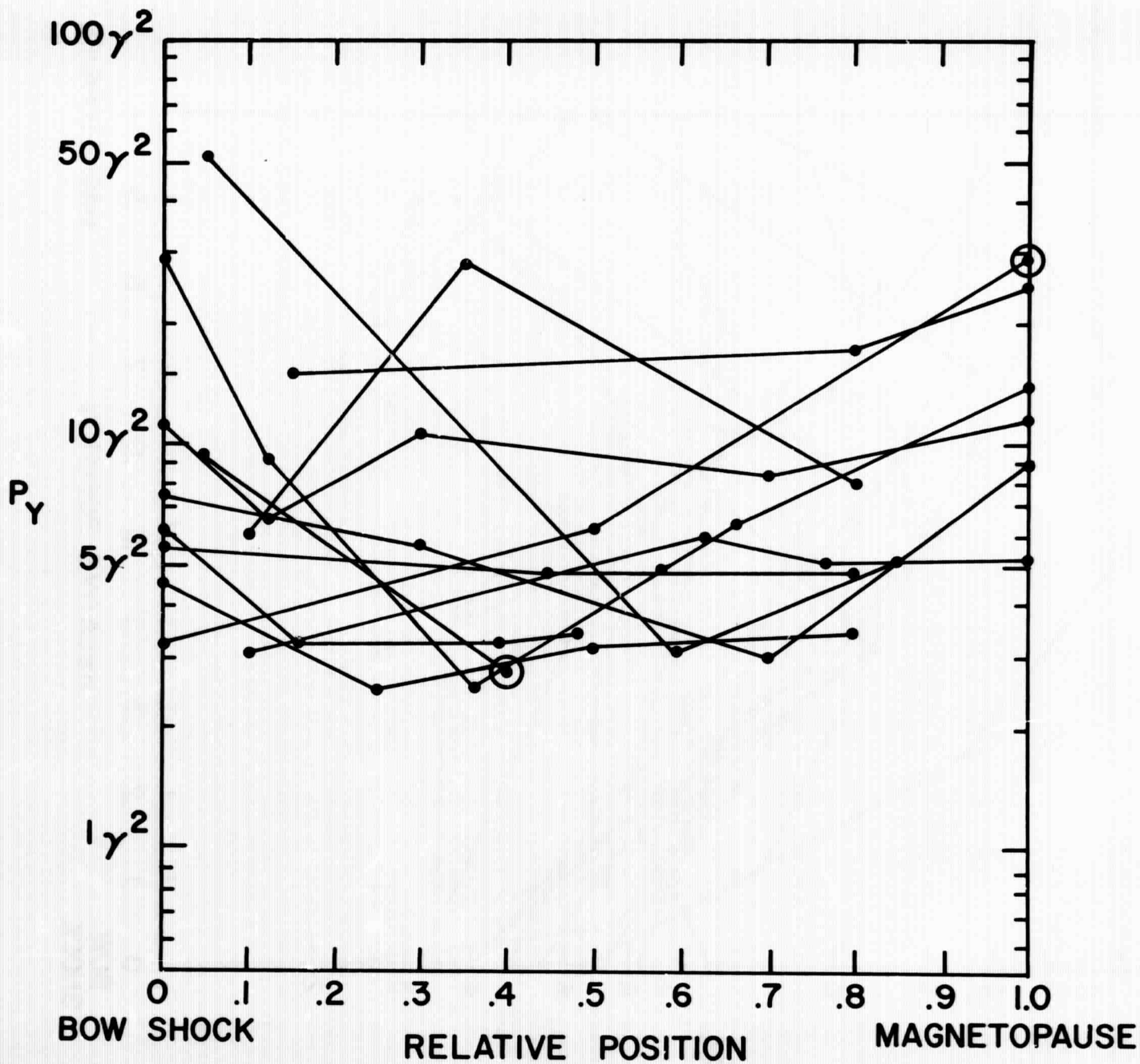
MAGNETOSHEATH
90%
SEPT 1, 1967
5:50-6:20
ATS
NOV 1, 1967
3:00-3:30
OGO-1
MARINER 4
JULY 31, 1967
8:55-9:25
P_F
γ^2/hz
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
.005 .01 .02 .05 .1 .2 f(hz)
200 100 50 20 10 5 T(sec)
MAGNETOSHEATH
SEPT 9, 1967
11:20-11:50
ATS
AUG 23, 1967
17:00-17:30
JULY 31, 1967
8:55-9:25
P_Y
γ^2/hz

FIGURE 1



100γ²
50γ²
10γ²
5γ²
1γ²
P_F
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
BOW SHOCK
RELATIVE POSITION
MAGNETOPAUSE

FIGURE 2



100γ²
50γ²
10γ²
5γ²
1γ²
P_Y
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
BOW SHOCK
RELATIVE POSITION
MAGNETOPAUSE

FIGURE 3

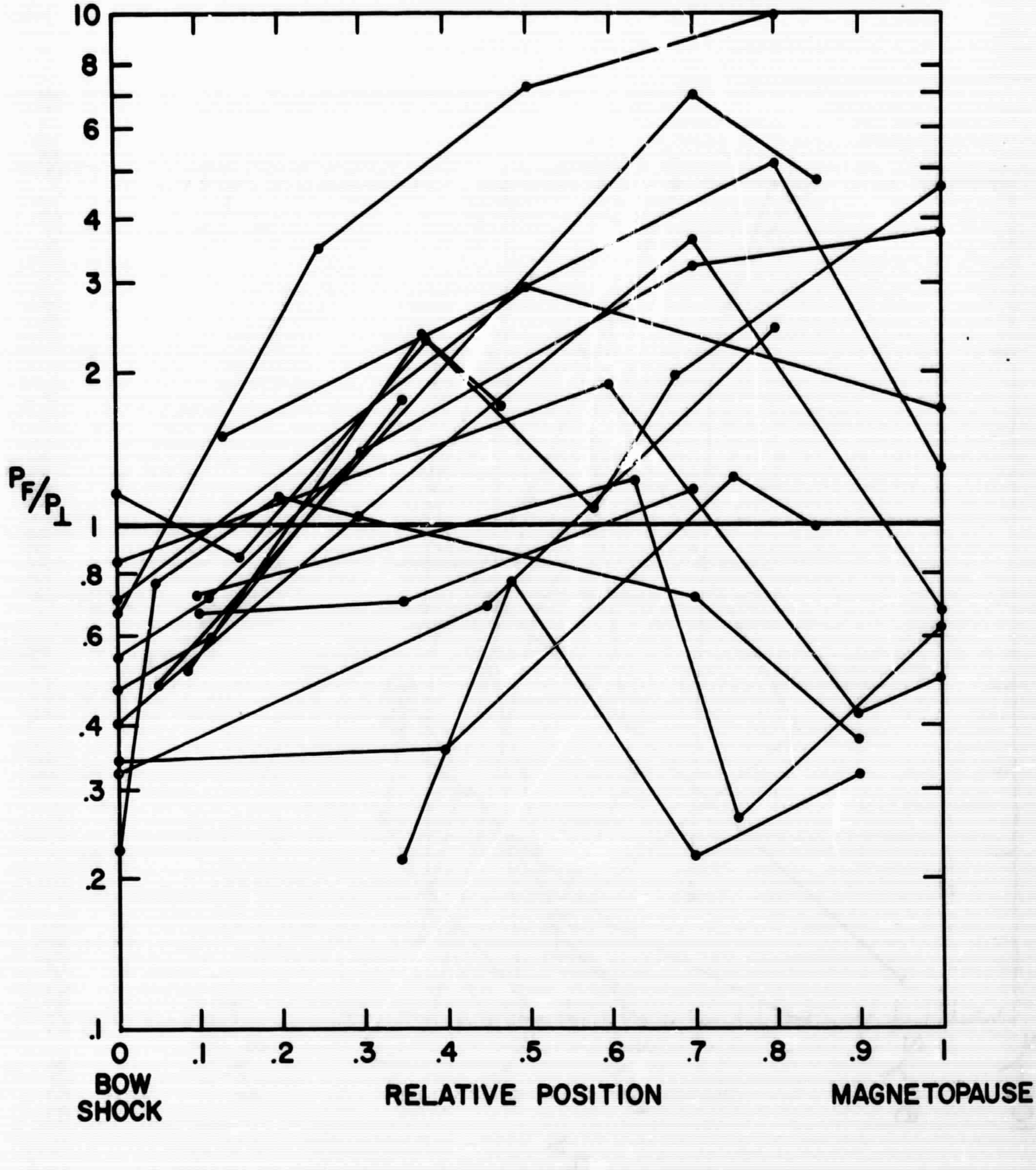

10
8
6
4
3
2
PF/P⊥
1
.8
.6
.4
.3
.2
.1
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1
BOW SHOCK
RELATIVE POSITION
MAGNETOPAUSE

FIGURE 4

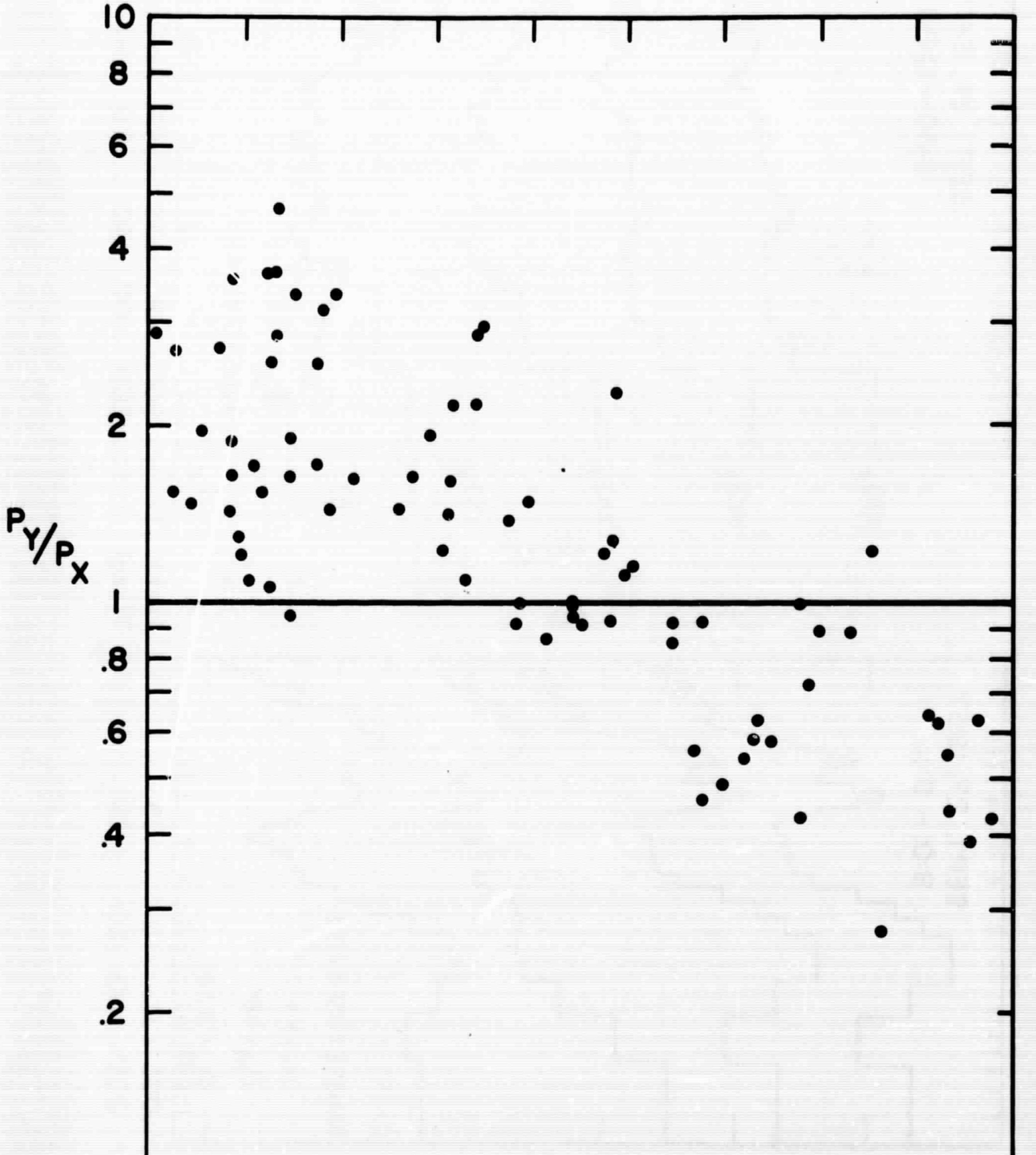

10
8
6
4
2
P_Y/P_X
1
.8
.6
.4
.2
.1
0
10
20
30
40
50
60
70
80
90
X AXIS-SHOCK NORMAL ANGLE

FIGURE 5

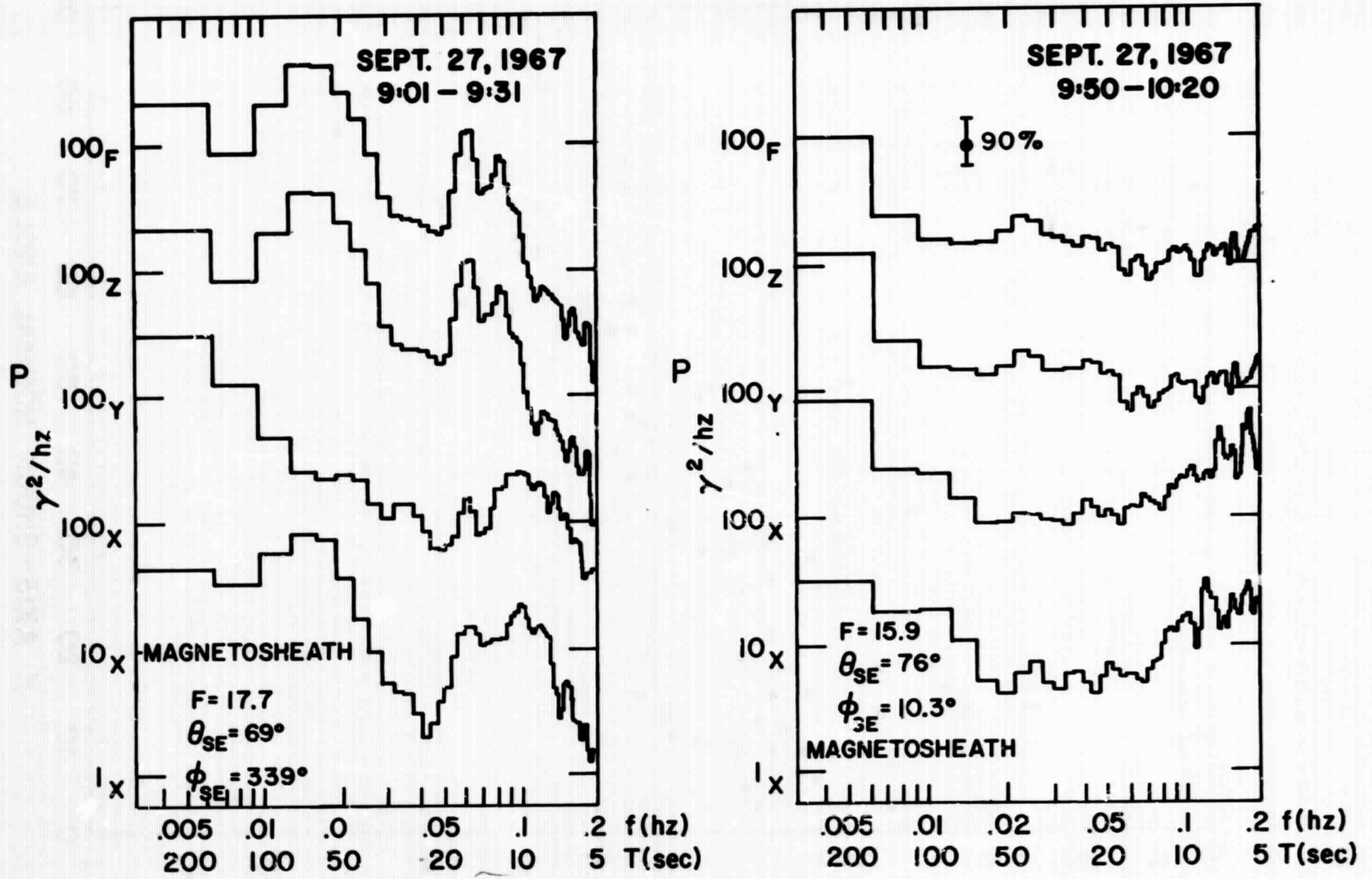
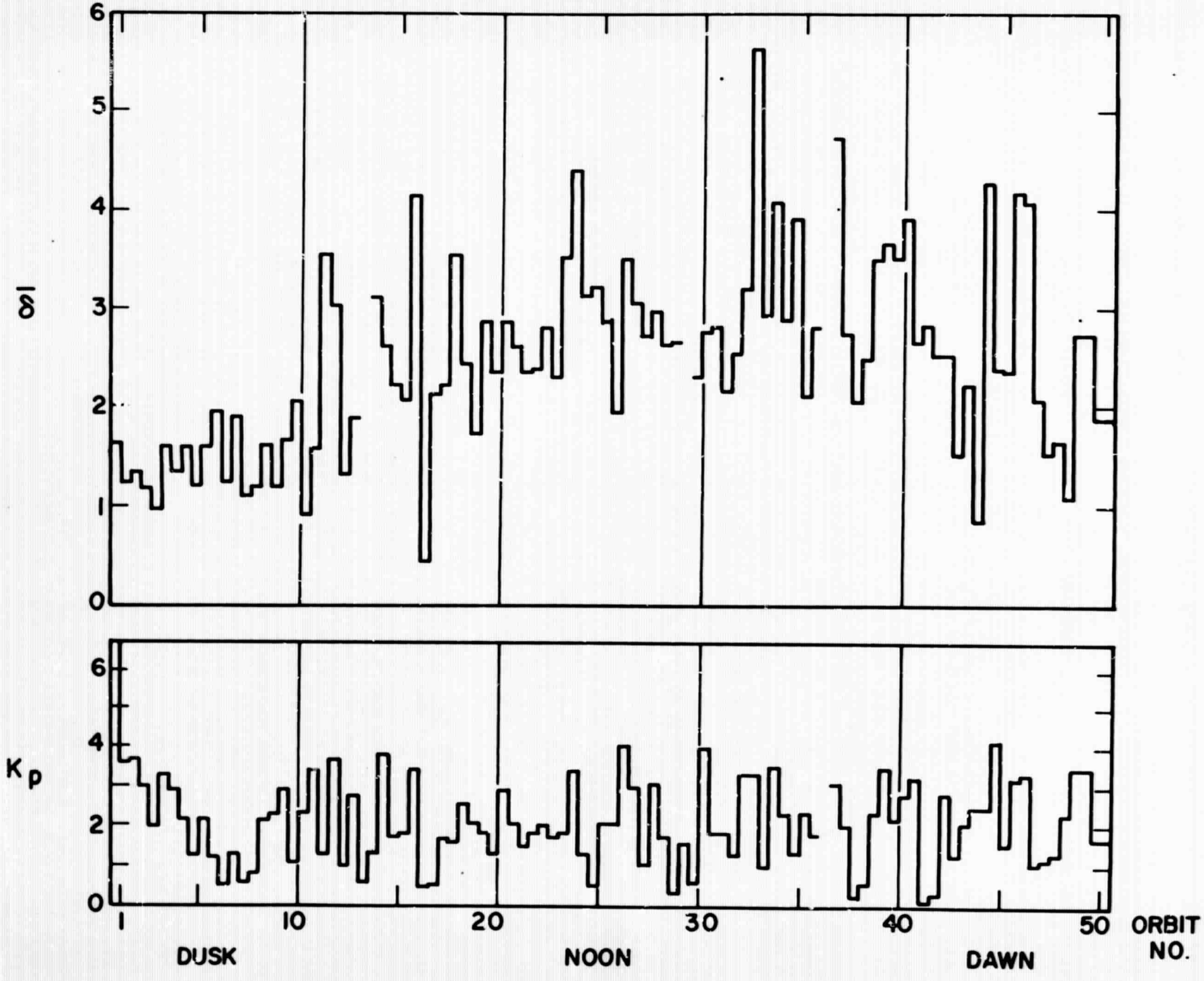

SEPT. 27, 1967
9:01 - 9:31
100F
100Z
100Y
100X
10X
1X
P
γ²/hz
MAGNETOSHEATH
F= 17.7
θSE= 69°
φSE = 339°
.005 .01 .0 .05 .1 .2 f(hz)
200 100 50 20 10 5 T(sec)
SEPT. 27, 1967
9:50-10:20
90%
F= 15.9
θSE= 76°
φSE= 10.3°
MAGNETOSHEATH
.005 .01 .02 .05 .1 .2 f(hz)
200 100 50 20 10 5 T(sec)

FIGURE 6



$\bar{\delta}$
6
5
4
3
2
1
0
K_p
6
4
2
0
1
10
20
30
40
50
ORBIT NO.
DUSK
NOON
DAWN

FIGURE 7