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A SURVEY OF LONG-TERM INTERPLANETARY MAGNETIC FIELD VARIATIONS

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MAY 1975

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

A Survey of Long-Term Interplanetary Magnetic Field Variations

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ABSTRACT

Interplanetary magnetic field data from 10 IMP, AIMP, and HEOS spacecraft have been merged into a composite data set spanning 1963-1974. A consideration of the mutual consistency of the individual data sets reveals agreement typically to within 0.2 gamma. Composite data set analysis reveals: (a) whereas the yearly averaged magnitudes of all field vectors show virtually no solar-cycle variation, the yearly averaged magnitudes of positive- and negative-polarity field vectors show separate solar-cycle variations, consistent with variations in the average azimuthal angles of positive- and negative-polarity field vectors; (b) there is no heliolatitude dependence of long-time average field magnitudes; (c) field vectors parallel to the Earth-Sun line are on the average 1 gamma less in magnitude than field vectors perpendicular to this line; and (d) the heliolatitude-dependent dominant polarity effect exhibits a complex sign reversal in the 1968-1971 period and a measure of symmetry in 1972-1974 not found in earlier data.

INTRODUCTION

A composite interplanetary magnetic field (IMF) data set has been generated at the National Space Science Data Center (NSSDC) using hourly averaged IMF parameters from eight IMP/AIMP spacecraft (N. F. Ness and colleagues at GSFC) and from two HEOS spacecraft (. . C. Hedgecock and colleagues at Imperial College, London). The data set contains data for 1215 hours between November 27, 1963, and February 15, 1964, and for 51,714 hours between June 1, 1965, and May 17, 1974. It is the most comprehensive multispacecraft IMF data set yet assembled. The data set is available from NSSDC on magnetic tape and, with fewer parameters, as a data book (*King*, 1975) with both numerical listings and plots. This data set will be updated as additional data become available.

The purpose of this paper is to discuss the mutual consistency of the individual data sets and various topics of interest in the study of interplanetary magnetic fields. These topics include solar-cycle variations, heliolatitude variations, and polarity-dependent asymmetry in average field azimuthal angle. Solar ecliptic coordinates are used throughout.

MUTUAL CONSISTENCY

The mutual consistency of the various data sets contributing to the newly available composite IMF data set has been examined. Two approaches were taken: to consider long-time scale averages (≥ 1 year) from the individual spacecraft and to generate quarter-year averages for pairs of spacecraft, folding into the averages data for only those hours common to the two spacecraft. The results are detailed in *King* (1975).

Briefly, it was found that in quarter-year and longer time scale averages there was agreement to within about 0.2 gamma for most spacecraft in both field magnitude and components, and corresponding agreement to within about 2 degrees in field latitude and longitude angles. However, when hourly differences in a given parameter were taken between two spacecraft and averaged, the rms deviations in these averages turned out to be surprisingly large -- of the order of 0.6 gamma for field magnitudes, 1.2 gammas for field components, and 15 and 25 degrees for field latitude and longitude. A significant portion of this apparent disagreement results from the fact that two spacecraft simultaneously measuring the IMF may be separated by typically 30-40 Earth radii, while the solar wind convects the IMF at about 230 Earth radii per hour. These results are approximately consistent with those of *Mariani et al* (1974), who intercompared for 1965-1969 Ness' IMP 3 and 4 and AIMP 1 and 2 data and a limited amount of HEOS data.

There were two noticeable exceptions to the measures of consistency as just described. First, it was found that IMP 1 and 3 field magnitudes were lower than later values by about 1 gamma. This may be caused by a real temporal variation, different methods of obtaining hourly averaged magnitudes, or some combination of the two. It is probable that most of the effect results from different averaging techniques, as is further discussed in the next section of this paper.

Second, it was found that IMP 1 and AIMP 2 had anomalously low spacecraft-life-averaged B_z values of -1.0 and -0.7 gamma, respectively. These low values are apparently spacecraft and/or sensor effects.

FIELD MAGNITUDE VARIATIONS

Annual mean field-magnitude values are contained in Figure 1 for: all points per year, all negative-polarity points per year, and all positive-polarity points per year. (A field vector has positive polarity if its solar ecliptic azimuthal angle lies between 45 and 225 degrees.) No negative- or positive-polarity averages are shown for 1965 or 1967 since these had the same values for each year. Typical rms standard deviations in the averages are 2 to 3 gammas. Estimated errors of the means are less than 0.1 gamma (obtained by dividing a typical hourly value standard deviation by the square root of number of hourly values in annual average, and then multiplying by 3 to compensate for statistical nonindependence between closely spaced hourly values). Numbers of points in each annual average are also plotted in Figure 1.

To within 0.4 gamma there is constancy of the all-points average during 1963-1965 and again during 1966-1974, with an apparent increase of about 1 gamma from the first to the second period. However, the 1963-1965 values result from IMP 1 and 3 hourly averages (obtained from magnitudes of vectors composed of 5.46-minute averaged Cartesian components) while the 1966-1974 values result from hourly averaged magnitudes obtained from 1- to 30-second magnitudes. Thus, the change from 1965 to 1966 is likely to be mainly the result of using two methods of data handling that are compatible only in the absence of field direction fluctuations with periods between a few seconds and a few minutes. See *Russell* (1972) for a discussion of the power in field fluctuations at these and longer periods. This conclusion is supported by the fact that the 1973 and 1974 data taken at approximately the same solar-cycle phase as the 1963-1965 data (i.e., near solar minimum) do not resemble the 1963-1965 data.

During 1966-1974, there are irregular variations in the all-points averages within the range 6.0 to 6.4 gammas. Although this variation lies outside the statistically estimated errors of the annual means, its significance is not clear. Indeed, much of the variation may be explained in terms of the 0.2-gamma level of mutual consistency of the individual data sets.

Except for 1964, which has fewer hourly values (583) than any other year, there is a tendency for negative-polarity annual magnitude averages to exceed positive-polarity averages through the first half of the solar cycle, with the reverse being true for the second half of the solar cycle. This surprising result will be subsequently discussed in connection with asymmetries in field azimuthal angles for negative- and positive-polarity fields.

Except for the apparent mid-solar-cycle reversal of negative- and positive-polarity fields as having larger average field magnitudes, the data are consistent with there being no significant solar-cycle variation in annual averaged magnitudes. To examine whether there may have been a significant solar-cycle variation in the distribution of field magnitudes, we have separately considered the solar-active period 1967-1969, the transition period 1970-1971, and the solar-quiet period 1972-1974.

For each period we have computed means and standard deviations, modal and median values, and histograms of the distributions. The results are given in Table 1 and Figures 2 and 3. Figure 3 is a finer scale histogram of the 4- to 7-gamma portion of the histogram of Figure 2. Note the bimodal character of the 1970-1971 data in Figure 3. The lower amplitude peak in the 1970-1971 data lies in the same gamma range as the single modes of the data for the other two epochs.

Table 1 shows no significant variation with solar-cycle phase of the mean field magnitudes, a barely significant variation of the median, and an apparently significant variation in the mode. Apparently, field magnitudes are somewhat more likely to be low during the transition interval 1970-1971 than during either the preceding more active period or the following more quiet period. Figure 3 suggests that field magnitudes are more likely to be larger during quiet times than active times. From Figure 2, it appears that there are fewer large field values (> 15 gammas) during the active period 1967-1969 than during the following periods.

TABLE 1: Statistical Characteristics of IMF Magnitudes

Years	Mean	Std Dev	Median	Mode	No. of Points
67-69	6.22	2.76	5.7	5.1	20,915
70-71	6.17	3.04	5.4	4.5	10,288
72-74	6.22	2.89	5.6	5.5	13,596

Heliolatitude dependence of field magnitudes has been sought by separating all available 1967-1974 data into two bins of equal duration: one consisting of periods when the Earth and its orbiting spacecraft were within about 5 degrees of the solar equatorial plane, and the other for heliolatitudes having absolute magnitudes between 5 and 7.25 degrees. Approximately 20,000 hourly values fell into each bin. The long-time averages for the equatorial and off-equatorial data were 6.24 and 6.23 gammas, consistent with no heliolatitude dependence.

As a final point related to field magnitudes, we have asked whether field vectors lying normal to a radius vector from the Sun are likely to have larger magnitudes than field vectors lying parallel to a radius vector. We have identified four field-vector-azimuth bins of 20-degrees width each, centered at 0 (toward the Sun), 90, 180, and 270 degrees, and we have averaged the magnitudes of the approximately 2000 1967-1974 vectors falling into each of these bins. The computed averages are 5.56, 6.49, 5.61, and 6.53 gammas for the 0-, 90-, 180-, and 270-degree bins, respectively. We conclude that magnetic fields normal to a solar radius are likely to be larger than fields parallel to a solar radius by an average of about 1 gamma.

DOMINANT POLARITY EFFECT

Over individual solar rotations the percent of interplanetary field vectors which have negative (or positive) polarity depends on the heliographic latitude (heliolatitude) of observation. This was first pointed out by *Rosenberg and Coleman* (1969) and confirmed by *Wilcox and Scherrer* (1972).

Their analyses have most recently been extended by *Fairfield and Ness* (1974) and by *Rosenberg* (1975).

We have extended these analyses through May 1974 by using the composite IMP/AIMP/HEOS data set. Figure 4 contains the number of hours of negative polarity observed over individual 27-day solar rotations. Also shown in Figure 4 is the heliolatitude of the Earth and of all the relevent spacecraft; note a total excursion of 14.5 degrees. From this now-standard plot format, it may be seen that there is a strong correlation between the heliolatitude of observation and the relative excess of negative-polarity vectors through 1967, and a weakening and virtual disappearance of this correlation in 1968 and 1969. In late 1970 an anticorrelation between the heliolatitude of observation and the relative excess of negative polarity sets in and persists through the end of the data stream in 1974.

As another way of demonstrating this effect, we have considered four successive 2- or 3-year intervals at differing solar-cycle phases. For each such interval we have considered each of four subintervals of equal durations during which the Earth was at its most southerly heliolatitudes (Jan 20-April 20), passing from south to north, most northerly heliolatitudes (July 20-Oct 20), and passing from north to south. Then for each subinterval, we determined the percentage of all observed field vectors falling in 0- to 90-, 90- to 180-, 180- to 270-, and 270- to 360-degree bins. Recall that the expected average positive-polarity vector lies near the middle of the 90- to 180-degree bin.

The percentages determined are given in the histograms of Figure 5, along with the number of hours of observations of each temporal subinterval. Figure 5 shows that early in the solar cycle (1965-1967) at both northerly and equatorial latitudes, positive polarity is dominant. Negative-polarity dominance at northerly latitudes is greater than positive-polarity dominance at southerly latitudes. During the solar-maximum period 1968-1969 negative polarity is dominant at all latitudes. In the next 2-year interval (1970-1971), positive-polarity dominance was reasserted in southerly latitudes. Neither polarity was dominant at northerly latitudes, but, anomalously, negative polarity was dominant during the quarters of passage of the Earth from negative to positive latitude. In the solar-minimum period 1972-1974 the dominant-polarity effect has clearly reversed from its pre-solar-maximum pattern. Also a measure of symmetry, not previously observed, was established. Negative-polarity dominance at southerly heliolatitudes and positive-polarity dominance at northerly heliolatitudes are of the same extent, while at equatorial latitudes neither polarity is dominant.

Rosenberg and Coleman (1969) noted that the dominant IMF polarity observed in the early portion of the solar cycle was the same as that of the solar-polar fields in the same hemisphere. They suggested that the IMF is an extension of the dipolar component of the Sun's field. That solar-maximum data indicated an excess of negative IMF polarity (characteristic of the northern solar pole up to the solar-maximum period) at all heliolatitudes of observation was interpreted as being caused by the more active nature of the northern solar hemisphere at that time, resulting in greater pressures in the north. This pressure in turn pushed the solar wind and its imbedded magnetic field originating in the northern solar hemisphere to points south of the solar equatorial plane (*Rosenberg*, 1970). The correlation between observation heliolatitude and excess of negative polarity reversed near solar maximum, and this reversal was interpreted in terms of the anticipated reversal of solar-polar fields.

Howard (1974a) has recently plotted mean solar fields during 1967-1973 in four latitude bands for each solar hemisphere (< 40, 40-50, 50-60, > 60 degrees). The most obvious aspect of these plots is the great variability in the solar fields. Except for the most northerly interval for 1972 and 1973, each heliolatitude band experiences some positive and some negative polarity for each year between 1967 and 1973. However, a study of the dominant polarity in each heliolatitude band led Howard to assert that the northern polar region became dominantly positive about August 1971 after about 4 years of weak variable fields, and that the southern polar field became dominantly negative in June or July 1969. The dominance of negative polarity in the south since mid-1969 has been less strong than the dominance of positive polarity in the north since August 1971. In both hemispheres the polar sign reversal started in the 40- to 50-degree zone and took about 1 year to reach the zone poleward of 60 degrees.

Thus, the reversal of the IMF dominant polarity effect is consistent with the reversal of the dominant polarity in the solar-polar regions. However, because of the complexity and variability of the solar-magnetic data, the attribution of asymmetries and other anomalies in the IMF data to interplanetary processes rather than to solar-source effects is premature.

FIELD AZIMUTH ASYMMETRY

Svalgaard and Wilcox (1974; denoted SW in the following) found that there exists a positive polarity - negative polarity asymmetry in the azimuth of the interplanetary magnetic field. Using data from five of the 10 spacecraft utilized in this report, plus Pioneer 9 data, SW generated field component averages of all positive-polarity field vectors per year and separately of all negative-polarity vectors. From these component averages they computed the included angles δ, the angles α_N and α_P, and the angle α defined as the average of α_N and α_P. See Figure 6 for definitions of these angles.

The angle δ is expected to be 180 degrees based on Parker's solar-wind theory and all refinements thereof. However, this angle was shown by SW to vary, decreasing monotonically from about 183 to 168 degrees between 1965 and 1968, and then increasing monotonically to a 1973 value of 187 degrees.

In the simple solar-wind theory, the spiral angle of the IMF is related to the solar-wind speed V according to tan $\alpha = \Omega R/V$. Here Ω is the solar-rotation frequency, and R is the heliocentric distance of observation. Thus the angle α is expected to be 40, 45, and 50 degrees for solar-wind velocities of 476, 400, and 335 km/sec, respectively. It was shown by SW that α varied in a quasi-random fashion in 44 to 49 degrees during 1965-1973.

We have repeated the SW analysis with the newly available composite IMF data set except that we have taken yearly averages of hourly azimuthal angles. We have used the numbers of hours indicated in Figure 1. The results are given in Figures 7 and 8, which show our values and the SW values for α and δ. (The two SW values of α for 1967 result from their separate treatment of Explorer 33 and 35 data.) Using the preceding simple relation between α and V, we have computed α values from the V values given by *Diodato et al* (1974) and have plotted these inferred α's in Figure 7.

Generally, our results confirm the earlier SW results. Some of the detailed differences between our points and the SW points result from the different averaging sequences used. Our values of α show a slightly greater spread than do the SW values, with a maximum of 46.5 degrees for 1969 and 1970, and a statistically significant, anomalously low minimum of 39.2 degrees for 1973. Our data also show a more uniform variation of α over the solar cycle than do the SW data. Both our data and the SW data are consistent with slightly lower solar-wind velocities near solar maximum and higher velocities near solar minimum, a trend not present in the velocity data. This lack of a simple relation between α and V was also pointed out by *Ness et al* (1971).

Our data show a smaller variation for the angle δ than do the SW data if our 1963 and 1964 values are disregarded because of relatively poor statistics. Note that the minimum in our δ values occurs in 1967, 1 year before the minimum in the SW δ values and 2 years before the minimum in our α values.

SW considered various interplanetary mechanisms to explain the variation in δ, but they rejected these mechanisms as being incapable of explaining the effect. One of the mechanisms considered was that the solar-wind speed may be statistically correlated with the IMF polarity. It is interesting to note that this same mechanism may also explain the previously discussed polarity dependence of field magnitude annual averages. If early in the solar cycle negative-polarity fields were associated with lower solar-wind speeds than were positive-polarity fields, with the reverse true after solar maximum, then the different extents of the winding up of spiral field lines could explain the behavior of both field magnitudes and directions. Note that since $B \cos \alpha = constant$ must be satisfied by equatorial variations in magnitudes and angles resulting from solar wind-speed variations, a 0.1-gamma difference between negative- and positive-polarity annual-averaged field magnitudes is predicted for each 1-degree difference between negative- and positive-polarity, annual-averaged α values. Because the relation between the observed magnitude and angle polarity-dependent variations is in order-of-magnitude agreement with $B \cos \alpha = constant$, further study along this line is warranted despite some detailed differences in the magnitude and angle effects (e.g., nonsimultaneous mid-solar-cycle reversals). A study of the long-term correlation between IMF polarity and solar-wind speed will be undertaken. (In the SW paper, the hypothesis of a correlation between IMF polarity and solar-wind speed was rejected on the basis of 1 year of solar-wind data - July 1967 to July 1968 - which implied a δ value of about 179 degrees. Note that the difference between this value and the SW δ values for 1967 and 1968 is significantly greater than the difference between 179 degrees and the 1967 and 1968 δ values of the present analysis.)

Howard (1974b) has suggested that the asymmetry in average azimuthal angles may result from a source effect, namely differing degrees of inclination of in- and out-field lines relative to local vertical at the solar surface.

SUMMARY

We have discussed a newly created composite interplanetary magnetic field data set, the mutual consistency of the 10 individual data sets contributing to the composite data set, and some of the physically interesting information found in the data. Some of the new results include: (1) a tendency for annual averages of negative-polarity field magnitudes to exceed positive-polarity field magnitudes for the first half of the solar cycle, with a reversal of this effect at solar maximum (this effect is consistent with asymmetries in field azimuths); (2) the lack of heliolatitude dependence of long-time averaged field magnitudes; (3) fields lying normal to the Earth-Sun line having magnitudes 1 gamma larger, on the average, than fields parallel to the Earth-Sun line; and (4) a much greater measure of symmetry in the heliolatitude-dependent, dominant-polarity effect for 1972-1974 than had been observed at any earlier time in solar-cycle 20. Members of the scientific community are invited to obtain copies of the composite IMF tape by request to the National Space Science Data Center.

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Figure 1

Annual-averaged IMF magnitudes for all data in year (the dots), for positive-polarity data (the P's), for negative-polarity data (the N's); and numbers of hours contributing to each average.

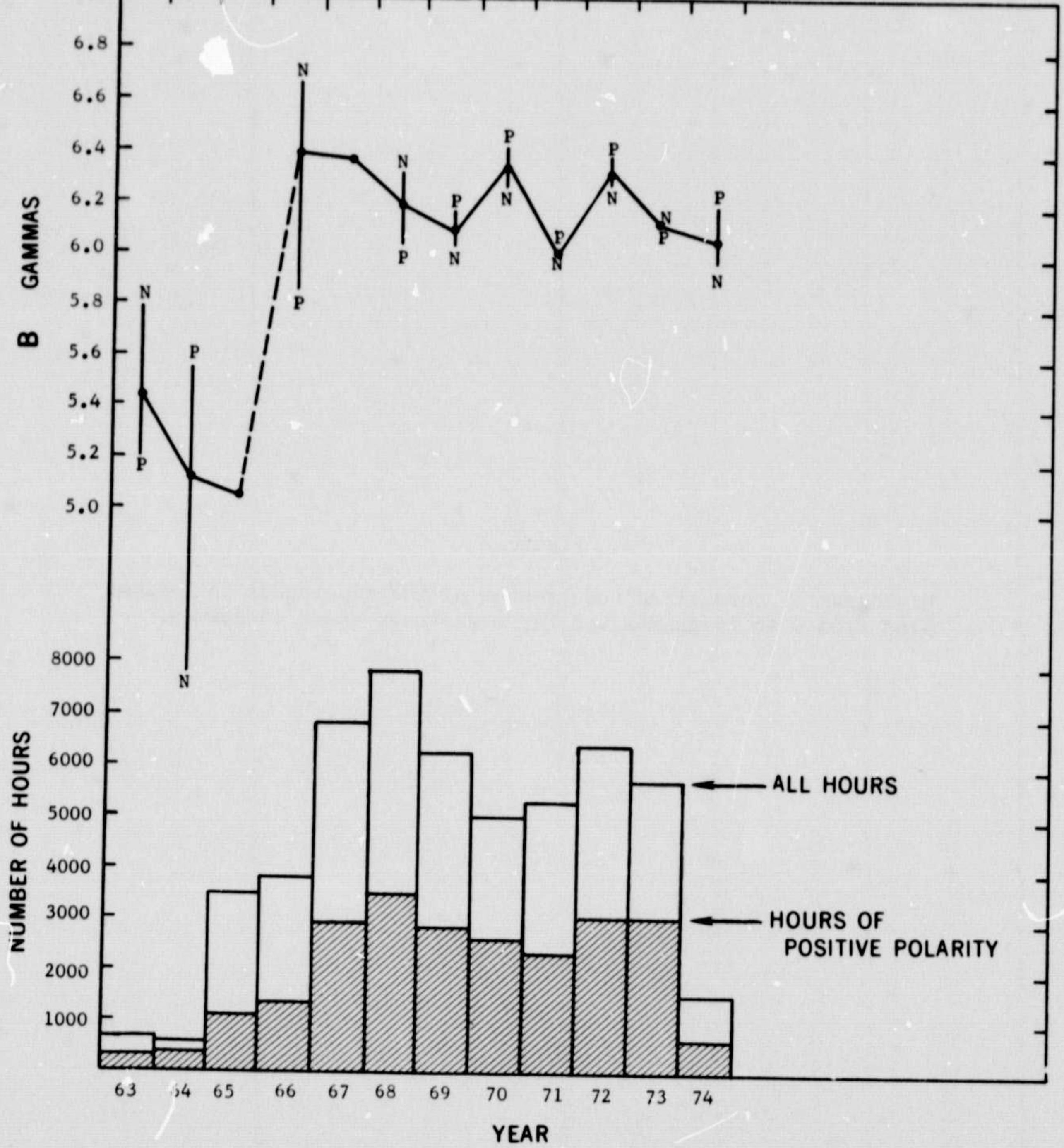
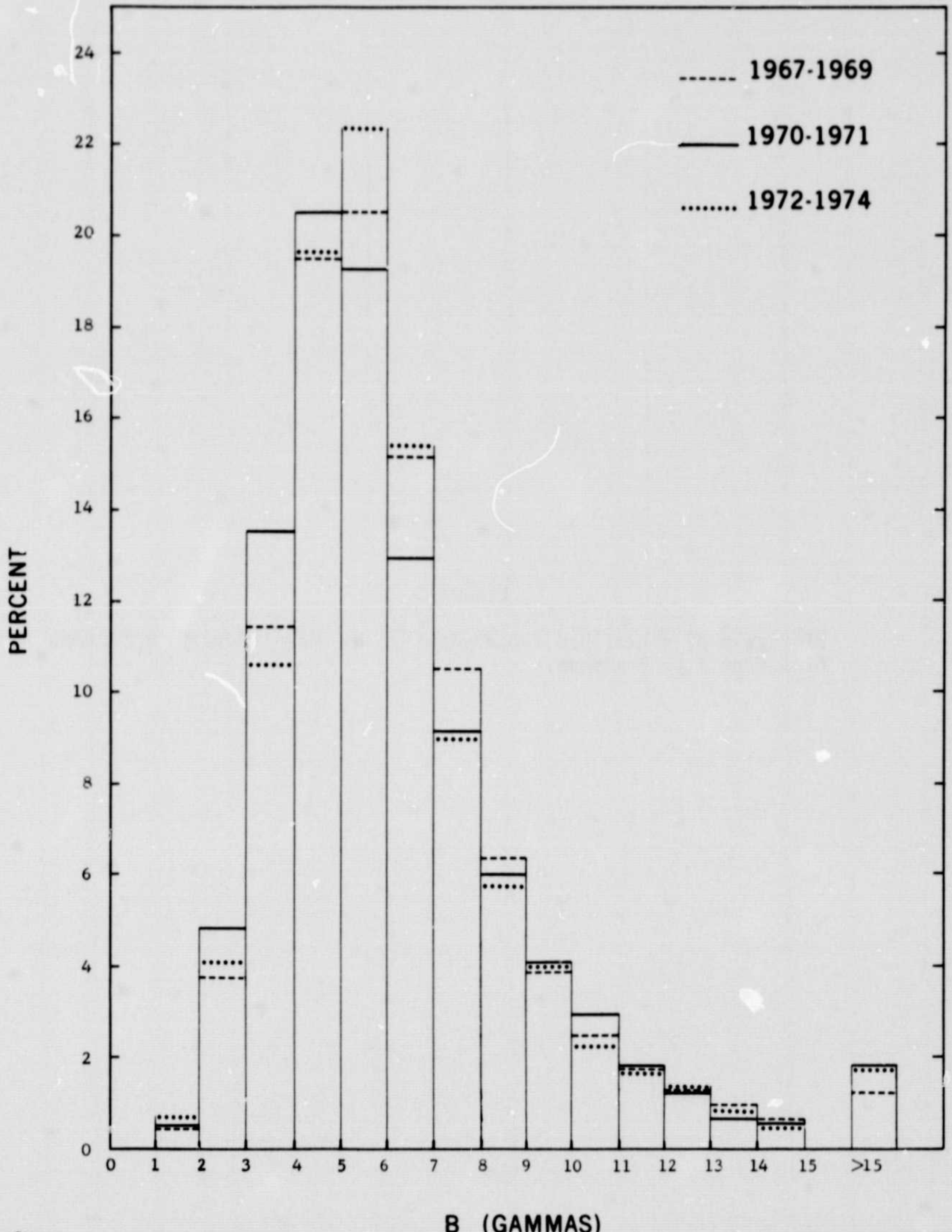

B GAMMAS
7.0
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
NUMBER OF HOURS
8000
7000
6000
5000
4000
3000
2000
1000
ALL HOURS
HOURS OF POSITIVE POLARITY
63 64 65 66 67 68 69 70 71 72 73 74
YEAR

Figure 2

Histogram of normalized occurrences of IMF magnitudes in 1-gamma bins from 0 to 15 gammas and for magnitudes above 15 gammas.



1967-1969
1970-1971
1972-1974
PERCENT
0
2
4
6
8
10
12
14
16
18
20
22
24
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
>15
B (GAMMAS)

Figure 3

Histogram of normalized occurrences of IMF magnitudes in 0.2-gamma bins from 4 to 7 gammas.

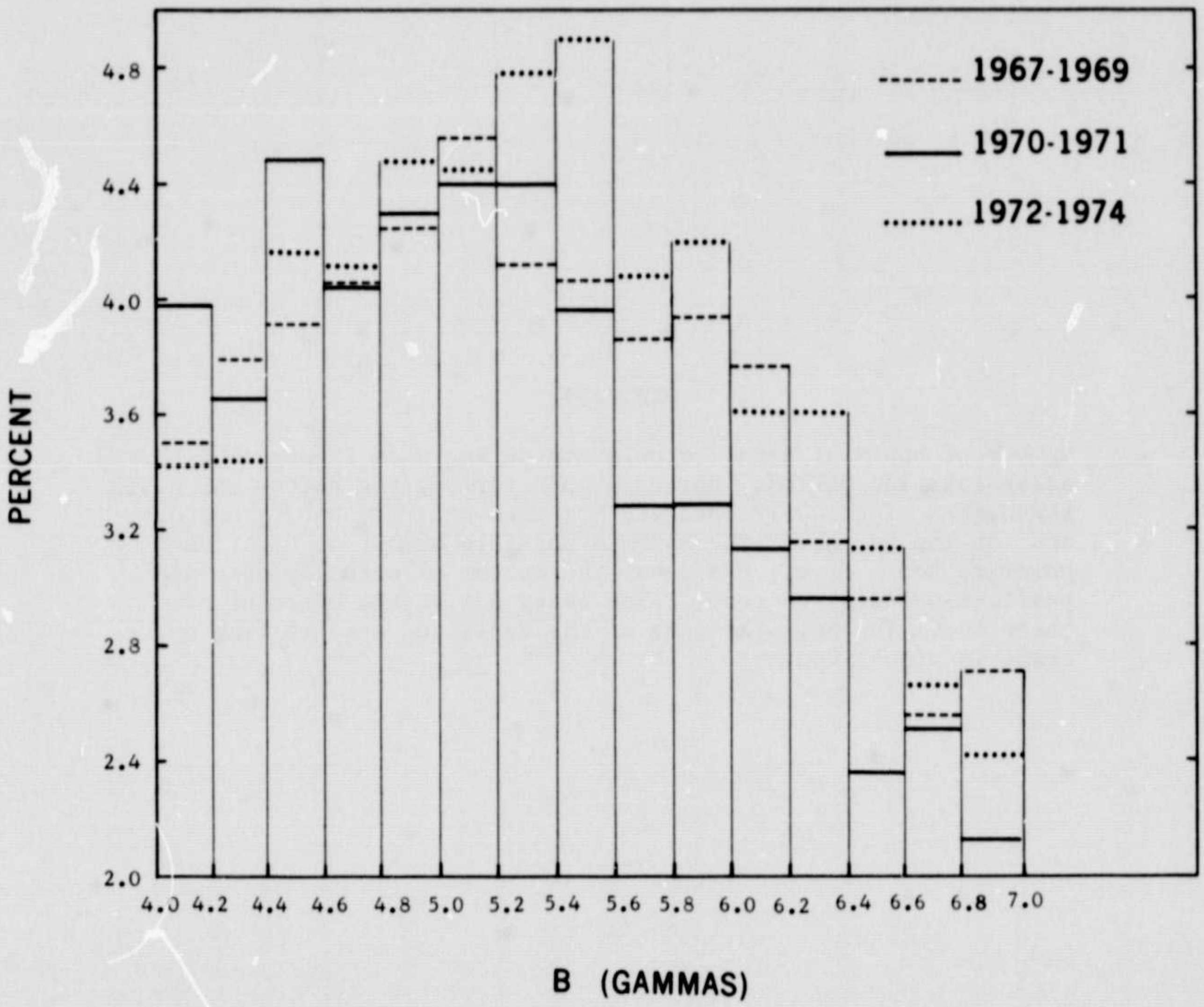

1967-1969
1970-1971
1972-1974
PERCENT
4.8
4.4
4.0
3.6
3.2
2.8
2.4
2.0
4.0 4.2 4.4 4.6 4.8 5.0 5.2 5.4 5.6 5.8 6.0 6.2 6.4 6.6 6.8 7.0
B (GAMMAS)

Figure 4

Number of hours of negative polarity during each 27-day (648 hours) solar rotation period. For each such period, the bottom bar gives the number of actually observed negative-polarity hourly vectors, and the top bar gives the maximum possible number of negative-polarity hours (i.e., 648 minus the number of actually observed positive-polarity vectors). The heavy dot is the midpoint of these two. The heliolatitude of the Earth and its orbiting spacecraft is also given.

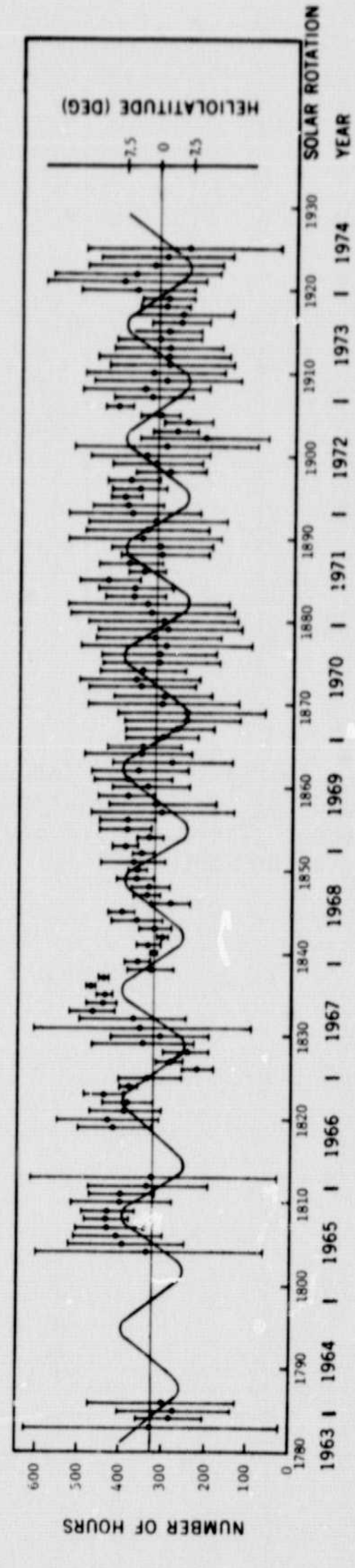

NUMBER OF HOURS
600
500
400
300
200
100
0
HELIOLATITUDE (DEG)
-2.5
0
2.5
SOLAR ROTATION
1780
1790
1800
1810
1820
1830
1840
1850
1860
1870
1880
1890
1900
1910
1920
1930
YEAR
1963
1964
1965
1966
1967
1968
1969
1970
1971
1972
1973
1974

Figure 5

Distribution of field azimuthal angles, for four solar-cycle phases (indicated on right) and for four heliolatitude ranges of observation (indicated on top). The number of hours with data for each histogram is given above the histogram.

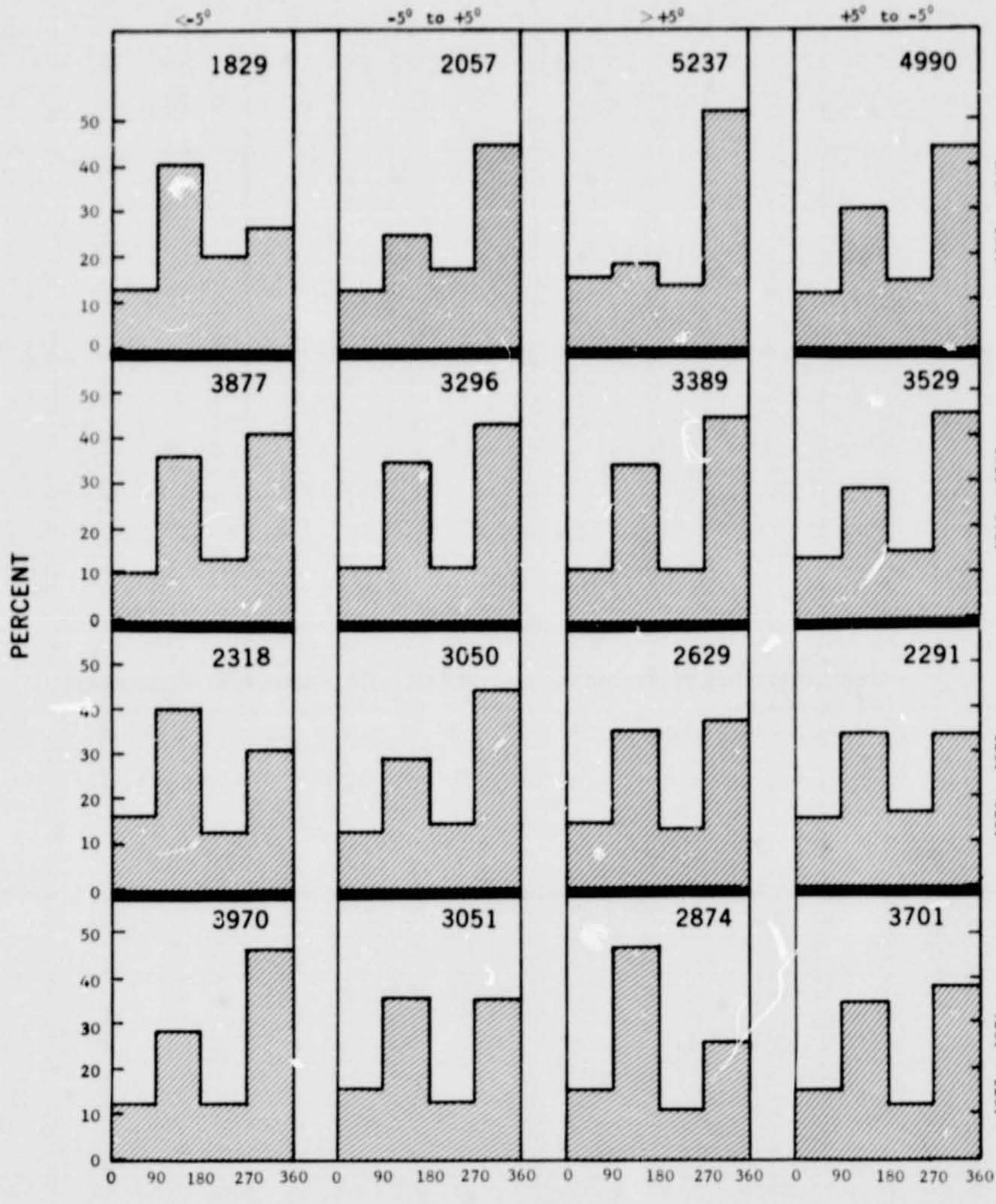


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Figure 6

Identification of angles α_N, α_p, and δ. The angle α is the average of α_N and α_p.

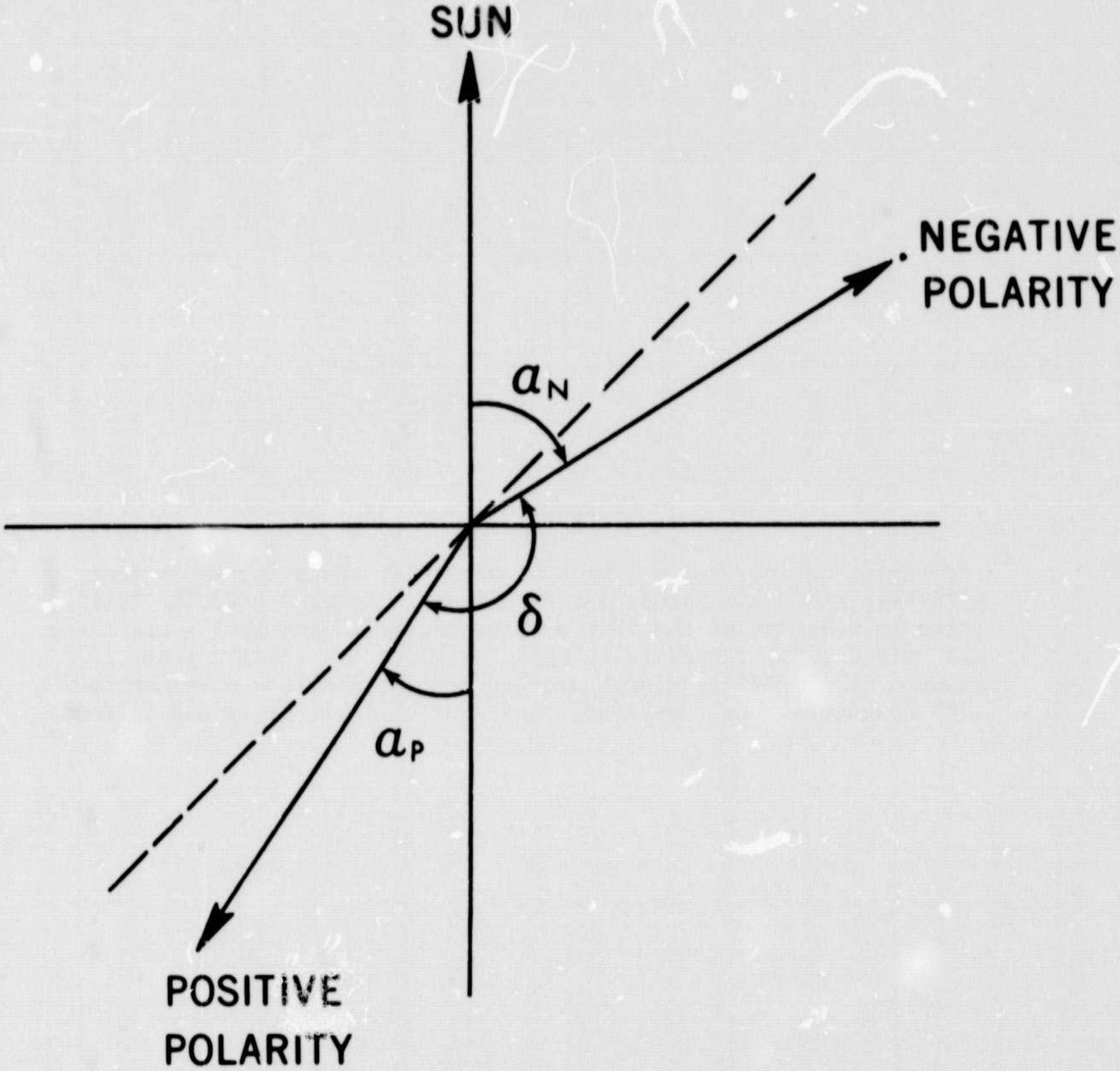

SUN
NEGATIVE POLARITY
a_N
δ
a_P
POSITIVE POLARITY

Figure 7

The angles α_N, α_P, and α from this analysis, the Svalgaard/Wilcox α values, and the α values inferred from solar-wind velocity data. There is only one of the last α values for 1970 and 1971 since there was only one solar-wind velocity value given for these 2 years in *Diodato et al* (1974). There are two Svalgaard/Wilcox α values for 1967 because of their separate treatment of Explorer 33 and 35 data.

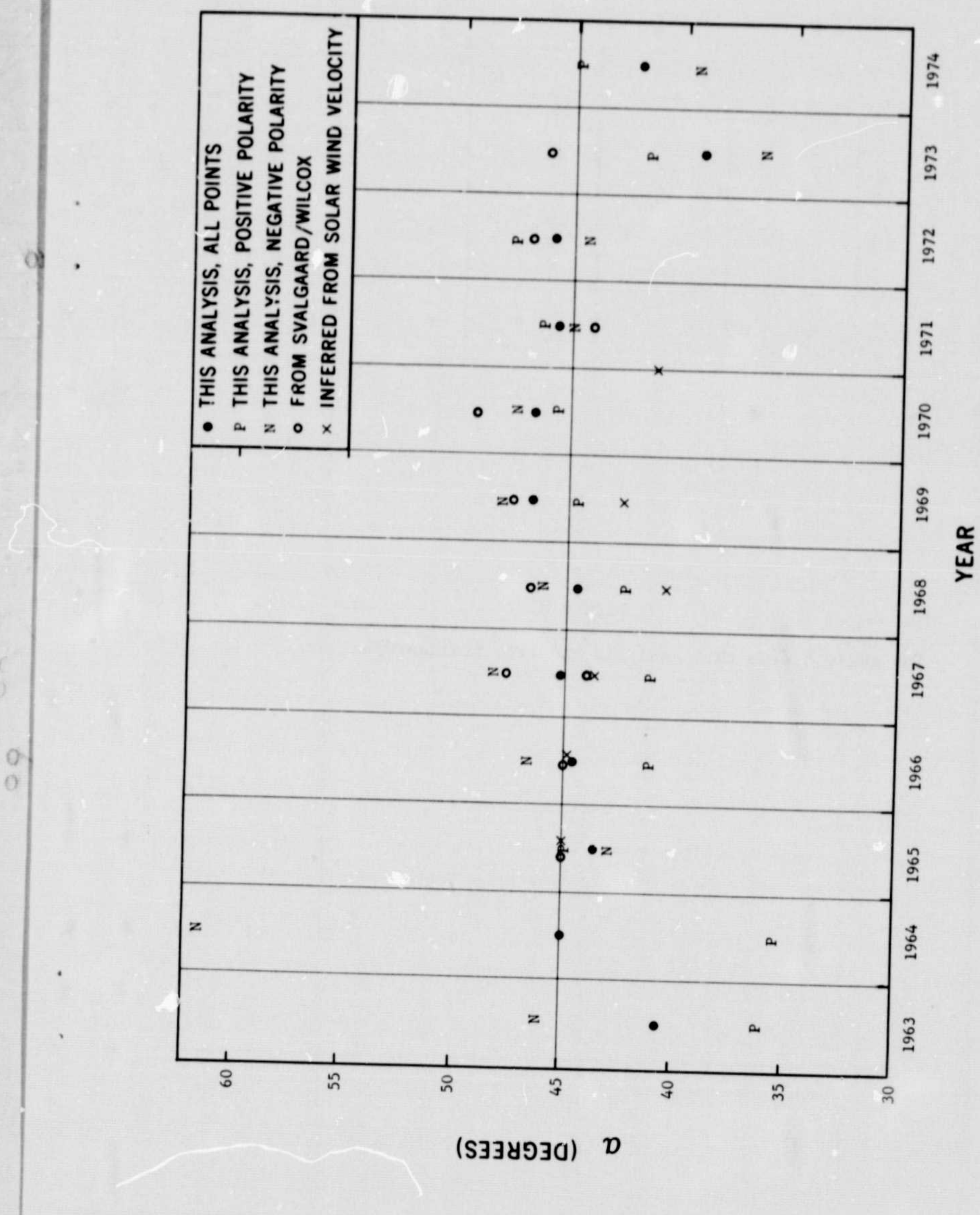
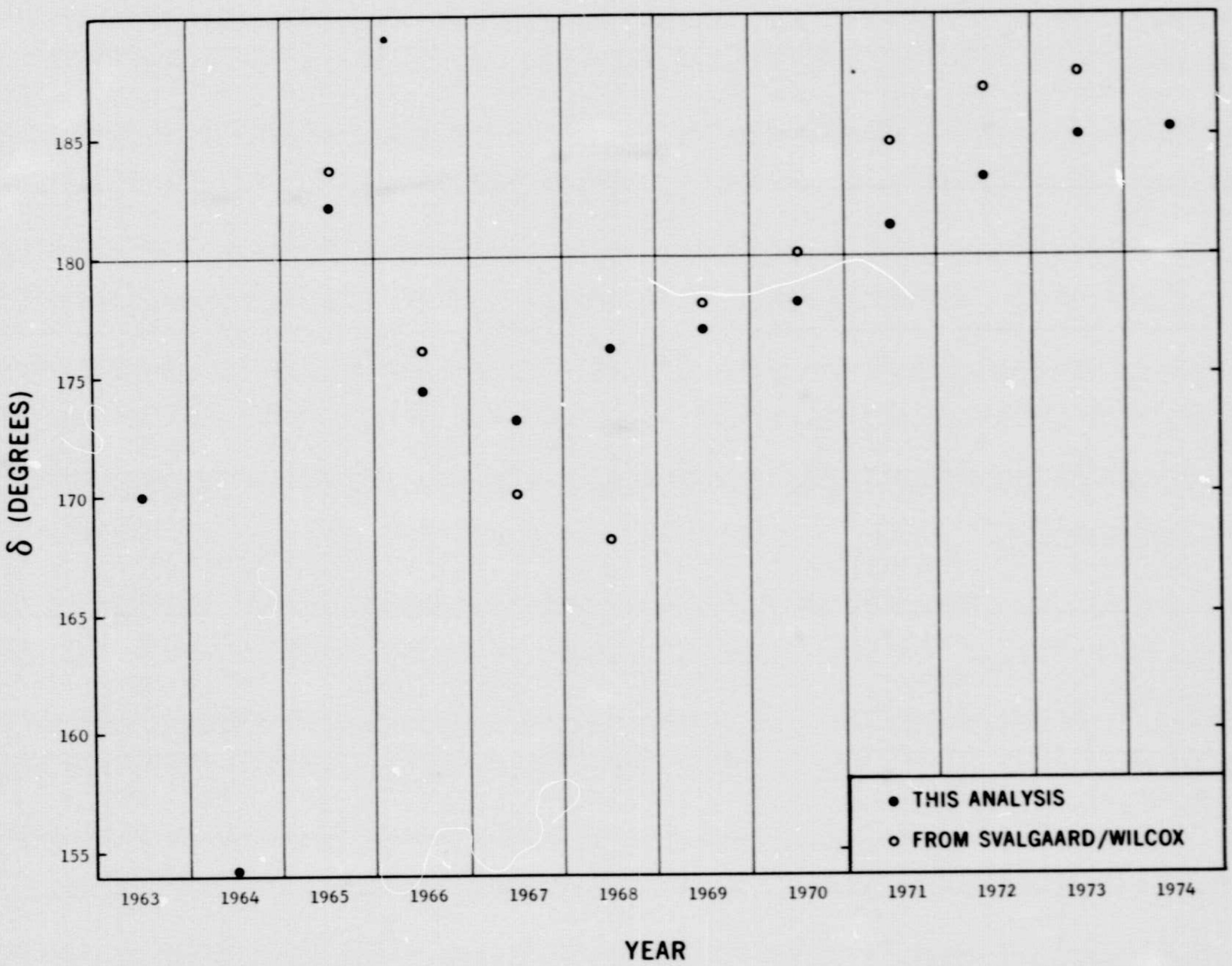

● THIS ANALYSIS, ALL POINTS
P THIS ANALYSIS, POSITIVE POLARITY
N THIS ANALYSIS, NEGATIVE POLARITY
o FROM SVALGAARD/WILCOX
× INFERRED FROM SOLAR WIND VELOCITY
α (DEGREES)
30
35
40
45
50
55
60
YEAR
1963
1964
1965
1966
1967
1968
1969
1970
1971
1972
1973
1974

Figure 8

The angle δ from this analysis and from Svalgaard/Wilcox.



δ (DEGREES)
185
180
175
170
165
160
155
1963
1964
1965
1966
1967
1968
1969
1970
1971
1972
1973
1974
YEAR
● THIS ANALYSIS
○ FROM SVALGAARD/WILCOX