Space Sciences Laboratory
University of California
Berkeley, California 94720

Response of the Geomagnetic Activity Index K_p to the Interplanetary Magnetic Field

Kenneth H. Schatten and John M. Wilcox

Technical Report

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Abstract

Interplanetary magnetic field observations with IMP-3 during eight solar rotations in the latter half of 1965 have been compared with the 3-hour K_p index. The results are consistent with those obtained with IMP-1 from three solar rotations in the winter of 1963-4, indicating a stability in the response of geomagnetic activity during these years near solar activity minimum. The larger data sample in the present investigation reduces the probable error and delineates some interesting results. The average value of K_p decreases as the angle between the interplanetary field and the ecliptic changes from south to north. This is consistent with the reconnection of interplanetary and geomagnetic field lines as suggested by Dungey. As a function of interplanetary field magnitude B, the average value of the index a_p is more linear than K_p, as might be expected. The relation can be described by $\overline{a_p} = (1.5 \pm 0.1)\ B + 0.7 \pm 0.5$. In the time interval covered by these observations the average value of K_p is consistently higher in sectors with interplanetary field directed away from the sun than in sectors with field directed toward the sun.

INTRODUCTION

The influence upon geomagnetic activity of the interplanetary magnetic field observed by the magnetometer experiment on the IMP-3 satellite has been studied. The results support an interconnection between the interplanetary and geomagnetic field lines as an important agent for transferring the solar wind energy into geomagnetic activity, as suggested by Dungey (1961) and later discussed by Levy et al. (1964).

Several observations and theories on the mechanisms for influencing geomagnetic activity have been discussed in our recent paper (Wilcox et al., 1967). After that paper was completed a number of authors have further discussed the relation between the interplanetary and geomagnetic fields. Lin and Anderson (1966) have reported evidence for the connection of geomagnetic tail lines to the interplanetary field on the basis that solar flare electrons with low magnetic rigidity readily appear in the geomagnetic tail. Patel et al. (1967) have compared the geomagnetic index a_p with the magnetosheath field observed by Explorer 12 and find that high a_p is associated with a southward field. They report an "interesting, but not conclusive" result that a moderate a_p is associated with four cases of a predominantly northward field, and point out that this result would not be consistent with Dungey's magnetic merging theory. Zhulin (1966) has discussed several mechanisms by which the interplanetary magnetic field may play the role of an intermediary in the interaction between the solar wind and the magnetosphere.

ANALYSIS

The IMP-3 (Explorer 28) satellite was launched on May 29, 1965 in a highly eccentric earth orbit with an initial apogee of 41.7 earth radii at a sun-earth-apogee angle of 120°E. This orbit allowed the satellite to sample the interplanetary magnetic field fairly continuously from the launch date until February, 1966, at which time the satellite remained within the magnetosphere and its tail during the entire orbit, temporarily preventing further interplanetary measurements. Almost 4000 hours of interplanetary measurements were accumulated by this time. A description of the IMP-1 magnetometer, similar to the IMP-3 magnetometer, is given by Ness et al. (1964). Due to a malfunction no plasma data is available.

The interplanetary magnetic field during this time interval was on the average stretched out in the ecliptic plane along the Archimedean spiral angle as proposed by Parker (1958). This field could be classified for the most part as being either in a sector with field directed predominantly toward the sun or in a sector with field predominantly away from the sun. The sector pattern is evolving more rapidly than was the pattern observed by IMP-1 (Wilcox and Ness, 1965) and IMP-2 (Fairfield and Ness, 1967).

The influence of the interplanetary magnetic field and plasma on the geomagnetic activity index K_p during the quasi-stationary sector structure observed by IMP-1 has been discussed by Wilcox et al. (1967). A similar analysis is now presented of the influence on geomagnetic activity of the interplanetary magnetic field observed by IMP-3 during eight solar rotations, with the increased amount of data allowing further results to be delineated. The method of analysis is similar to that of Wilcox et al. (1967) and is discussed with reference to Figure 1, which shows the relation between K_p and the magnitude B of the interplanetary magnetic field. It is desired to investigate the influence on a dependent variable K_p of an independent variable B, under conditions in which K_p is also being influenced by a number of other variables. The large amount of scatter in the figure is attributed to the influence of these other variables, and it is desired to isolate the specific relation between K_p and B. Each small dot represents a 3-hour value of K_p and the associated 3-hour average interplanetary field magnitude. Each (quantized) value of K_p is plotted close to but not precisely at its actual value in order to avoid an overlap of the individual points. A means of obtaining a statistically significant average K_p response to a given interplanetary stimulus is then provided in the following manner:

a) Each solid circle represents the average of all the small points falling within a column which contains one-tenth of the total data.

b) Thus each solid circle represents the average response of K_p to a given small range of field magnitude, and has about the same statistical uncertainty as each of the other nine large circles; a bar over K_p refers to this kind of average. (The largest and smallest probable errors in the ordinates are shown.)

c) Although a well-defined relation is observed between $\overline{K_p}$ and interplanetary field magnitude, individual events cannot be explicitly predicted from this analysis.

Figure 2 is a reproduction of Figure 2 of Wilcox et al. (1967) showing the relation between K_p and interplanetary field magnitude obtained during three solar rotations observed by IMP-1 in the winter of 1963-4. The large solid circles of Figure 1 of the present paper have been added as triangles.

The IMP-3 results are consistent with the IMP-1 results, indicating that response of geomagnetic activity to interplanetary field magnitude remains quite similar at the time of IMP-3 even though the sector pattern is evolving somewhat more rapidly. IMP-1 observed near the end of the old (19th) eleven-year sunspot cycle, while at the time observed by IMP-3 the sun was dominated by new-cycle activity.

The index K_p is a semilogarithmic measure of geomagnetic activity while the index a_p is a linear measure of geomagnetic activity. Figure 3 shows the relation between a_p and interplanetary field magnitude B. It can be seen that $\overline{a_p}$ fits a linear relationship with B more closely than does $\overline{K_p}$ (Figure 1). The straight line drawn in Figure 3 is described by the equation $\overline{a_p} = (1.5 \pm 0.1)\ B + 0.7 \pm 0.5$.

It was suggested by Wilcox et al. (1967) that a southward interplanetary field has a greater geomagnetic effectiveness than a northward field, and it was pointed out that a larger number and range of observations would clarify the issue. Figure 4 shows the relation observed by IMP-3 between K_p and the angle θ , which is the angle between the direction of the interplanetary magnetic field and ecliptic. The larger sample now clearly delineates an essentially monotonically decreasing value for $\overline{K_p}$ as θ changes from south to north. This supports the suggestion by Dungey (1961) and by Levy et al. (1964) of the interconnection of interplanetary and geomagnetic field lines.

Figures 5, 6 and 7 show the relation between K_p and the three solar ecliptic components of interplanetary magnetic field. Figure 5 shows the decline of $\overline{K_p}$ as the perpendicular component of the interplanetary field chnages from south to north. The small increase in $\overline{K_p}$ at the largest northward component is presumably related to the relation between $\overline{K_p}$ and field magnitude shown in Figure 1. If any single component of the field becomes large then the total field magnitude also becomes large, which will tend to increase $\overline{K_p}$ as shown in Figure 1. The tendency for $\overline{K_p}$ to increase as the magnitude of the field components increases can also be observed in Figures 6 and 7. Figure 6 shows the relation between $\overline{K_p}$ and the radial component of the interplanetary magnetic field, and Figure 7 shows the relation between $\overline{K_p}$ and the azimuthal component of the interplanetary field. These figures also show an asymmetry that is more clearly seen in Figure 8, which shows the relation between $\overline{K_p}$ and the angle ϕ , the azimuthal direction of the interplanetary field component parallel to the ecliptic. The relation between $\overline{K_p}$ and the angle ϕ is in marked contrast to the relation between $\overline{K_p}$ and the north-south angle θ that was shown in Figure 4. $\overline{K_p}$ is to first approximation independent of ϕ , except that the values for sectors with interplanetary magnetic field directed away from the sun are a small but significant amount larger than the values of $\overline{K_p}$ for sectors with field toward the sun. The greater geomagnetic effectiveness of away sectors is also evident in the influence of K_p of the radial component of the interplanetary field shown in Figure 6 and the azimuthal component of the interplanetary field shown in Figure 7.

The difference between away and toward sectors is shown in more detail in Figure 9, which shows the average value of K_p for the away sectors and for the toward sectors within each Bartels solar rotation. In each solar rotation observed by IMP-3 the away sectors produced a larger average value of K_p than did the toward sectors. For the entire interval observed by IMP-3 the average value of K_p in the away sectors was 1.94 ± 0.15, and the average value of K_p in the toward sectors was 1.44 ± 0.15. The probable errors include an estimate of the effect of the conservation property of K_p (Chapman and Bartels, 1940). The difference in the average value of K_p between away and toward sectors could be caused by differences in the average value of field magnitude B, north-south angle θ or solar wind velocity V. If the relation between K_p and solar wind velocity at the time of IMP-3 was the same as that in Figure 3 of Wilcox et al. (1967), then an average solar wind velocity in away sectors about 20 km/sec larger than in toward sectors could account for the difference shown in Figure 9. Since solar wind velocity measurements are not available from IMP-3 due to a malfunction this possibility cannot be further evaluated at the present time. The difference in the average values of K_p shown in Figure 9 does not appear to be caused by differences in the average values of either field magnitude B or north-south direction angle θ. From Figure 1 one can estimate that in order to account for the difference the away sectors would need to have an average value of field magnitude about 1.7 γ (1 γ = 10 microgauss) larger than the toward sectors, whereas the observed average values of field magnitude in toward and away sectors were equal within the estimated probable error of $\pm$ 0.2 γ. Similarly from Figure 4 one can estimate that to explain the difference in K_p the average value of θ in away sectors would have to be about 27° more southward (negative) than in toward sectors, whereas the observed average values of θ in toward sectors was $0 \pm 1^\circ$ and the average value in away sectors was $7 \pm 1^\circ$.

A seasonal influence on the average value of K_p could arise from the tilt of the earth's rotational axis to the ecliptic. During (northern hemisphere) winter an interplanetary magnetic field directed toward the sun and parallel to the ecliptic would appear to have a small southward component as viewed in a geomagnetic coordinate system, and thus from the results of Figure 4 might be expected to be slightly more geomagnetically effective than an interplanetary field directed away from the sun during the winter season. In the summer these conditions would of course reverse. Figure 9 includes portions of both summer and winter; in the left (summer) portion of the figure this effect of the tilt of the earth's axis would cause the away (solid) curve to fall above the toward (dashed) curve, but in the right (winter) portion of the figure the away curve would be below the toward curve. Since the latter effect is not observed in Figure 9 the tilt of the earth's axis cannot explain the result. A further discussion of the average value of K_p as a function of a sector structure interpolated between the observations of IMP-1 and IMP-2 during 1964 will be given in a paper under preparation.

The temporal relation between the nearby interplanetary field magnitude and K_p is shown in the top curve of Figure 10, which is a crosscorrelation of these quantities as a function of time lag. A positive peak in correlation occurs at a lag of zero, indicating that most of the response occurs within the 3-hour period of K_p. The sawtooth nature of the curve is probably related to the large scale-structure of the interplanetary field. The bottom curve of Figure 10 shows the temporal relation between the north-south angle θ of the field direction and K_p. The minimum at zero lag is consistent with the relation shown in Figure 4 in which the maximum value of K_p occurs at the most southward (negative) value of θ . In each of the curves of Figure 10 the width of the peak at zero lag appears to be related to the conservation property of the data (Chapman and Bartels, 1940).

The top curve of Figure 11 shows an autocorrelation of the interplanetary field magnitude, the middle curve is an autocorrelation of Θ , and the bottom curve is an autocorrelation of K_p. The autocorrelations of field magnitude and of K_p in Figure 11 show a relatively wide peak near zero lag corresponding to the wide peak in their crosscorrelation in Figure 10, while the autocorrelation of Θ in Figure 11 shows a much narrower peak near zero lag corresponding to the narrow peak in the Θ crosscorrelation of Figure 10. Thus the widths of the peaks in Figures 10 and 11 are mainly related to the structure of the interplanetary field and not to its interaction with the geomagnetic field.

SUMMARY

1. The average K_p response to interplanetary field magnitude observed by IMP-3 in 1965 is consistent with the IMP-1 observations in the winter of 1963-4.
2. A semilogarithmic tendency is observed in the relation between $\overline{K_p}$ and field magnitude, whereas the relation between $\overline{a_p}$ and field magnitude is more linear, having the form $\overline{a_p} = (1.5 \pm 0.1)\ B + 0.7 \pm 0.5$.
3. The average value of K_p is a decreasing function of the angle between interplanetary magnetic field and the ecliptic as this angle changes from south to north.
4. The above analysis supports the connection of interplanetary and geomagnetic field lines as suggested by Dungey (1961).
5. In each Bartels solar rotation observed by IMP-3 the average value of K_p during away sectors was larger than the average value of K_p during toward sectors.
6. Crosscorrelation analysis suggests that most of the geomagnetic response to the interplanetary medium occurred during the 3-hour period of K_p.

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Figure Captions

Figure 1. Scatterplot of the 3-hour K_p values with the 3-hour average interplanetary magnetic field magnitudes. The small dots represent the original 3-hour data values, and the solid circles are each the average of 131 original data points, as explained in the text. The largest and smallest probable errors associated with the solid circles are indicated. One gamma equals ten microgauss.

Figure 2. Similar scatterplot showing the 3-hour IMP-1 (1963-4) data points as small open circles and the average as solid circles. The IMP-3 (1965-6) averages (the solid circles in Figure 1) are shown for comparison as triangles.

Figure 3. Scatterplot of the linear geomagnetic index a_p with interplanetary field magnitude. The line is described by $\overline{a_p} = (1.5 \pm 0.1)B + 0.7 \pm 0.5$.

Figure 4. Scatterplot of K_p with Θ, the angle between the interplanetary magnetic field and the ecliptic.

Figure 5. Scatterplot of K_p with the north-south component of the interplanetary magnetic field.

Figure 6. Scatterplot of K_p with the radial component of the interplanetary magnetic field.

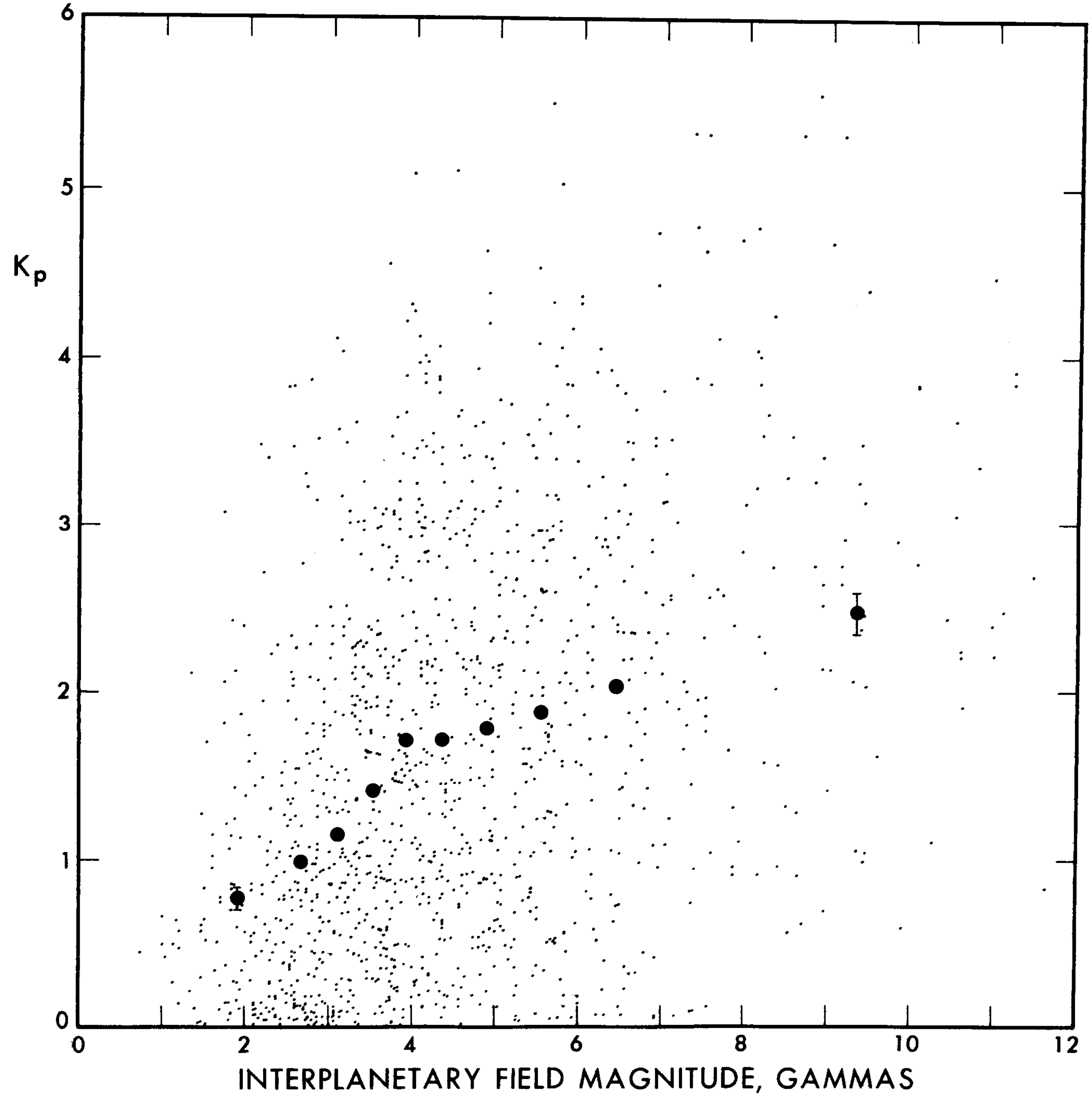
Figure 7. Scatterplot of K_p with the azimuthal component of the interplanetary magnetic field.

Figure 8. Scatterplot of K_p with the direction of the interplanetary magnetic field component in the ecliptic plane.

Figure 9. Average value of K_p for the away sectors and the toward sectors within each Bartels solar rotation. Typical probable errors are shown including an estimate of the effect of the conservation property of the data.

Figure 10. Top curve crosscorrelation as a function of time lag of K_p and interplanetary field magnitude. Bottom curve crosscorrelation of K_p and the north-south angle θ of the field.

Figure 11. Autocorrelations of interplanetary magnetic field magnitude, north-south field direction angle θ , and of K_p.



Kp
0
1
2
3
4
5
6
0
2
4
6
8
10
12
INTERPLANETARY FIELD MAGNITUDE, GAMMAS

Figure 1

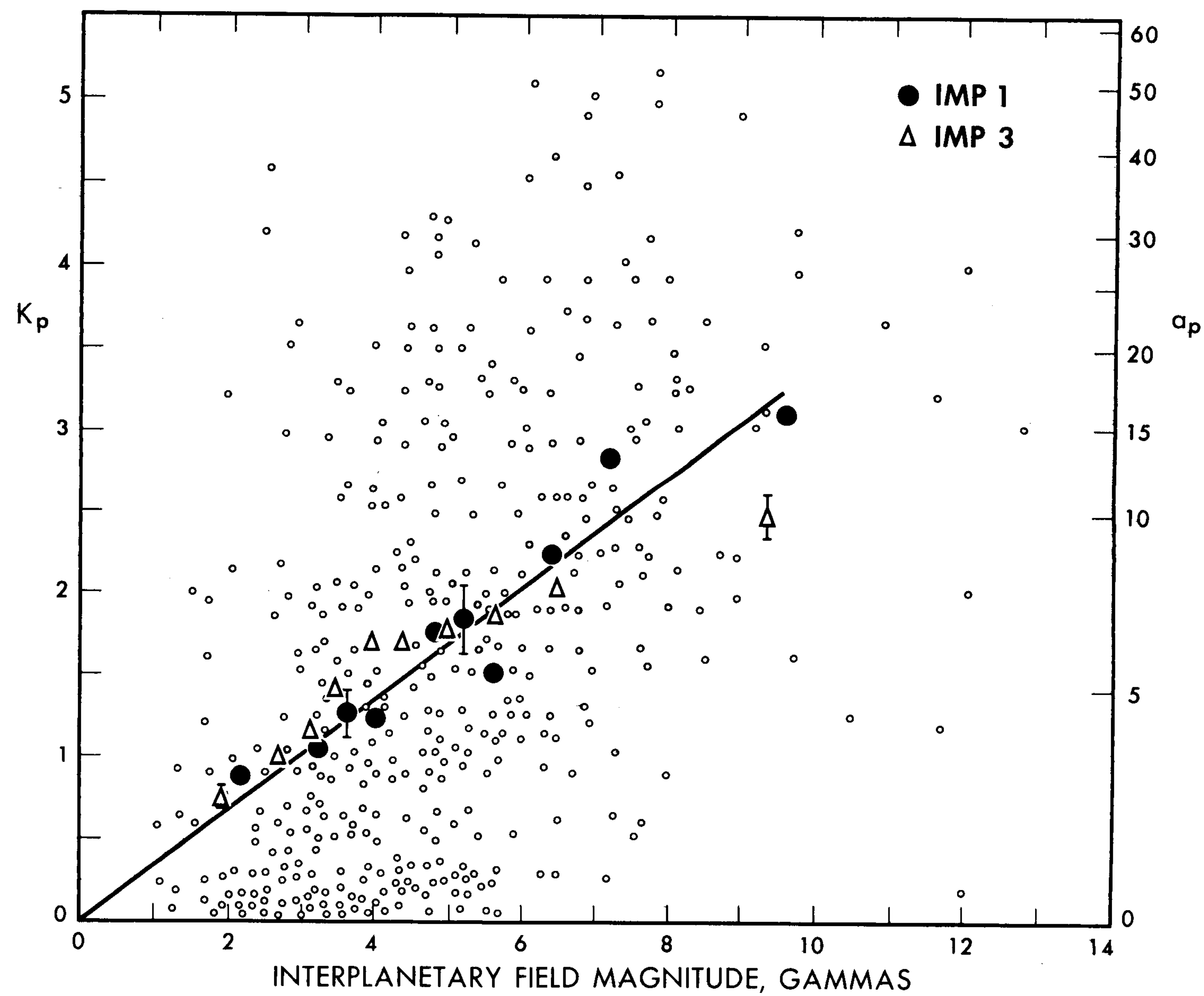
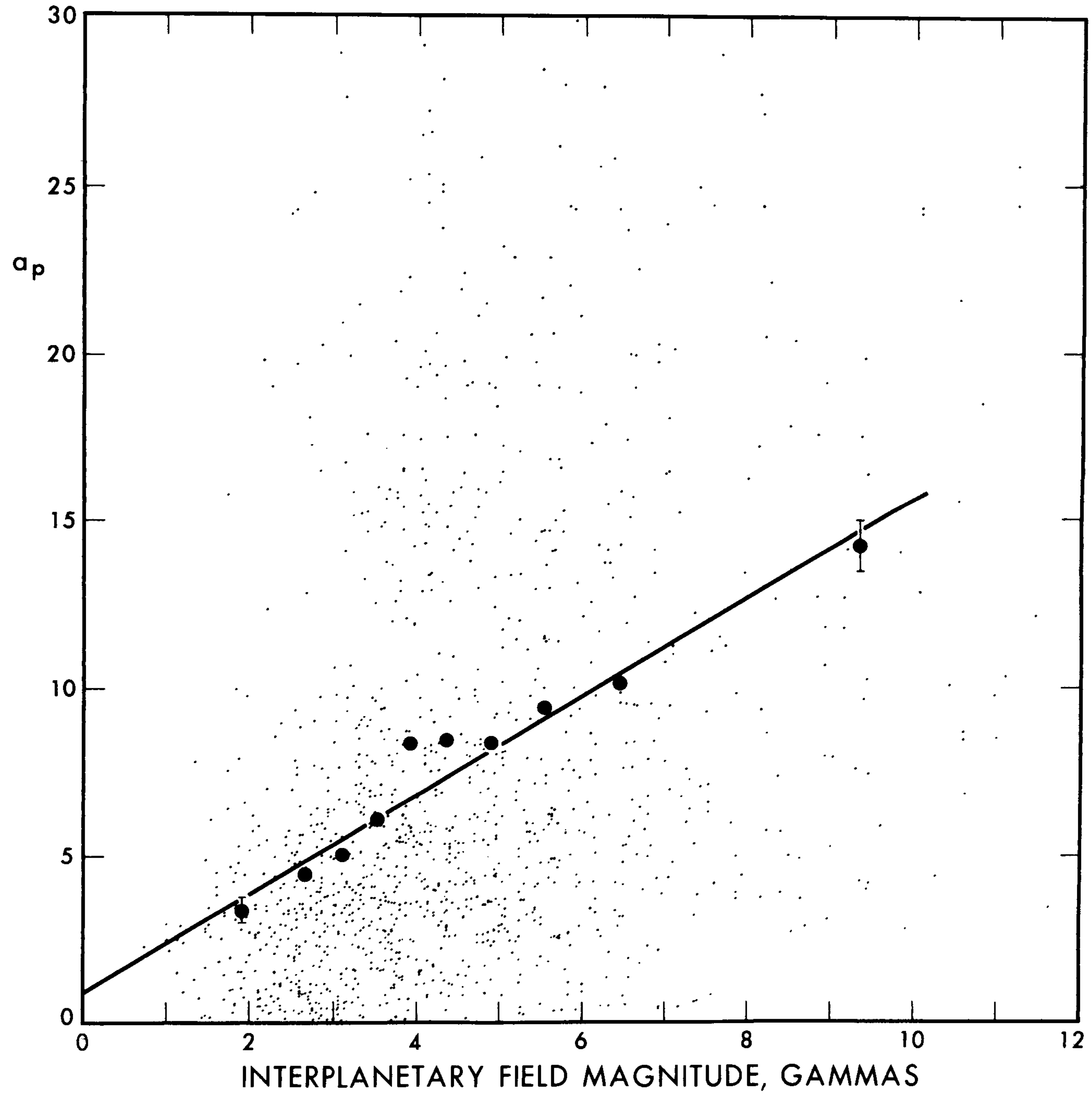
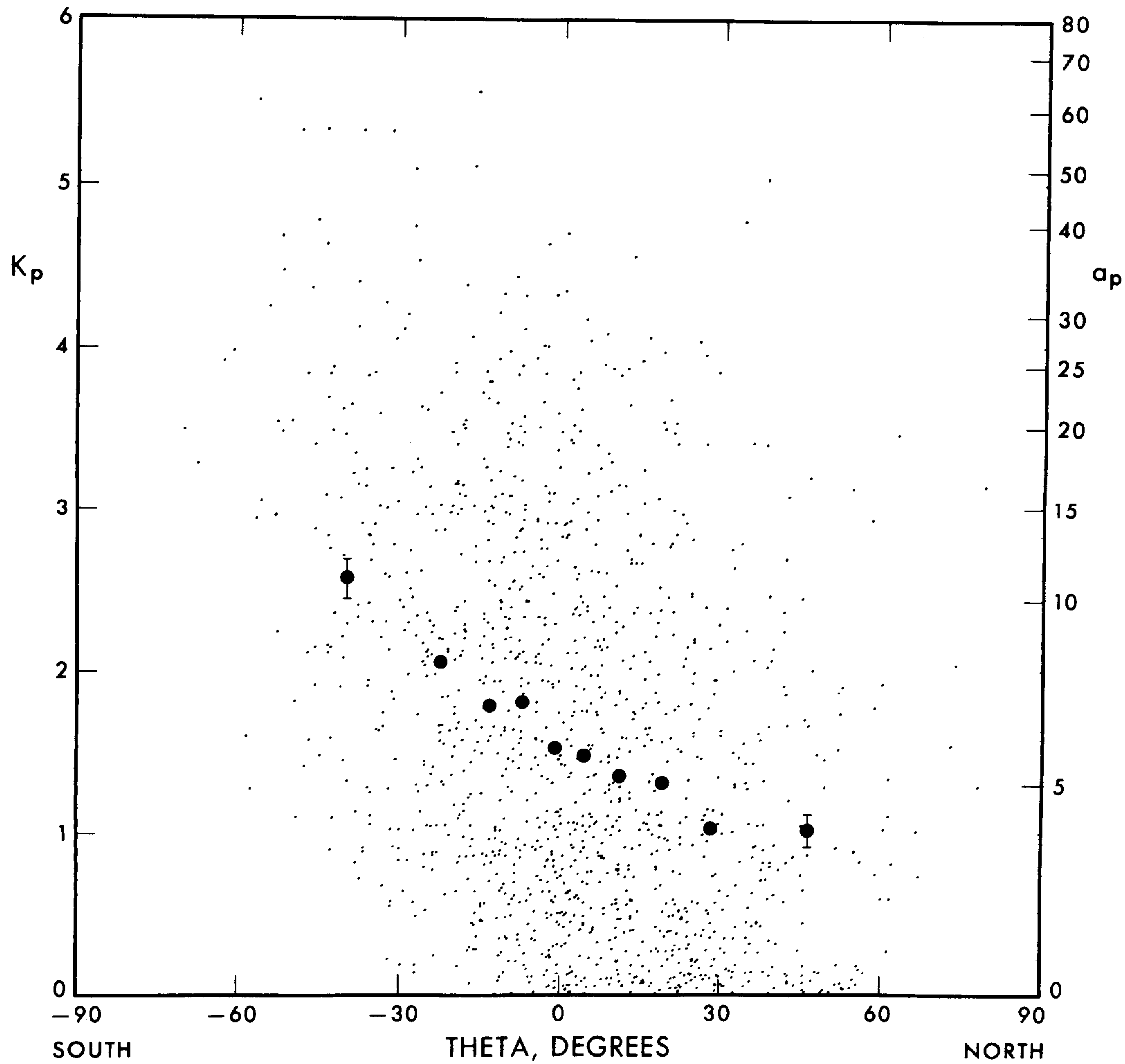

IMP 1
IMP 3
K_p
a_p
0
1
2
3
4
5
0
5
10
15
20
30
40
50
60
0
2
4
6
8
10
12
14
INTERPLANETARY FIELD MAGNITUDE, GAMMAS

Figure 2



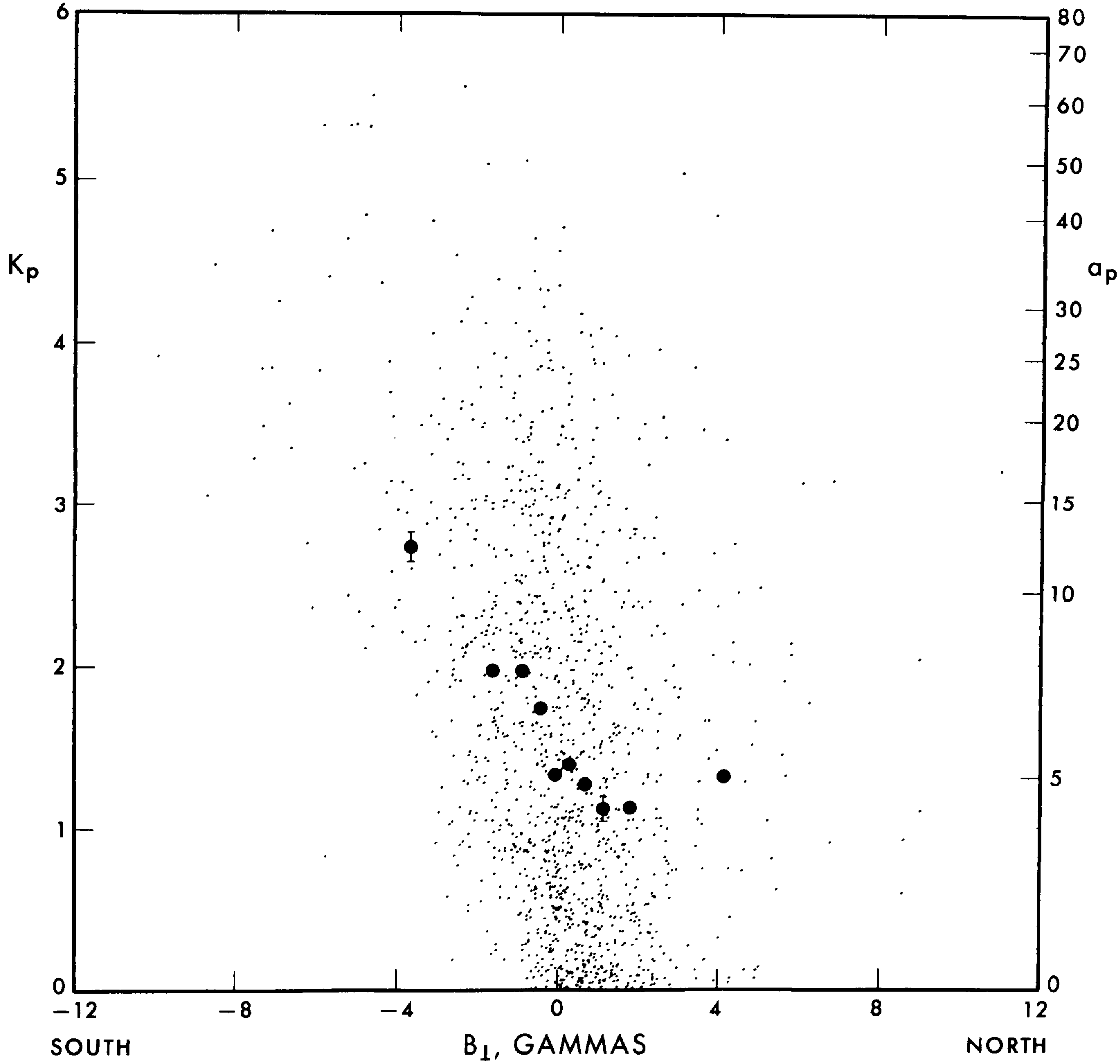
30
25
20
15
10
5
0
a_p
0
2
4
6
8
10
12
INTERPLANETARY FIELD MAGNITUDE, GAMMAS

Figure 3



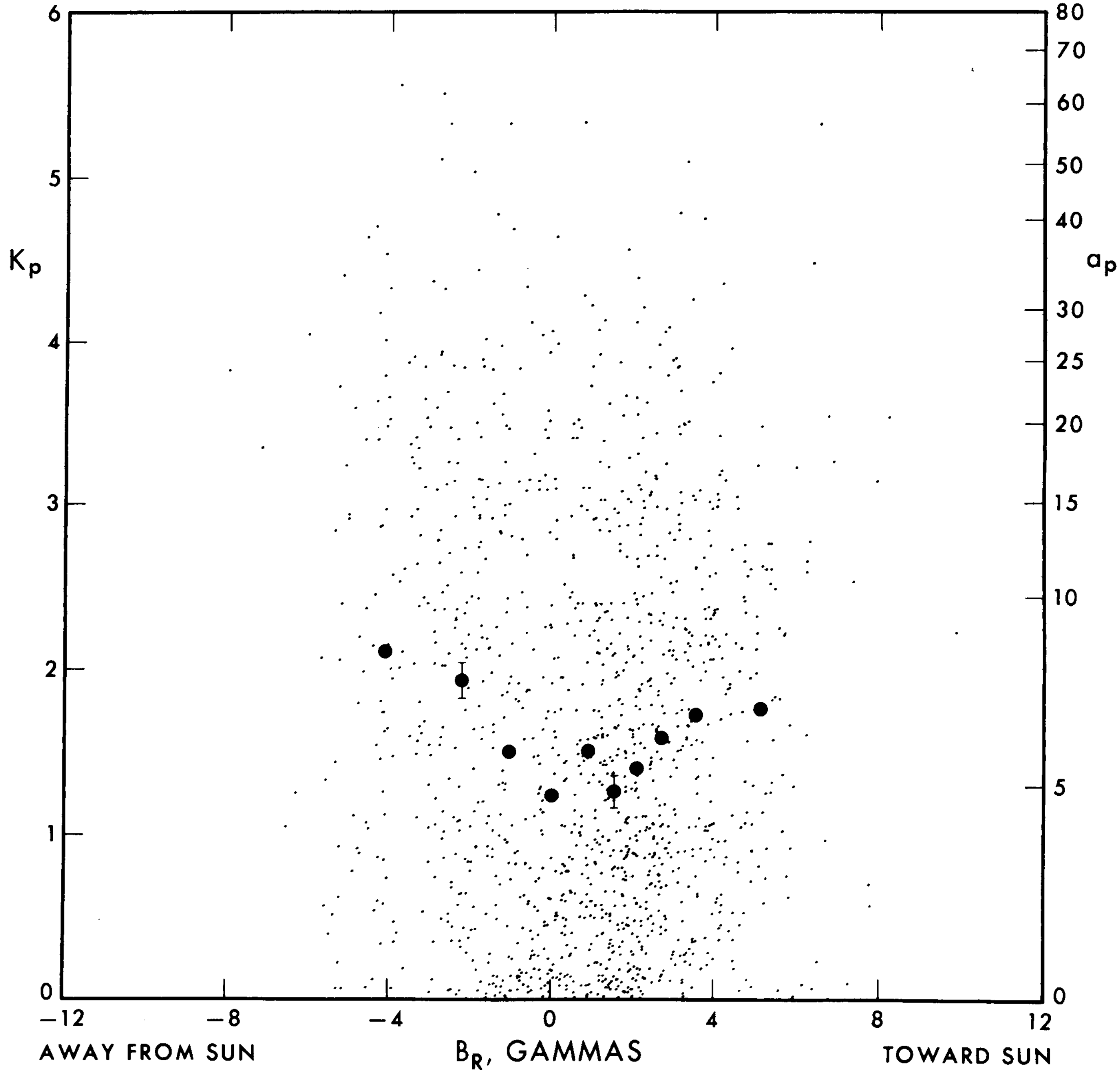
6
5
4
3
2
1
0
K_p
80
70
60
50
40
a_p
30
25
20
15
10
5
0
−90
−60
−30
0
30
60
90
SOUTH
THETA, DEGREES
NORTH

Figure 4



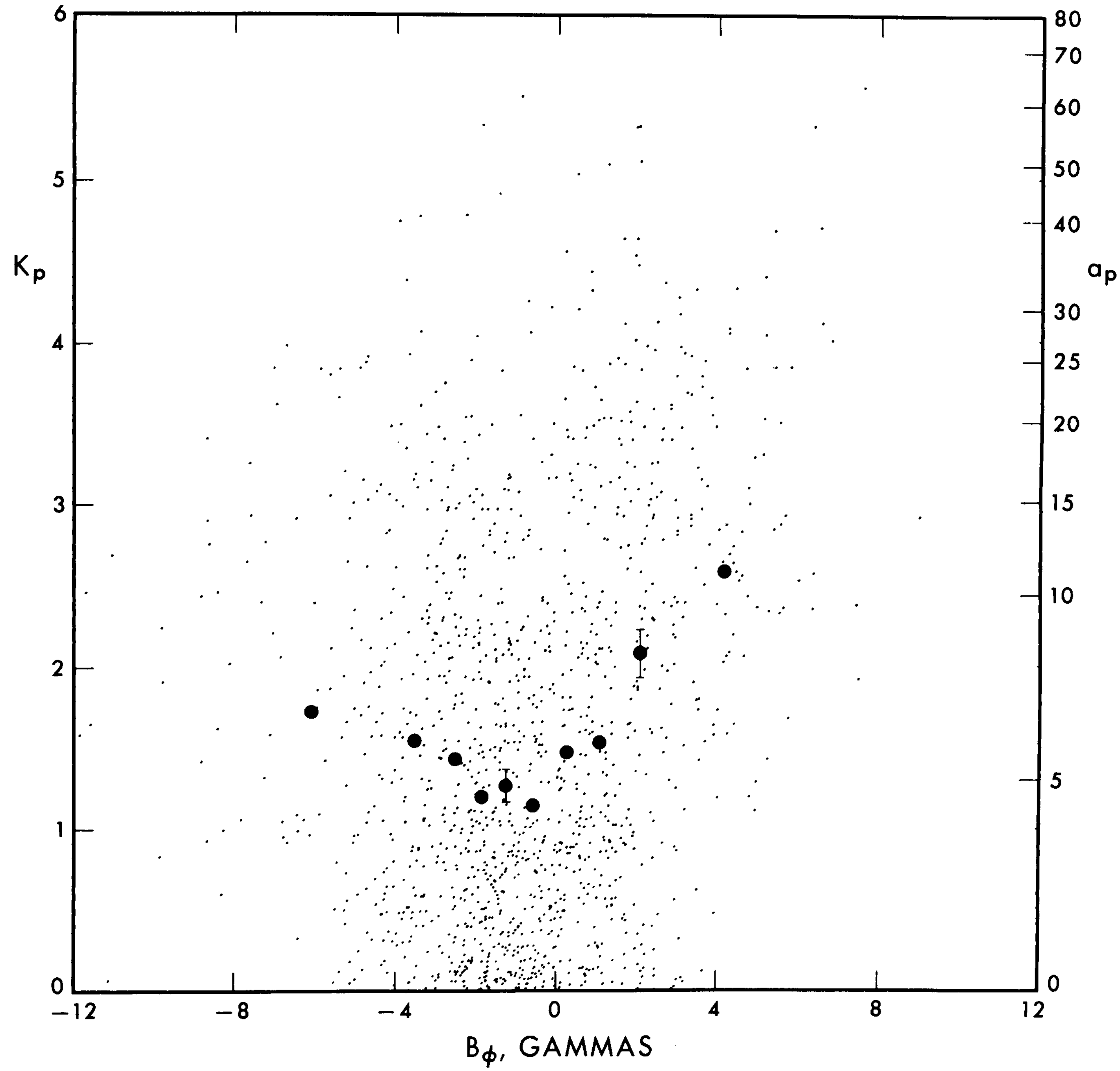
6
5
4
3
2
1
0
K_p
80
70
60
50
40
30
25
20
15
10
5
0
a_p
−12
−8
−4
0
4
8
12
SOUTH
$B_{\perp}$, GAMMAS
NORTH

Figure 5



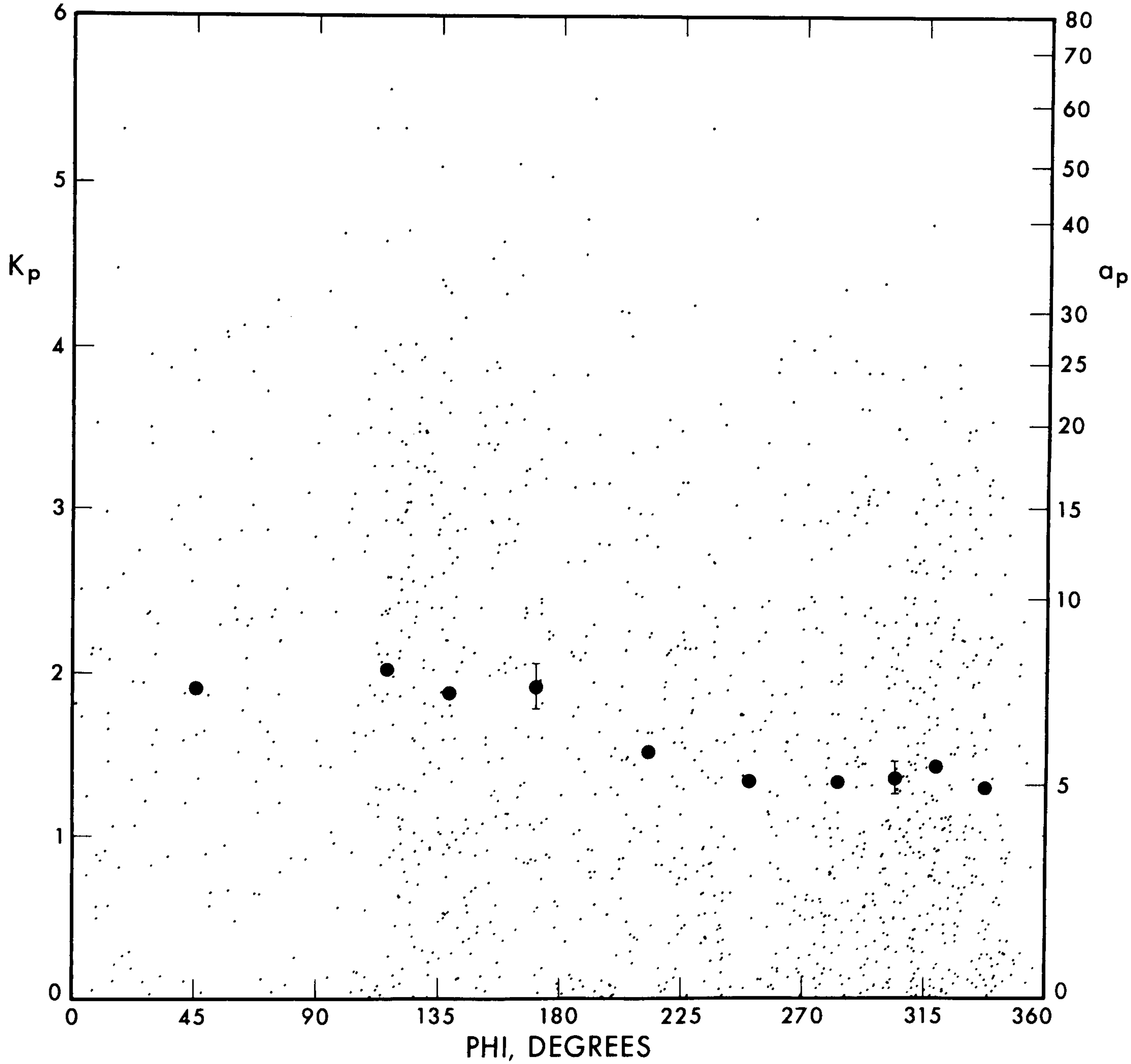
Kp
ap
6
5
4
3
2
1
0
80
70
60
50
40
30
25
20
15
10
5
0
−12
−8
−4
0
4
8
12
AWAY FROM SUN
BR, GAMMAS
TOWARD SUN

Figure 6



6
5
4
3
2
1
0
K_p
80
70
60
50
40
30
25
20
15
10
5
0
a_p
−12
−8
−4
0
4
8
12
B_ϕ, GAMMAS

Figure 7



6
5
4
3
2
1
0
K_p
80
70
60
50
40
30
25
20
15
10
5
0
a_p
0
45
90
135
180
225
270
315
360
PHI, DEGREES

Figure 8

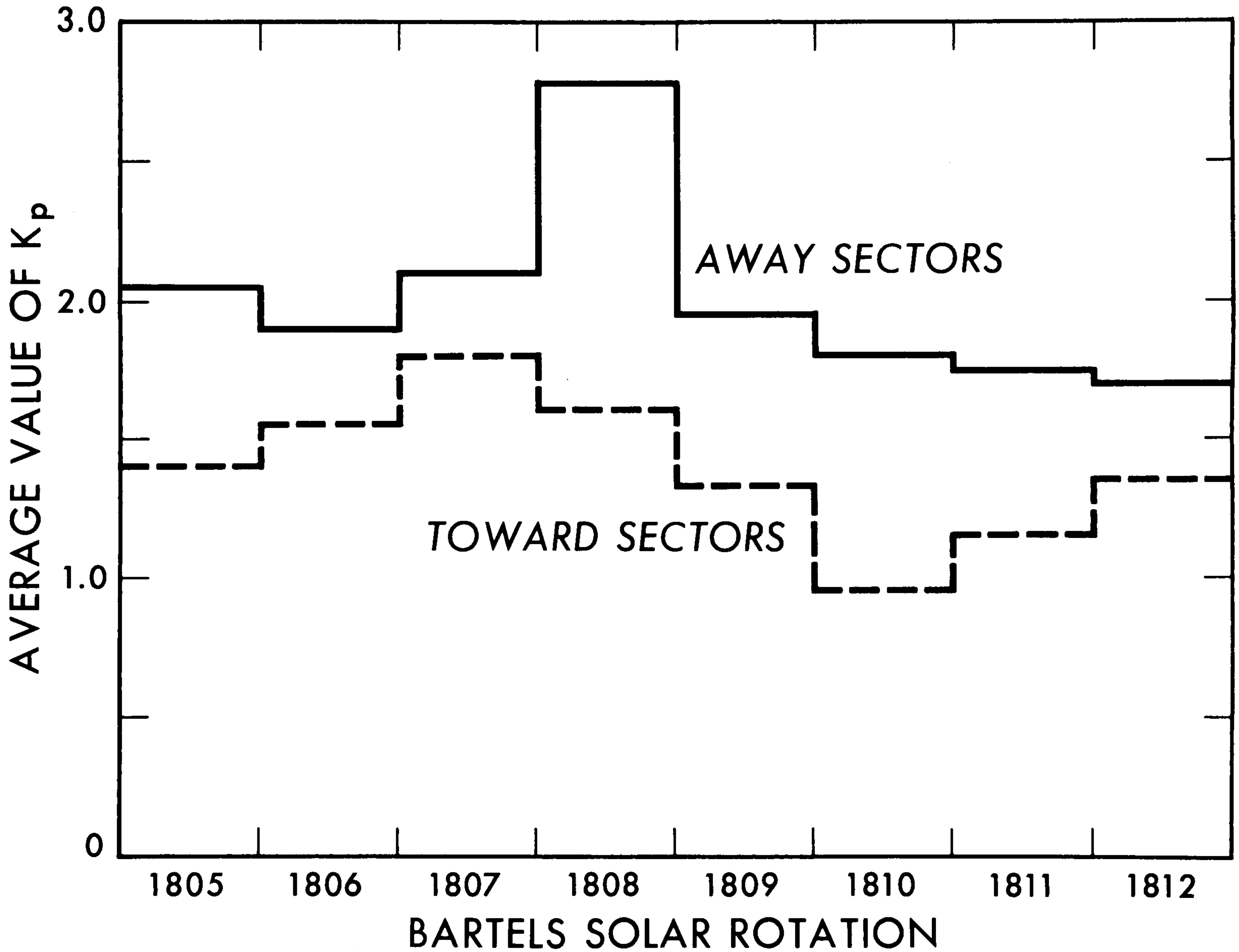
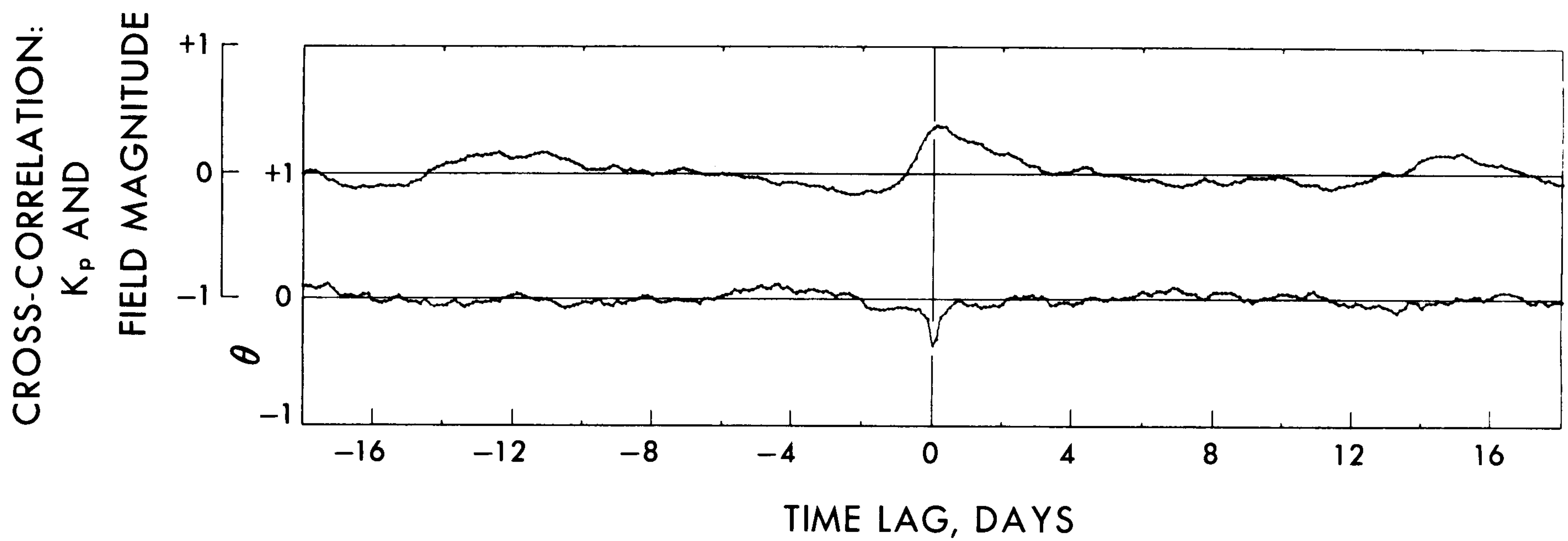

3.0
2.0
1.0
0
AVERAGE VALUE OF K_p
AWAY SECTORS
TOWARD SECTORS
1805
1806
1807
1808
1809
1810
1811
1812
BARTELS SOLAR ROTATION

Figure 9



CROSS-CORRELATION:
K_p AND
FIELD MAGNITUDE
+1
0
−1
+1
0
θ
−1
−16
−12
−8
−4
0
4
8
12
16
TIME LAG, DAYS

Figure 10

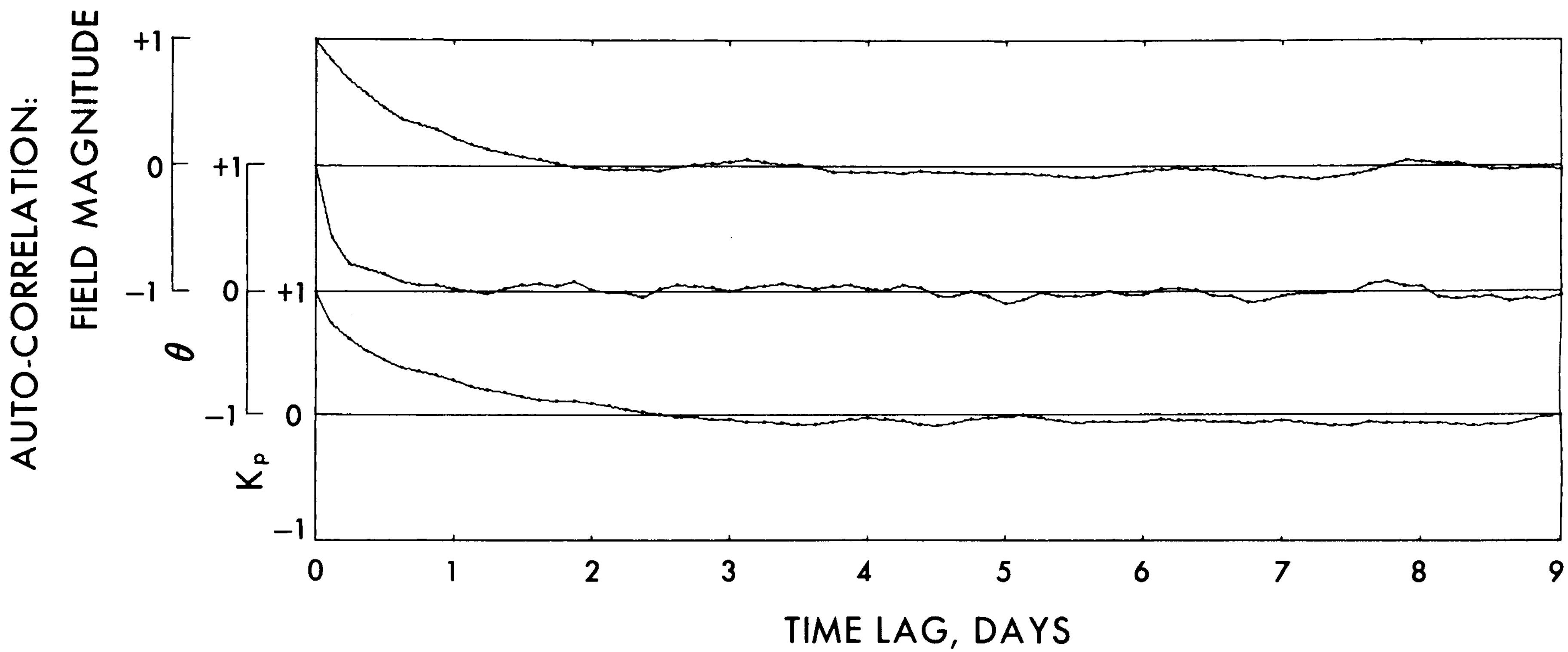

AUTO-CORRELATION:
FIELD MAGNITUDE
θ
K_p
+1
0
-1
TIME LAG, DAYS
0 1 2 3 4 5 6 7 8 9

Figure 11

UNCLASSIFIED
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	ROLE	WT	ROLE	WT	ROLE	WT
Interplanetary magnetic field						
Geomagnetic activity						
Reconnection of magnetic field lines						

13. Abstract--cont'd.

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