X-616-69-61
PREPRINT

NASA TM X- 63471

# SPATIAL VARIATIONS OF THE MAGNETOSHEATH MAGNETIC FIELD

KENNETH W. BEHANNON
DONALD H. FAIRFIELD



EBRUARY 1969

GSFC
GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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Kenneth W. Behannon
Donald H. Fairfield
Laboratory for Space Sciences
NASA-Goddard Space Flight Center
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Extraterrestrial Physics Branch Preprint Series

Abstract

Measurements by Explorers 28, 33, 34 and 35 have been used to study the spatial characteristics of the magnetic field in the magnetosheath to a distance of 70 $R_E$ behind the earth. During 1966-1967 there were 1661 hours when one spacecraft of this multi-satellite system was monitoring the interplanetary medium while at least one other satellite was making magnetosheath measurements. This has made possible a separation of time and space variations and has permitted a study of the direction and magnitude of the magnetosheath field as a function of position and interplanetary field orientation. Results indicate that the magnetosheath field is several times the strength of the simultaneously measured interplanetary field in the sunward magnetosheath. This magnetosheath to interplanetary magnitude ratio decreases with distance from the subsolar point to values which are frequently less than unity at distances beyond 30 $R_E$ and away from the bow shock. This ratio also displays a dawn-dusk asymmetry which is dependent on the interplanetary field orientation. Interplanetary field lines perpendicular to the earth-sun line are associated with symmetrically distorted magnetosheath field lines in the dawn and dusk hemispheres and are consistent with the draping of field lines around the magnetosheath. When the interplanetary field is aligned near the spiral angle, fields measured in the dusk hemisphere are

much more ordered than those measured in the dawn hemisphere behind the earth. These experimental results are in general agreement with the theoretical predictions of the magnetogasdynamic models.

## Introduction

Satellite measurements indicate that solar magnetic fields frozen in the solar plasma are convected away from the sun by the solar wind (Ness and Wilcox, 1966; Fairfield, 1968). The problem of solar wind plasma flow past the geomagnetosphere has been studied theoretically by Spreiter et al. (1966,1968), Alksne (1967), and Dryer and Heckman (1967) using a magnetogasdynamic approach. The plasma flow is determined from a gasdynamic solution which is then used to calculate the three dimensional deformation of the geomagnetic field in the magnetosheath. The predicted spatial features of the magnetic field may be summarized as follows:

1. The ratio of the magnitude of the magnetosheath field to the simultaneous interplanetary field, $B/B_o$, varies from values greater than 4 near the stagnation point to values less than unity in the downstream magnetosheath;
2. Interplanetary field lines convected into the magnetosheath become draped about the magnetosphere in a manner that depends on the direction of $\vec{B}_o$. This dependence results in a dawn-dusk asymmetry of both direction and $B/B_o$ distribution for oblique orientations of the external field.

Experimental measurements with the IMP 2 satellite in the noon-dawn region of the magnetosheath showed a general agreement with these predictions (Fairfield, 1967). The results indicated that the magnetic field is convected through the earth's bow shock where it undergoes an increase in magnitude but relatively little change in orientation. Fairfield further concluded that as the field is convected deeper into the magnetosheath, it is subjected to a greater distortion in direction until it is aligned tangent to the magnetopause. Now a considerable number of additional measurements are available to extend the experimental study to the region of the magnetosheath behind the earth on both the dawn and the dusk sides of the magnetosphere.

In practice the steady-flow constant field conditions assumed in the theory do not exist and the normal time variations of the interplanetary field are also seen in the magnetosheath. These time variations present the primary difficulty in comparing experimental results and the time independent theory. The best technique for overcoming this difficulty is to use simultaneous satellite measurements. Since the typical scale of interplanetary field variations is large compared to the dimensions of the magnetosphere, it is reasonable to consider an interplanetary measurement of $\vec{B}_o$ on any earth-orbiting spacecraft as representative of conditions across the entire extent of the bow shock. It is then possible to investigate simultaneous data from a second spacecraft measuring $\vec{B}$ in the magnetosheath and to attribute the difference in vector measurements to interaction with the shock and magnetosphere. This technique has been utilized in analyzing 1661 hours of simultaneous data obtained by the satellites

Explorers 28, 33, 34 and 35 during the period July 1966-January 1968. The spatial distribution of $B/B_0$ and the directional characteristics of the magnetosheath field have been determined in the region back to 70 $R_E$ behind the earth. These results have been compared to the theoretical results and general agreement has been found.

## Satellites and Instrumentation

The Explorer 28 (IMP 3) satellite was launched on May 29, 1965 into a highly eccentric earth orbit with an initial apogee of approximately 42 $R_E$ and an orbital period of 5.8 days. A single mono-axial magnetometer sampled the vector magnetic field once every 40.96 seconds with digitization error of $\pm 0.4\gamma$. The instrumentation and data analysis were similar to those of IMP 1 (Ness et al., 1964) and IMP 2 (Fairfield and Ness, 1967).

The Explorer 33 satellite was launched into an extremely high-apogee high-perigee orbit on July 1, 1966. This spacecraft had an initial apogee of 70 $R_E$ and orbital period of 14 days. A triaxial fluxgate magnetometer, with a sensor range of $\pm 64\gamma$, measures the vector magnetic field every 5.11 seconds with a digitization error of $\pm 0.25\gamma$. The instrumentation has been described in detail by Behannon (1967).

Explorer 34 was placed in a high inclination (67.4°) orbit on May 24, 1967, with an apogee of 34 $R_E$ and an orbital period of 4.3 days. A triaxial fluxgate magnetometer makes a vector magnetic field measurement every 2.56 seconds with a digitization error of $\pm 0.16\gamma$ and $\pm 0.64\gamma$ in the low and high sensor ranges of $\pm 32\gamma$ and $\pm 128\gamma$, respectively. The instrumentation has been described by Fairfield (1968).

The Explorer 35 satellite was launched on July 19, 1967 and injected into lunar orbit on July 22. This spacecraft performs magnetic field measurements of the interplanetary field, the magnetosheath field and the geomagnetic tail field at an approximately constant geocentric distance of 60 $R_E$. The experiment and analysis are essentially identical to those used on Explorer 33 except that a range switch was added to the Explorer 35 instrument which automatically choses the appropriate $\pm 24\gamma$ or $\pm 64\gamma$ sensor range with its corresponding $\pm .09\gamma$ or $.25\gamma$ digitization errors (Ness et al., 1967).

## Analysis

Figure 1 shows the relative positions of Explorers 33, 34 and 35 in September-October 1967. On September 20-21, 1967, Explorer 34 was at apogee in the interplanetary medium on the sunward side of the earth while Explorer 33 was in the dusk magnetosheath and Explorer 35 was in the dawn magnetosheath. The relative positions of these spacecraft at other times during the interval of interest has been published elsewhere (Behannon et al. 1968).

Figure 2 shows typical detailed simultaneous magnetosheath and interplanetary data (81.81 second averages for Explorer 33 and 20.45 second averages for Explorer 34) for a 12 hour period on September 20-21, 1967 when the two spacecraft were separated by a distance of approximately 75 $R_E$ along the earth-sun direction. Figure 2 shows that the magnetic field directions at the two satellites, as given by the solar ecliptic latitude angle $\theta$ and azimuthal angle $\varphi$ , were quite similar. The field magnitude trends were also similar; however, the magnetosheath field magnitude was enhanced relative to the interplanetary magnitude.

Large field discontinuities such as those near 2200 UT arrive at the two spacecraft with time delays which are consistent with frozen-in magnetic fields being convected with the plasma velocity. Even for this case of near maximum separation of the two spacecraft, the time delay between observations of field discontinuities at the respective satellites is only of the order of 15 minutes. Since this time delay is always small in comparison to one hour and since the field usually changes by only a small amount from one hour to the next, averages for the same hour have been considered as representative of "simultaneous" interplanetary and magnetosheath conditions. Hourly average magnitudes were computed from the hourly averages of the field components.

Figure 3 shows typical hourly average field magnitudes and directions, in this case for Explorer 33 in the dawn magnetosheath and IMP 3 in the interplanetary medium on the sunward side of the magnetosphere. Five days of simultaneous observations by the two spacecraft from an outbound passage of IMP 3 through the bow shock (0500 UT August 27) to the next inbound passage through the shock (2000 UT September 1) are shown. Field magnitudes and directions generally are not identical but good correlation between changes in the fields is seen. The observed gradual increase with time in the magnetosheath field-magnitude enhancement is due to the movement of Explorer 33 toward the bow region of the magnetosheath. The occurrence of transient disturbances such as those associated with the magnetic storm sudden commencements at 1315 UT on August 29 and 1112 UT on August 30 emphasizes the need to normalize the magnetosheath field magnitude to the simultaneous interplanetary field magnitude in order to separate the spatial variations.

To facilitate comparison of experiment and theory, both the satellite positions in the magnetosheath and the field vectors have been transformed from solar ecliptic coordinates to the coordinate system used by Spreiter et al. (1968). This transformation consists of a rotation of less than $90^\circ$ about the solar ecliptic X axis until the Y axis is in the plane defined by the X axis and the interplanetary magnetic field vector. In this plane interplanetary fields oriented in the spiral angle quadrants $90^\circ < \varphi_{SE} < 180^\circ$ and $270^\circ < \varphi_{SE} < 360^\circ$ make angles $0^\circ < \psi < 90^\circ$ with the X axis. Fields oriented in the quadrants $0^\circ < \varphi_{SE} < 90^\circ$ or $180^\circ < \varphi_{SE} < 270^\circ$ make angles with the X axis of $-90^\circ < \psi < 0^\circ$. This is illustrated in Figure 4. In this new coordinate system the geomagnetic dipole will assume a variety of orientations but if the magnetosphere is a blunt body exhibiting symmetry about the X axis, as is assumed in the theories of hydromagnetic magnetospheric flow, this will not be an important consideration and the new coordinate system will be appropriate.

The 1661 hourly average magnetosheath field-magnitude values were sorted according to the corresponding interplanetary field orientations using eighteen $10^\circ$ $\psi$ angle sectors. Figure 4 shows the resulting data distribution as a function of $\psi$. The asymmetry in the distribution reflects both the preference of the interplanetary field for the spiral angle and a three dimensional geometrical effect. The latter effect is due to the fact that the earth-sun line is a pole about which all possible orientations of the plane of the interplanetary field form a spherical distribution of field vectors. In this distribution the number of possible orientatiors of the field increases away from the pole.

The selection of magnetosheath data for this study was carried out with particular care. Generally hours during which a spacecraft was sampling only magnetosheath fields could be identified unambiguously. On those occasions when traversal of either the magnetopause or the bow shock wave was not clear, data was omitted rather than risk inclusion of magnetosphere or interplanetary data.

Magnitude Distribution

The general agreement of the observations with theoretical contours of $B/B_o$ is illustrated in Figure 5. The dashed theoretical contours shown are reproduced from Alksne (1967) and were computed for a plane offset from the XY plane by approximately 6.7 $R_E$, using a Mach number M=8 and a specific heat ratio of 5/3. Theoretical contours are labeled with circled numbers and experimental measurements of $B/B_o$ are indicated by uncircled numbers. The measurements were performed at distances from the XY plane lying within the $|Z|$ range of 4-15 $R_E$. Some values have been omitted because of crowding. Theoretical data correspond to an interplanetary magnetic field orientation of $\psi = 90^o$ while experimental data are for interplanetary fields with angles $80^o < \psi < 90^o$. For this case a magnitude distribution pattern which is symmetric with respect to the earth-sun line is predicted.

In all cases studied, the experimental data are in general agreement with the theory even though the data used correspond to a wide range of Z coordinates, a $10^o$ range of $\psi$ angles, and varying flow parameters for the solar wind during the long period covered by the observations. The measured magnitude ratios in Figure 5 are seen to decrease from values as high as 6 near the bow to values less than one downstream. A predominance of values less than one are found at greater distances downstream.

Although 1661 hourly averages were used in this study, they were spread over a large region of space and were divided among 18 angular intervals in the analysis. Eighty-seven percent of these hours are from positions in the magnetosheath with $X < -10\ R_E$, a region not covered in detail by the published theory. For these reasons, experimental contours could not be drawn with the resolution of the theoretical contours. In spite of these limitations, statistical analysis of the data yields results in agreement with the principal features predicted by the theory.

Figure 6 shows averages of the magnitude ratio computed for intervals of 10 $R_E$ along the earth-sun line from 20 $R_E$ sunward of the earth to 80 $R_E$ in the antisolar direction. Averaged together are magnetosheath data from all values of Y and Z in each X interval, and for all orientations of the external field. The error bars represent the standard deviations computed for each 10 $R_E$ interval. The continuous decrease is seen from a gross average of approximately 4 to values of the order of one and finally to less than one well downstream. There are many cases of $B/B_0 < 1$ beyond -50 $R_E$ but higher values near the shock tend to raise these averages. The gradient can be described as an exponential decrease as is shown in Figure 6.

More complex asymmetrical effects can be seen by dividing the data into dawn and dusk distributions for various interplanetary field orientations. There were 1082 cases of the interplanetary direction lying in the dawn quadrant containing the spiral angle, and 579 cases in the dusk quadrant. The results of this are summarized in Figure 7. These data demonstrate, in a statistical sense, the dependence of magnetosheath magnitude on the orientation of the external field. Distributions for the interplanetary field orientation in the quadrant of the spiral angle (A) and in the perpendicular quadrant (B) are shown. Theory predicts that for orientations in the spiral angle quadrant the magnetosheath field should be stronger on the dusk (+Y) side than on the dawn (-Y) side. This relationship is generally seen for these distributions. For orientations in the dusk quadrant the situation should be reversed, and except for one interval that was found to be the case.

Magnetosheath Field Directions

To study the spatial variations of magnetic field direction in the magnetosheath the hourly average field vectors were normalized in magnitude to the simultaneous interplanetary field magnitudes and projected on the XY plane. Two cases, corresponding to $80^\circ < \psi < 90^\circ$ and $30^\circ < \psi < 40^\circ$, are shown in Figures 8 and 9, respectively. For simplification of presentation, field polarities in the magnetosheath were reversed whenever the corresponding interplanetary measurements had a component directed from the dawn to the dusk meridian. The field vectors in Figures 8 and 9 that are located near the X axis correspond to measurements made at large $|Z|$. The direction of these vectors is generally found to be near the interplanetary field direction.

One of the most striking features observed in the data for the various interplanetary field orientations was a marked lack of symmetry in the ordering of the vectors on the dawn and dusk sides. When the field is aligned nearly perpendicular to the earth-sun line as in Figure 8, the vectors are quite orderly and consistent with the draping pattern back to $X = -70\ R_E$. For other interplanetary field orientations where there is a smaller angle between the field and the earth-sun line, a smaller percentage of the orientations are consistent with this draping pattern in the dawn hemisphere. Figure 9 is typical in that a rather wide variety of orientations are seen in the dawn hemisphere while the dusk hemisphere remains quite orderly.

This difference between the hemispheres may be attributed to conditions at the shock when it is realized that the interplanetary field is oriented nearly parallel to the average bow shock position in the dusk hemisphere but is approximately perpendicular to the shock in the dawn hemisphere. Dusk side fields are then able to convect through the shock with little angle change but dawn side fields must undergo a large angle change in order to conserve the normal component of magnetic field flux across the shock. When the field is oriented nearer the earth-sun line, the minimum angle change necessary to conserve flux is achieved by rotating the field in the direction opposite to that expected from draping. This effect can be seen in the theoretical work (Alksne, 1967).

To determine whether the magnetosheath field lines were bent clockwise (looking down from the north pole) or counterclockwise relative to the interplanetary orientation, vector plots in the dawn hemisphere were studied. The number of cases clearly in agreement with the draping orientation and those in agreement with the opposite tendency were tabulated and are shown in Table 1. The last column contains the number of magnetosheath measurements in the dawn hemisphere associated with the ranges of interplanetary $\psi$ values listed in the first column. The intermediate columns 2 through 5 exhibit the separation of these cases according to whether the magnetosheath measurement is rotated clockwise or counterclockwise.

Columns 6 and 7 list cases where the angular difference between the interplanetary field and the magnetosheath field projection in the XY plane was less than $10^{\circ}$. Only the XY field components were considered in preparing Table 1, even though Z components were sometimes large. Large Z components tended to be associated with the cases tabulated in columns 4 and 5.

Results indicate that fields perpendicular to the earth-sun line are almost always rotated in the direction consistent with both the draping of field lines and minimum deviation of the field at the shock. For smaller $\psi$ angles the percentage of fields rotated in this direction decreases. For $\psi < 40^{\circ}$ where the conditions of draping and minimum angle change dictate opposite directions of rotation, there are an approximately equal number of rotations in either direction. Because most of the experimental data used correspond to large negative X positions, the field direction results cannot be directly compared with the theory since detailed theoretical results are not available for that region of the magnetosheath.

Summary of Results

Simultaneous observations from four satellites have produced an experimental mapping of the magnetic fields in the magnetosheath that is in zeroth order agreement with the predictions of magneto-gasdynamic theory. These experimental results support the theoretical prediction that the ratio of the magnetosheath field magnitude relative to the interplanetary field magnitude has a value of 4 or more near the bow but decreases to less than unity downstream. The observations also support the predicted dependence of the magnetosheath field magnitude at a given point on the orientation of the field external to the magnetosheath. In particular the analysis reveals a dawn-dusk asymmetry in the magnitude distribution in which the magnitude difference between dusk and dawn reverses sign as the interplanetary field orientation changes from the spiral angle direction to the spiral angle $\pm 90^{\circ}$.

The experimental results also support the predicted dawn-dusk asymmetry in field orientation. When the interplanetary field is aligned near the spiral angle, the hourly average field vectors in the dusk hemisphere are more ordered than those in the dawn magnetosheath. Distortion of the field direction due to draping extends at least as far downstream as $-70R_E$ in the case of the external field perpendicular to the earth-sun line. The tendency for the downstream field to have an orientation consistent with draping decreases as the angle between the interplanetary field and the earth-sun line decreases, suggesting that conditions at the bow shock may sometimes be the more important factor influencing the magnetic field direction.

Although the experimental data presented above clearly agrees with the steady state magnetogasdynamic theory in the zeroth order, there is still a considerable amount of scatter among the hourly average data points. Some of this scatter is undoubtedly due to the inadequacies in removing time variations from the data. Errors are involved in ignoring convection time delays when comparing hourly averages and in assuming interplanetary measurements as representative of fields across the entire shock surface. Scatter also arises from comparing measurements made at different positions and at times when the values of various solar wind parameters are different. In addition to these experimental difficulties, it is possible that first order effects included in the steady-state magnetogasdynamic theory are responsible for some scatter. Geomagnetic dipole orientation might be important in a first order treatment and the assumption of axial symmetry used in the zeroth order theory would no longer be valid.

Acknowledgements

The authors wish to thank Dr. N. F. Ness, the principal magnetic field experimenter on Explorers 28, 33, 34 and 35, for helpful suggestions during the course of this investigation. We also acknowledge the contributions of Mr. C. S. Scearce, Dr. S. C. Canterano, and Mr. J. B. Seek to the design, development and successful operation of these experiments.

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COMPARISON WITH DRAPING ORIENTATION

| $\psi$ (Deg.) | Agreement # Cases | % | Non-Agreement # Cases | % | Undeviated in Direction # Cases | % | Total # Cases |
|---|---|---|---|---|---|---|---|
| 80-90 | 41 | 89 | 2 | 4 | 3 | 7 | 46 |
| 70-80 | 44 | 81 | 3 | 6 | 7 | 13 | 54 |
| 60-70 | 42 | 79 | 7 | 13 | 4 | 8 | 53 |
| 50-60 | 56 | 75 | 14 | 20 | 4 | 5 | 74 |
| 40-50 | 36 | 46 | 18 | 23 | 25 | 31 | 79 |
| 30-40 | 21 | 38 | 19 | 35 | 15 | 27 | 55 |
| 20-30 | 18 | 53 | 12 | 35 | 4 | 12 | 34 |
| 10-20 | 3 | 21 | 7 | 50 | 4 | 29 | 14 |
| 0-10 | 1 | 20 | 1 | 20 | 3 | 60 | 5 |

TABLE 1

Figure Captions

Figure 1 Solar ecliptic XY plane projections of trajectories of Explorers 33, 34 and 35 during September 17-October 16, 1967. Orbits 27-31 are shown for Explorer 34. Distances are in earth radii (Behannon, Fairfield and Ness, 1968).

Figure 2 Simultaneous magnetosheath and interplanetary magnetic field measurements from Explorers 33 and 34. The field magnitude $\overline{F}$ and solar ecliptic latitude and longitude angles $\theta$ and $\varphi$ are shown.

Figure 3 Simultaneous hourly average magnetic field data from Explorer 33 in the dawn side magnetosheath and IMP 3 in the interplanetary medium during August 28-September 1, 1966.

Figure 4 Distribution of magnetosheath data used in the analysis as a function of interplanetary field orientation. As is shown schematically, $\psi$ is the angle between the interplanetary field and the earth-sun line in the plane of the field vector and the earth-sun line.

Figure 5 Comparison between experimental values of field magnitude radio $B/B_o$ and theoretical contours, for the case of the interplanetary field oriented transverse to the earth-sun line.

Figure 6 Averages of normalized magnetosheath magnetic field magnitude for intervals of 10 $R_E$ along the earth-sun line showing the continuous decrease of the magnetosheath field with distance downstream to values less than the interplanetary field magnitude.

Figure 7 Illustration of asymmetry in average field magnitude between dawn and dusk sides of the magnetosheath. When the interplanetary field is aligned in the quadrant of the spiral angle (case A) the field magnitude on the dusk side is shown generally to be larger than for orientations corresponding to case B. The reverse is seen to be true for the dawn side field.

Figure 8 Projection of normalized magnetosheath field vectors onto the XY plane defined by the interplanetary field and the earth-sun line, for cases when the interplanetary field was approximately transverse to the earth-sun line. Note the high degree of symmetry between the field patterns on the dawn and dusk sides.

Figure 9 XY plane projection of magnetosheath field vectors for cases when the interplanetary field was oriented at $30^{\circ}$-$40^{\circ}$ from the earth-sun line. In this case less symmetry between dawn and dusk fields is evident than is seen in Figure 8.

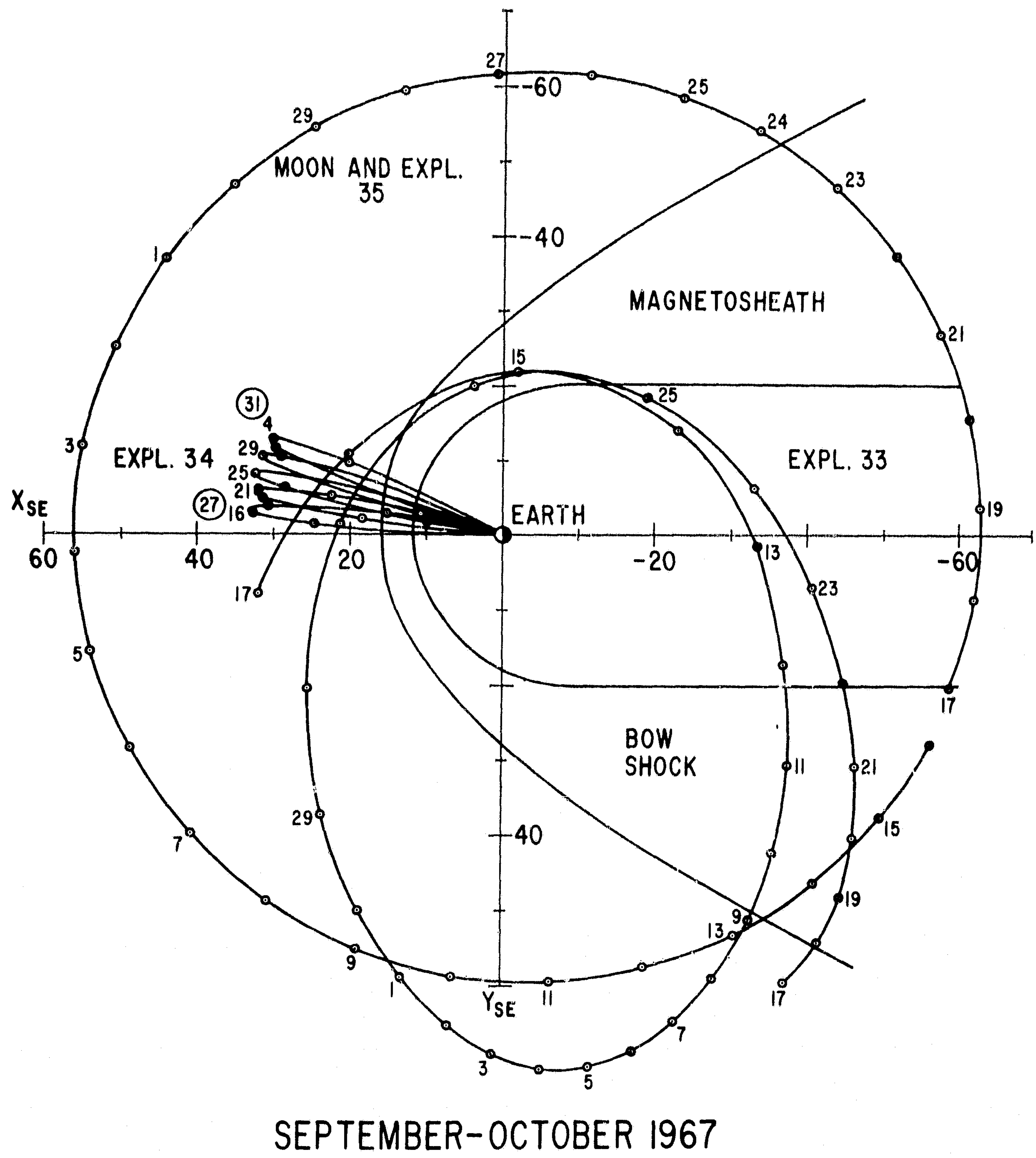

MOON AND EXPL. 35
MAGNETOSHEATH
EXPL. 34
EXPL. 33
EARTH
BOW SHOCK
$X_{SE}$
$Y_{SE}$
60
40
20
-20
-60
-40
SEPTEMBER-OCTOBER 1967

FIGURE 1

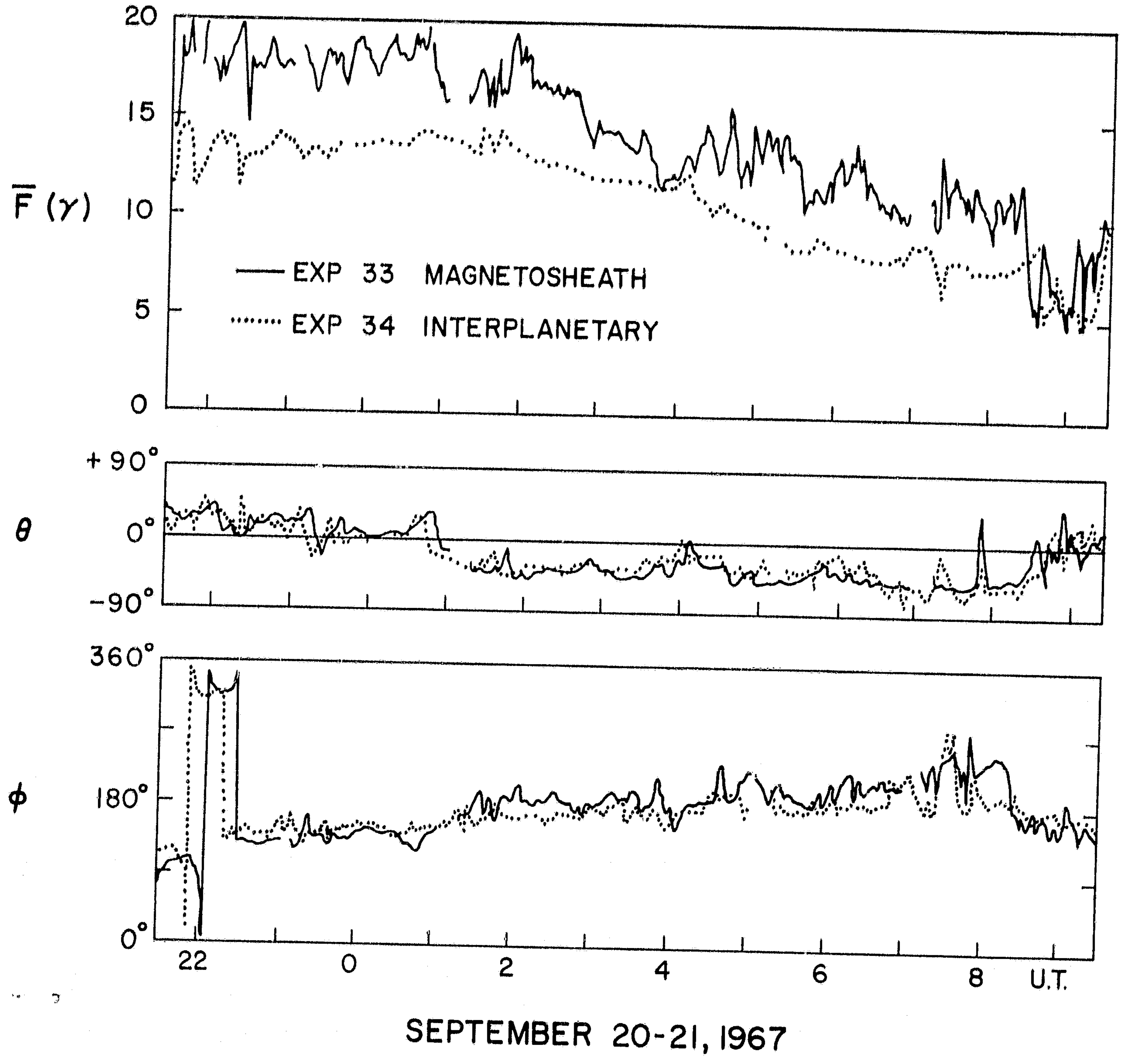
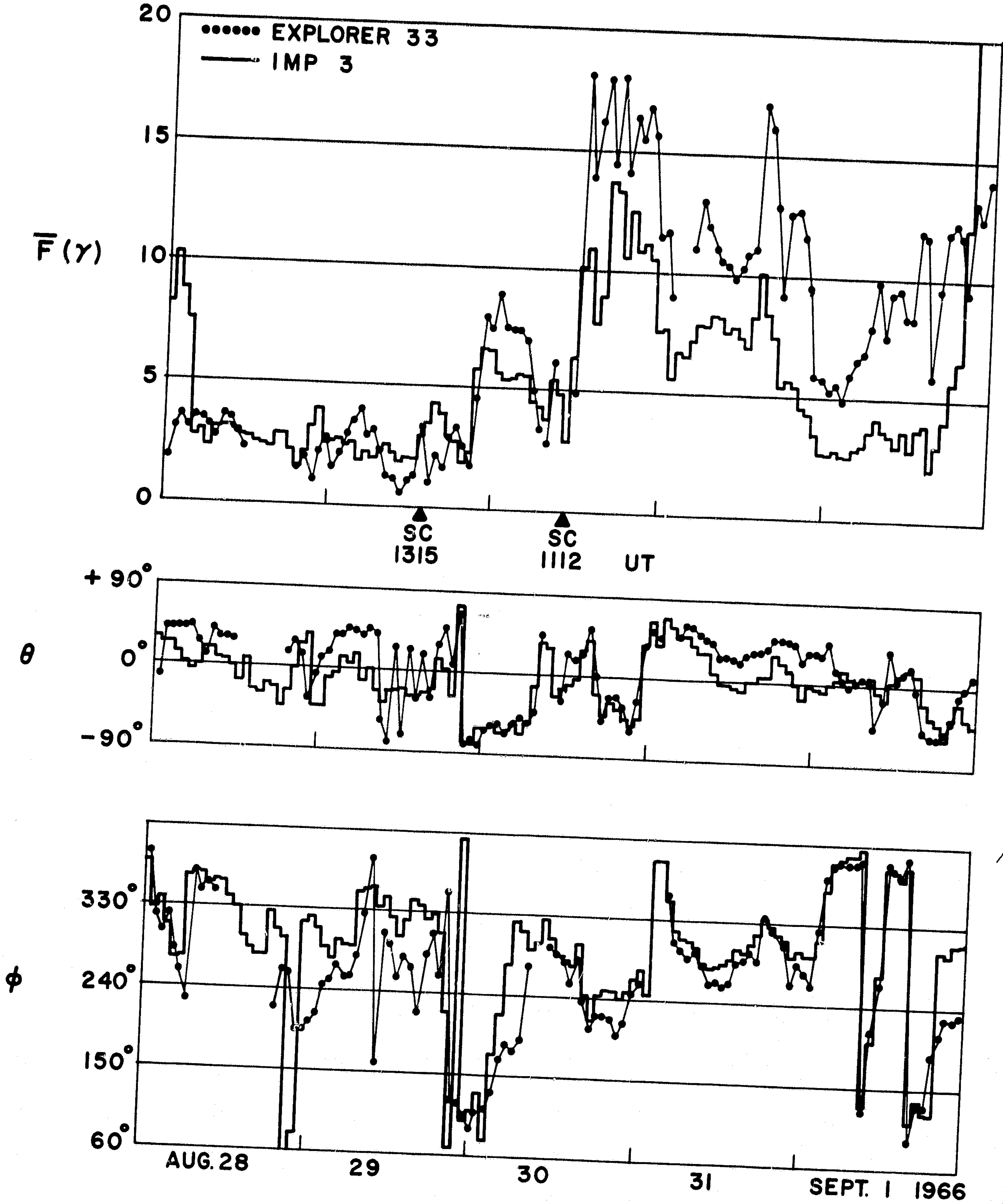

20
15
10
5
0
F̄ (γ)
—— EXP 33 MAGNETOSHEATH
······· EXP 34 INTERPLANETARY
+90°
θ
0°
-90°
360°
φ
180°
0°
22
0
2
4
6
8
U.T.
SEPTEMBER 20-21, 1967

FIGURE 2



EXPLORER 33
IMP 3
20
15
10
5
0
F̄(γ)
SC
1315
SC
1112
UT
+90°
0°
-90°
θ
330°
240°
150°
60°
φ
AUG. 28
29
30
31
SEPT. 1 1966


FIGURE 3

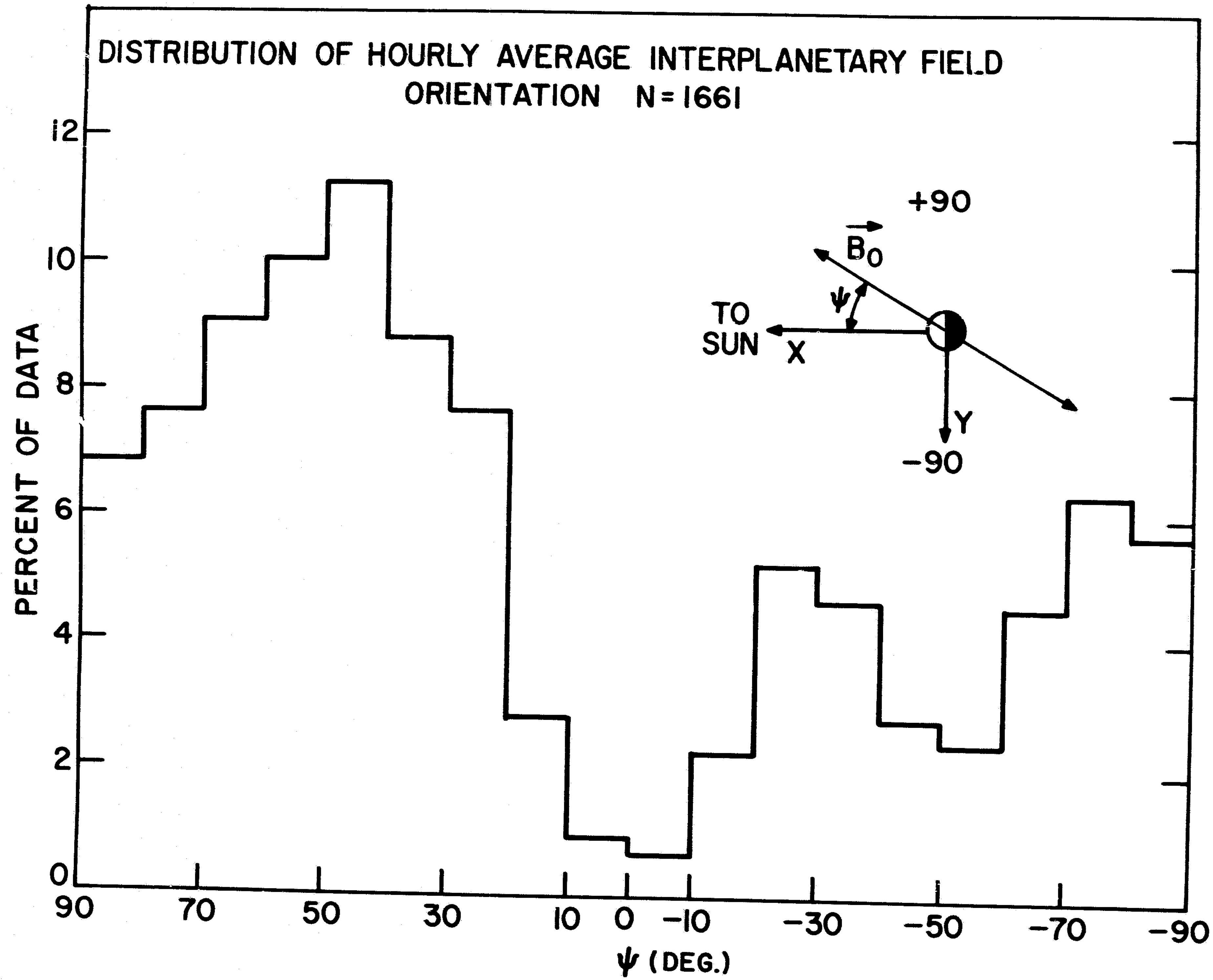
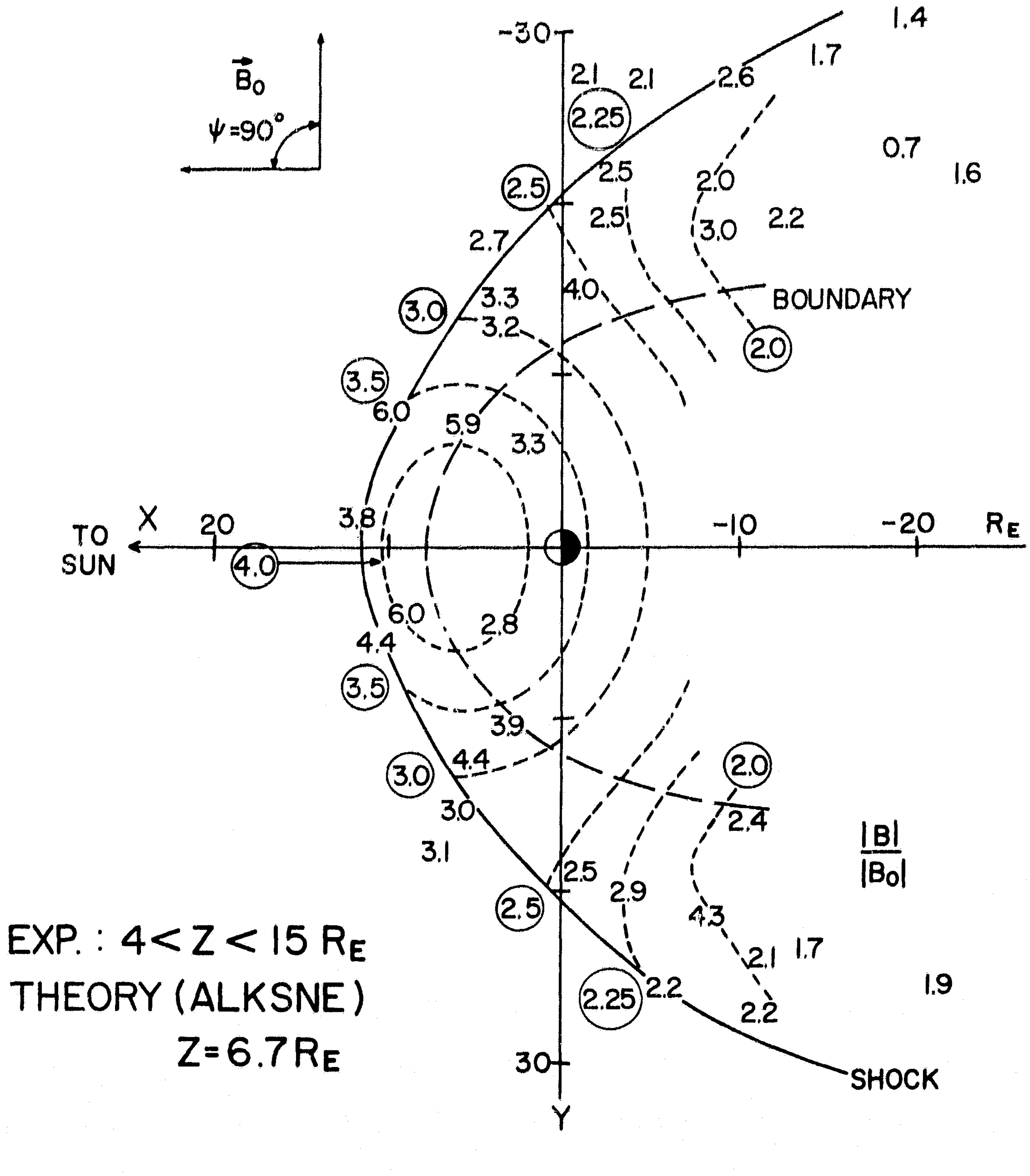

DISTRIBUTION OF HOURLY AVERAGE INTERPLANETARY FIELD
ORIENTATION N = 1661
PERCENT OF DATA
12
10
8
6
4
2
0
90
70
50
30
10
0
−10
−30
−50
−70
−90
ψ (DEG.)
+90
−90
B0
ψ
TO
SUN
X
Y

FIGURE 4



$\vec{B}_0$
ψ=90°
-30
30
TO SUN
X
20
-10
-20
$R_E$
Y
1.4
1.7
2.1
2.1
2.6
2.25
0.7
1.6
2.5
2.5
2.0
2.5
3.0
2.2
2.7
3.0
3.3
4.0
BOUNDARY
3.2
2.0
3.5
6.0
5.9
3.3
3.8
4.0
6.0
2.8
4.4
3.5
3.9
4.4
3.0
2.0
3.0
2.4
3.1
|B|
|B0|
2.5
2.9
2.5
4.3
2.1
1.7
2.25
2.2
2.2
1.9
SHOCK
EXP. : 4 < Z < 15 $R_E$
THEORY (ALKSNE)
Z=6.7 $R_E$


FIGURE 5

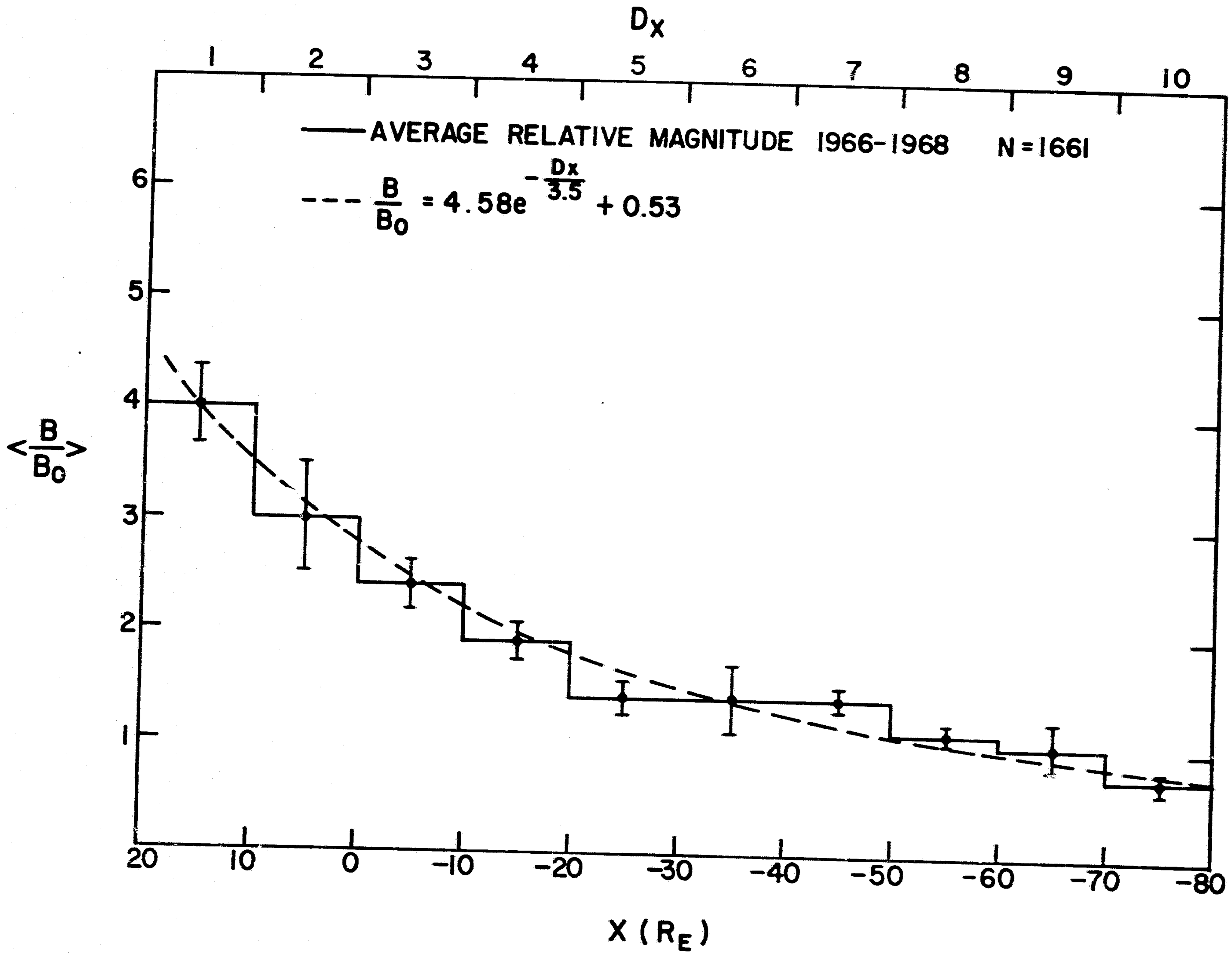
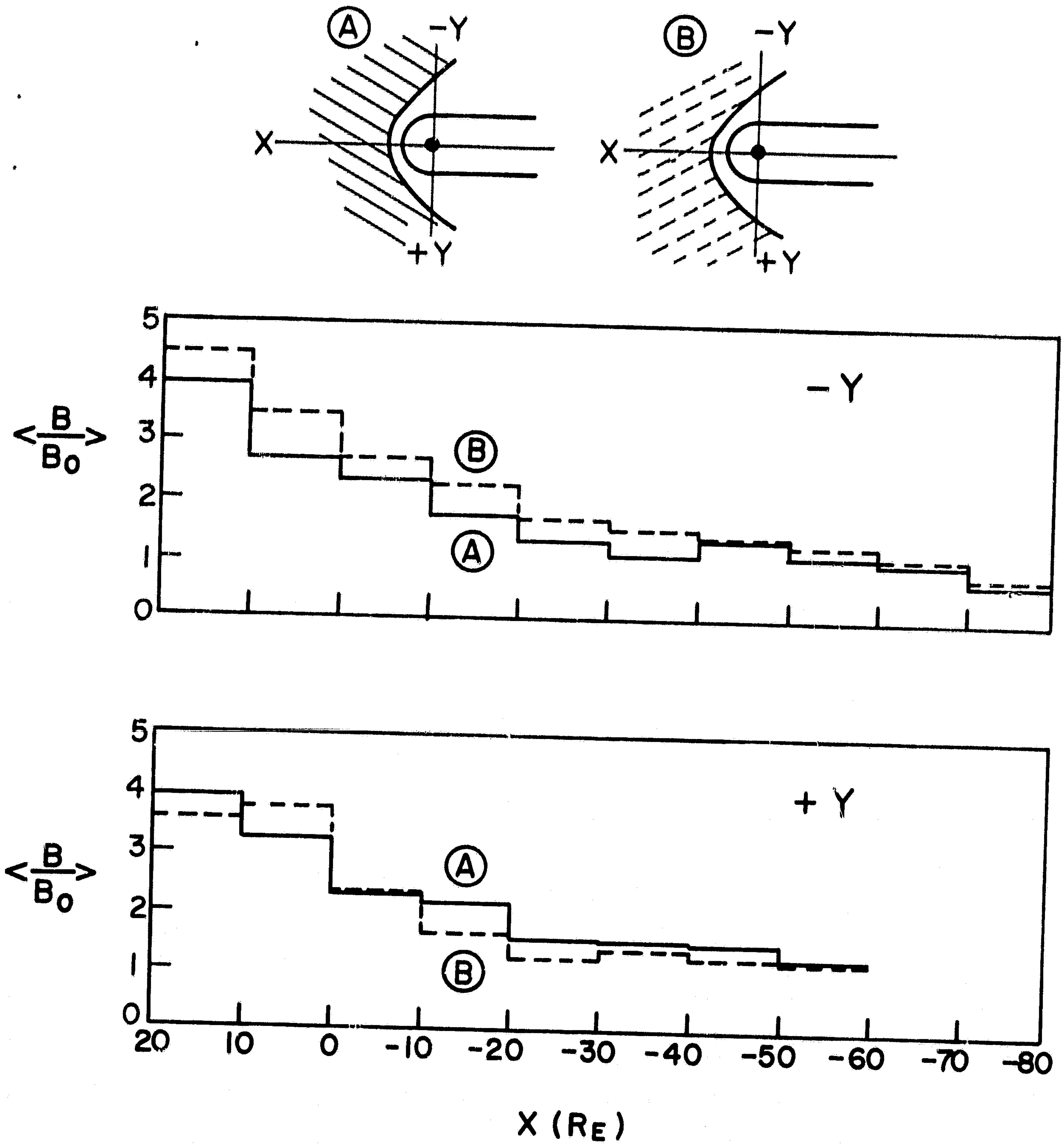

Dx
1
2
3
4
5
6
7
8
9
10
AVERAGE RELATIVE MAGNITUDE 1966-1968
N=1661
B/Bo = 4.58e^(-Dx/3.5) + 0.53
<B/Bo>
6
5
4
3
2
1
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
X (RE)

FIGURE 6



A
-Y
X
+Y
B
-Y
X
+Y
5
4
3
2
1
0
<B/Bo>
-Y
B
A
5
4
3
2
1
0
<B/Bo>
+Y
A
B
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
X (RE)


FIGURE 7

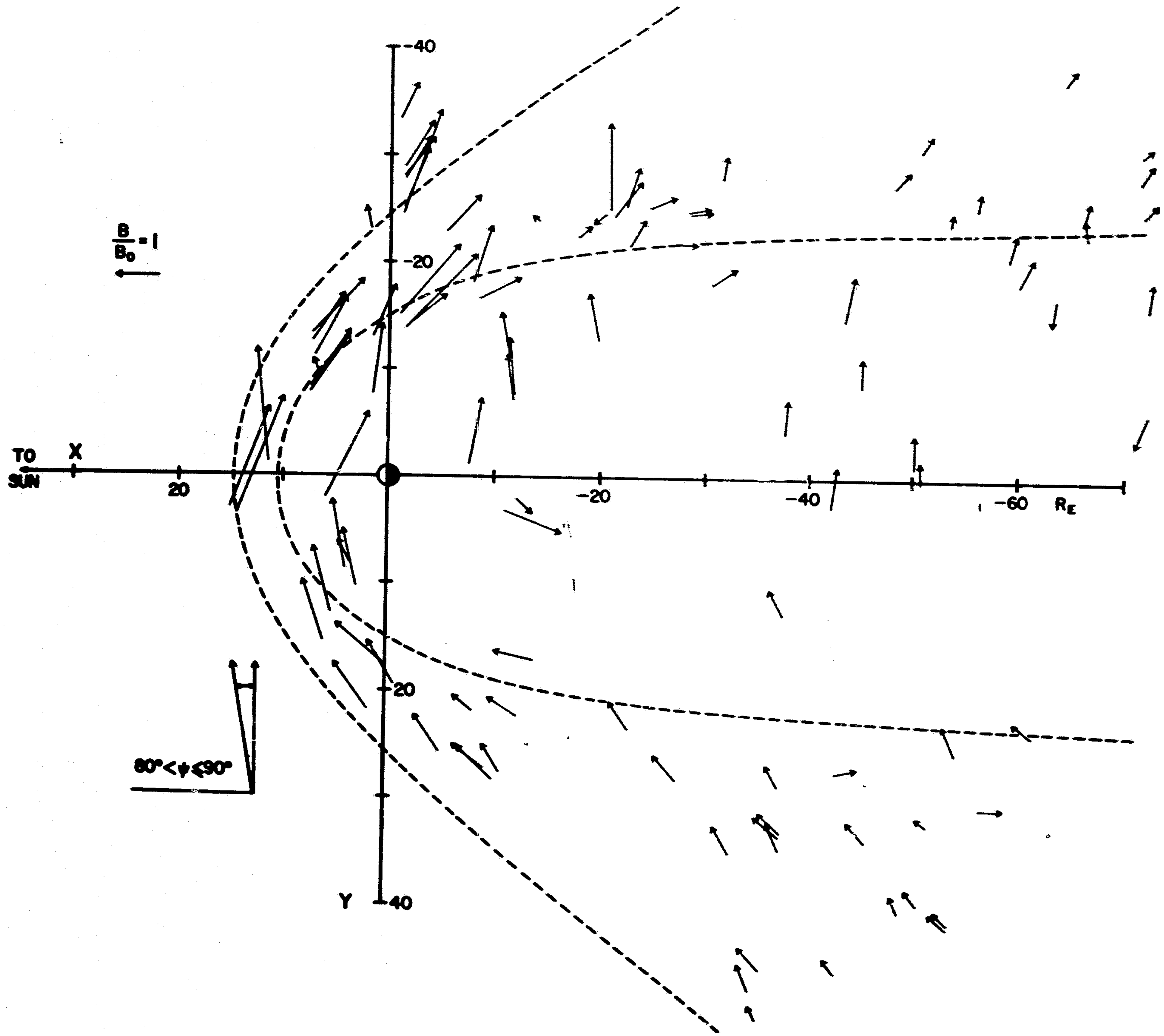



FIGURE 8

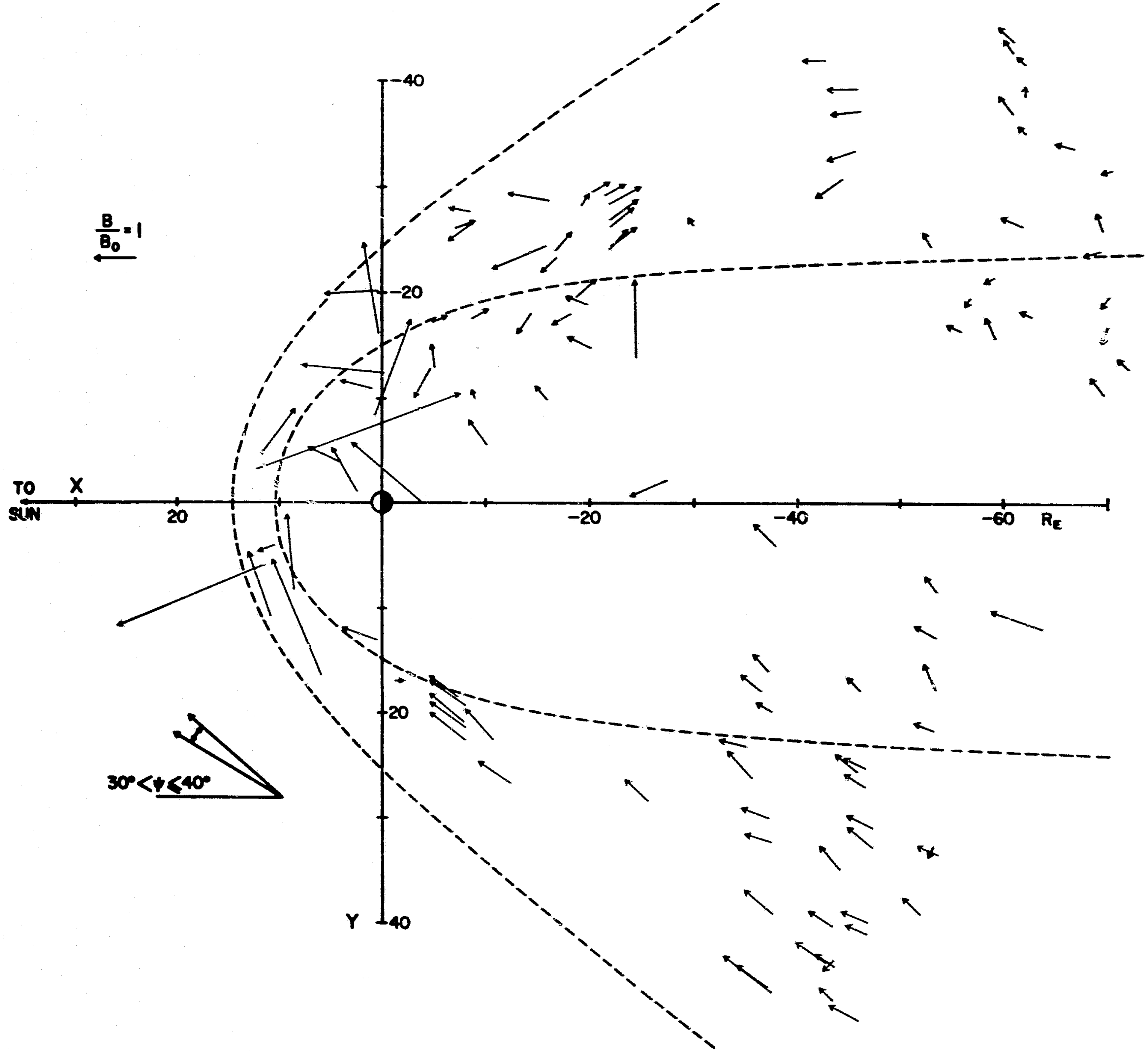



FIGURE 9