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Interplanetary Sector Structure, 1962-1966

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Abstract

Some properties of the interplanetary magnetic field observed by IMP-3 in the latter half of 1965 are discussed with relation to previous satellite observations of the interplanetary field. The sector property remains a prominent feature of the observations, with the average field direction at the Archimedes spiral angle. The sector pattern has a 27-day recurrence period from 1962 to 1964, and during the year 1964 the pattern appears to be quasi-stable. In 1965 the recurrence period is about 28 days, and the evolution of the pattern is more rapid, with new sectors appearing and expanding.

The interplanetary sector structure has been a prominent feature of the interplanetary medium from the first extended observations of the interplanetary magnetic field by Mariner 2 in 1962 through the observations obtained by IMP-3 in 1965 and 1966. Interplanetary sector structure is defined as the property of the field, as observed by spacecraft near the ecliptic and at distances from the sun ranging from Venus to Mars, that for several consecutive days the sense of the field is either predominantly toward the sun or predominantly away from the sun. The average field direction is at the Archimedes spiral angle predicted by PARKER (1958), but the variations about the average direction are often very prominent. This dynamic character of the interplanetary field is graphically demonstrated by a movie (which may be borrowed from the authors, WILCOX et al., 1966). The present status of the interplanetary magnetic field and solar wind has recently been reviewed (DESSLER, 1967).

Figure 1 shows the daily geomagnetic character index C9, as prepared by the Geophysikalisches Institut in Göttingen. Geomagnetic activity for each day is characterized on a scale running from 0 to 9, and the physical size of the numbers increases with their magnitude. The index is plotted using Bartels solar rotation periods of 27 days. Thus a recurrent geomagnetic structure having a period of about 27 days will appear as a vertical column whereas, for example, a structure having a period of 28 days will slant downward toward the right. The polarity (toward the sun or away from the sun) of the interplanetary field observed by spacecraft is indicated for each Bartels rotation. In the case of the earth satellites IMPs-1, 2 and 3, there are gaps of a fraction of a day corresponding to the intervals when the satellite is near perigee and therefore within the magnetosphere or magnetosheath. (The orbital period of IMP-1 was 3.9 days and of IMP-3 was 5.8 days.) Whenever such a perigee gap has a given field polarity both before the satellite entered the magnetosphere and after the satellite returned to the interplanetary medium, the gaps have been filled with that polarity. This assumption is justified in two ways; first, the interplanetary probes, Mariners 2 and 4 (COLEMAN et al., 1966) have shown that the sector structure usually is continuous for several days, and second, analysis of the sector structure observed by IMP-1 indicates that each of the four sectors in a solar rotation is a coherent entity (WILCOX and NESS, 1965). In this paper we discuss the large-scale organization of the interplanetary field, setting aside the filaments and other small-scale exceptions to the sector patterns. The interval we discuss is near solar minimum; at times of greater solar activity the perturbations to the sector pattern may be more prominent.

For these investigations the large amount of information contained in the observations of the dynamic interplanetary field over a 3-hour interval is compressed into a simple quantized decision that the field was either predominantly toward the sun or away from the sun. What is the degree of approximation involved in this procedure? For IMP-1, Figures 4 and 5 of WILCOX and NESS (1965) show two typical 24-hour intervals in which almost every individual 5-minute average of the field direction falls within the limits of either a toward sector or an away sector. For IMP-2 FAIRFIELD and NESS (1967) report that during each sector the ratio of the number of fields along the spiral angle in one direction to that in the opposite direction was typically 100 to 1. On this basis it was possible to assign a definite sector polarity to almost all of the observations by the IMPs. In the Mariner 4 observations (COLEMAN et al., 1967) most of the intervals are assigned a definite sector polarity, but occasionally the field is designated as mixed polarity. In our Figure 1 we have usually accepted the mixed designations of COLEMAN et al. (1967), but occasionally we have replaced their mixed polarity by a definite polarity in cases in which this polarity was predominant through an interval of a few days. The most important example of this is the long interval designated mixed by COLEMAN et al. (1967) in solar rotation number 1799, which we have changed to away. The situation is illustrated in Figure 2, which is a reproduction of Figure 1a of COLEMAN et al. (1967). Figure 2 shows the component B_w in the direction of the theoretical spiral angle of the interplanetary field observed by Mariner 4. A point is plotted for each 3-hour period in which some data were obtained. The value plotted for B_w is the center value of the 1-γ range that was recorded most frequently during the corresponding 3-hour period. When B_w is positive the field is directed away from the sun, and when B_w is negative the field is directed toward the sun. COLEMAN et al. (1967) have designated the interval from January 21 to January 29 in solar rotation 1799 as mixed polarity. Since in this interval more than eighty percent of the observations are away from the sun with only scattered 3-hour intervals toward the sun, we have designated it as an away sector in Figure 1. The distinction is of interest since Figure 1 indicates that a large toward sector which had probably existed essentially unchanged for well over a year disappeared between solar rotations 1798 and 1799.

In the case of the interplanetary probes such as the Mariners and Pioneers which reach considerable distances from the earth both in the radial direction and in the azimuthal direction, a correction must be applied to the observed field before it can be compared with geomagnetic activity. This correction is made on the assumption that the solar wind velocity is uniform and radial. For example, in the latter stages of its journey to Mars Mariner 4 was at a larger radial distance from the sun and had azimuthal separations from the earth of up to about 90°, in the sense that a corotating structure would reach Mariner 4 before reaching the earth. One must compute the difference Δ t between the time at which a stream of plasma from a given longitude on the sun is intercepted by Mariner 4 and the time at which this same plasma stream is intercepted by the earth. (Differences in the heliographic latitudes of Mariner 4 and the earth are ignored.) This time interval Δ t is given by COLEMAN et al. (1967) as $\Delta t \simeq \left[(r_m - r_e)/V_p\right] + \left[(\phi_m - \phi_e)/\Omega_s\right]$ where r is the radial distance from the sun, V_p is the radial velocity of the solar wind, ϕ is heliographic longitude, Ω_s is the sidereal angular velocity of the sun, and the subscripts m and e refer to Mariner 4 and the earth. COLEMAN et al. (1967) used the sidereal angular velocity of the sun, whereas the synodic angular velocity would be more nearly correct. The most accurate angular velocity for this calculation would be one computed from the recurrance time of the actual interplanetary magnetic field during the time interval under consideration as observed from an earth coordinate system. The recurrence time of the interplanetary field observed by IMP-3 in the months following the Mariner 4 observations was about 28 days. All of these considerations would change the Δ t computed for Mariner 4 by less than half of a day in most cases, so that the correction is a rather small one for the sector patterns displayed in Figure 1.

The Mariner 4 interplanetary observations commence just where the IMP-2 observations end, so a simultaneous comparison of the two spacecraft cannot be made. The interplanetary sector structure has been observed simultaneously by Mariner 4 and IMP-3. At this time Mariner 4 was near Mars and was as much as 90° in azimuth removed from the earth. A comparison of the two observations is shown in Figure 3. The agreement appears satisfactory considering the evolving character of the sector structure and the distance of Mariner 4 from the earth. Changes in the solar wind velocity can cause the observed arrival time of a sector boundary to vary by a day or more.

The interval of one year between the first observations of IMP-1 and the last observations of IMP-2 apparently contained a quasi-stationary sector structure. The four sectors observed by IMP-1 were also observed by IMP-2, although in some cases the sizes of individual sectors had changed slightly. Evidence from the geomagnetic field indicates that the internal structure of these sectors also remained remarkably constant. Figure 4 shows the average value of the geomagnetic activity index K_p as a function of position within an average sector for IMP-1 (WILCOX and NESS, 1965) and for IMP-2 (FAIRFIELD and NESS, 1967). The response of geomagnetic activity as the sectors rotate past the earth is very similar in the two cases, including for example the knee that appears in the middle of the sectors. The pattern of the sector structure assumed during 1964 is sketched in Figure 1, utilizing the observation that geomagnetic activity tends to rise in the early portions of a sector. It is clear that in the interval in 1965 beginning with the observations of Mariner 4 the sector pattern evolved more rapidly; therefore the quasi-stationary structure of 1964 may be quite useful for investigations of solar-terrestrial physics.

From the Mariner 2 observations in 1962 through the IMP-2 observations at the end of 1964 the sector patterns are essentially vertical when plotted on the 27-day recurrent Bartels diagram. Thus the interplanetary field had approximately a 27-day recurrence during this interval (see, for example, the autocorrelation of the IMP-1 field in Figure 6 of WILCOX and NESS, 1965). In the IMP-3 observations in the latter half of 1965, when new 11-year sunspot cycle activity was becoming prominent on the sun, the small away sectors have a noticeable downward tilt toward the right, indicating a longer recurrence period. An autocorrelation of the direction of the interplanetary field observed by IMP-3 is shown in Figure 5. The position of the recurrence peak is at 28 $\pm$ 1/8 days. This suggests that the heliographic latitude of the source of the nearby interplanetary magnetic field may be at even higher latitudes than the 15^{o}N that has been suggested (WILCOX and NESS, 1967) for the IMP-1 observations. A discussion of the solar origin of the sector structure shown in Figure 1 will be given in a paper under preparation.

Although the recurrence period of the interplanetary field observed by IMP-3 in the latter half of 1965 has increased appreciably, the direction of the field is still consistent with the Archimedes spiral model and the field is predominantly parallel to the ecliptic. Figure 6 shows the histograms of the direction of the 5.46-minute average components of the observed field parallel to the ecliptic plane and normal to the ecliptic plane. Sectors with field directed toward the sun were predominant during the interval observed by IMP-3, as can also be seen in Figure 1. However the small young away sectors produced most of the geomagnetic activity, as has been discussed by SCHATTEN and WILCOX (1967).

Figure 6 shows histograms of all the field observations by IMP-3. In evaluating theoretical descriptions of the interplanetary plasma and fields and their relations to solar structures it is of interest to know what happens during unusually quiet situations and in the most disturbed times. Figures 7a and 7b show the histograms from IMP-1 and IMP-3 respectively of the direction of the field component parallel to the ecliptic as averaged in 3-hour intervals during times in which K_p is equal to 0_o. Similarly Figures 7c and 7d show the results from IMPs 1 and 3 during times in which K_p was greater than 3. The Archimedes spiral angle is still prominent in these four figures in spite of the very limited statistics. In Figures 7a and 7b showing the distributions for K_p equal to 0_o there is some suggestion that for away sectors the direction radially away from the sun is relatively more populated than in the histogram for the entire body of observations. This effect is not seen in the toward sectors however.

A stable recurring away sector is associated with the well-known sequence of recurring geomagnetic storms that appears in the first quarter of the Bartels solar rotation periods during the interval from the middle of 1962 to the beginning of 1965, and perhaps for a few rotations thereafter. This is perhaps the most interesting sector, since during much of its life it was populated by protons of a few MeV energy that were quite well contained within the boundaries of the sector (WILCOX and NESS, 1965). The proton intensity reaches a maximum early in the sectors and declines in the trailing portions of the sectors in a manner similar to that observed for the magnitude of the interplanetary field and the solar wind velocity.

The change in the sector pattern of the interplanetary magnetic field from the old sunspot cycle to the new appears to come near the end of 1964. Before that time the pattern appears to be quasi-stationary and to have a 27-day recurrence interval. After that time the evolution of the sector pattern is more rapid and the recurrence time is 28 days, probably associated with the high latitude activity of the new sunspot cycle. Near the end of the old cycle there is little new activity to break up the large-scale magnetic patterns in the photosphere, so that they can persist in a quasi-stationary manner over wide intervals of heliographic latitude and longitude. As activity increases in the new cycle these patterns are interrupted by new activity and the resulting interplanetary sector pattern shows a more rapid evolution.

Acknowledgement

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Figure Captions

Figure 1. Observed sector structure of the interplanetary magnetic field, overlayed on the daily geomagnetic character index C9, as prepared by the Geophysikalisches Institut in Göttingen. Light shading indicates sectors with field predominantly away from the sun, and dark shading indicates sectors with field predominantly toward the sun. Diagonal bars indicates periods of mixed polarity. An assumed quasi-stationary structure during 1964 is indicated. The observations are from Mariner 2 (COLEMAN _et al._, 1966), IMP-1 (WILCOX and NESS, 1965), IMP-2 (FAIRFIELD and NESS, 1967), Mariner 4 (COLEMAN _et al._, 1967), and IMP-3.

Figure 2. Component of the interplanetary magnetic field in the direction of the ideal spiral field observed by Mariner 4 (see text). After COLEMAN _et al._ (1967) Figure 1a.

Figure 3. Comparison of the sector structure as observed by Mariner 4 and by IMP-3. The Mariner 4 observations are shown on the top line and the IMP-3 observations on the bottom line of each solar rotation.

Figure 4. Average response of the geomagnetic activity index (24-hour sum K_p) as a function of position within a sector for the IMP-1 and IMP-2 satellites.

Figure 5. Autocorrelation of the direction of the interplanetary magnetic field observed by IMP-3.

Figure 6. Distribution of the IMP-3 interplanetary magnetic field directions in the plane of the ecliptic and normal to the ecliptic, averaged over 5.46

minute intervals. Both histograms show the field angular distribution per unit solid angle; the dashed circles would correspond to an isotropic distribution of the same number of vectors.

Figure 7. Distributions of the interplanetary magnetic field directions observed by IMP-1 and IMP-3 in the plane of the ecliptic for K_p values equal to 0_o and for K_p values greater than 3. The dashed circles would correspond to an isotropic distribution of the same number of vectors.

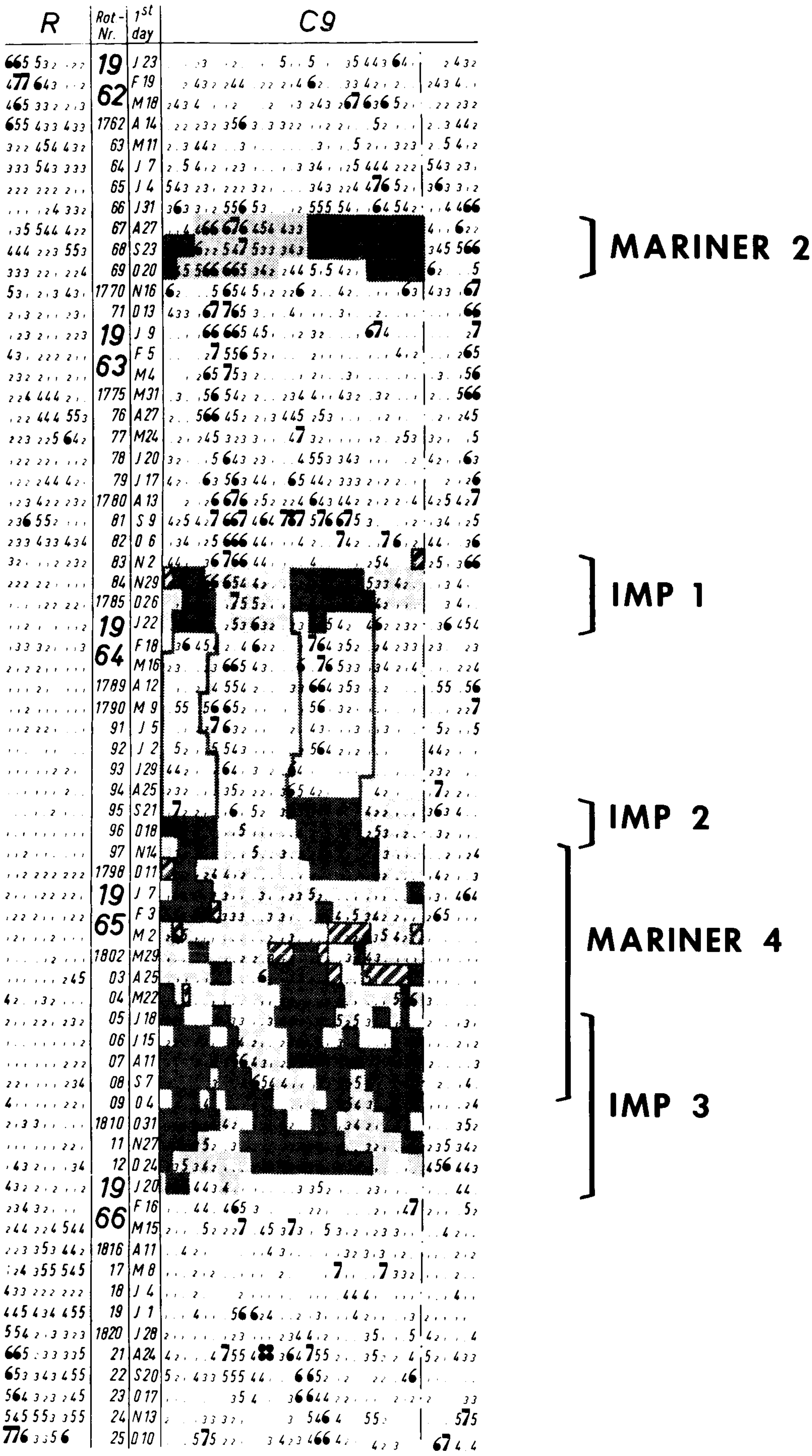


Figure 1

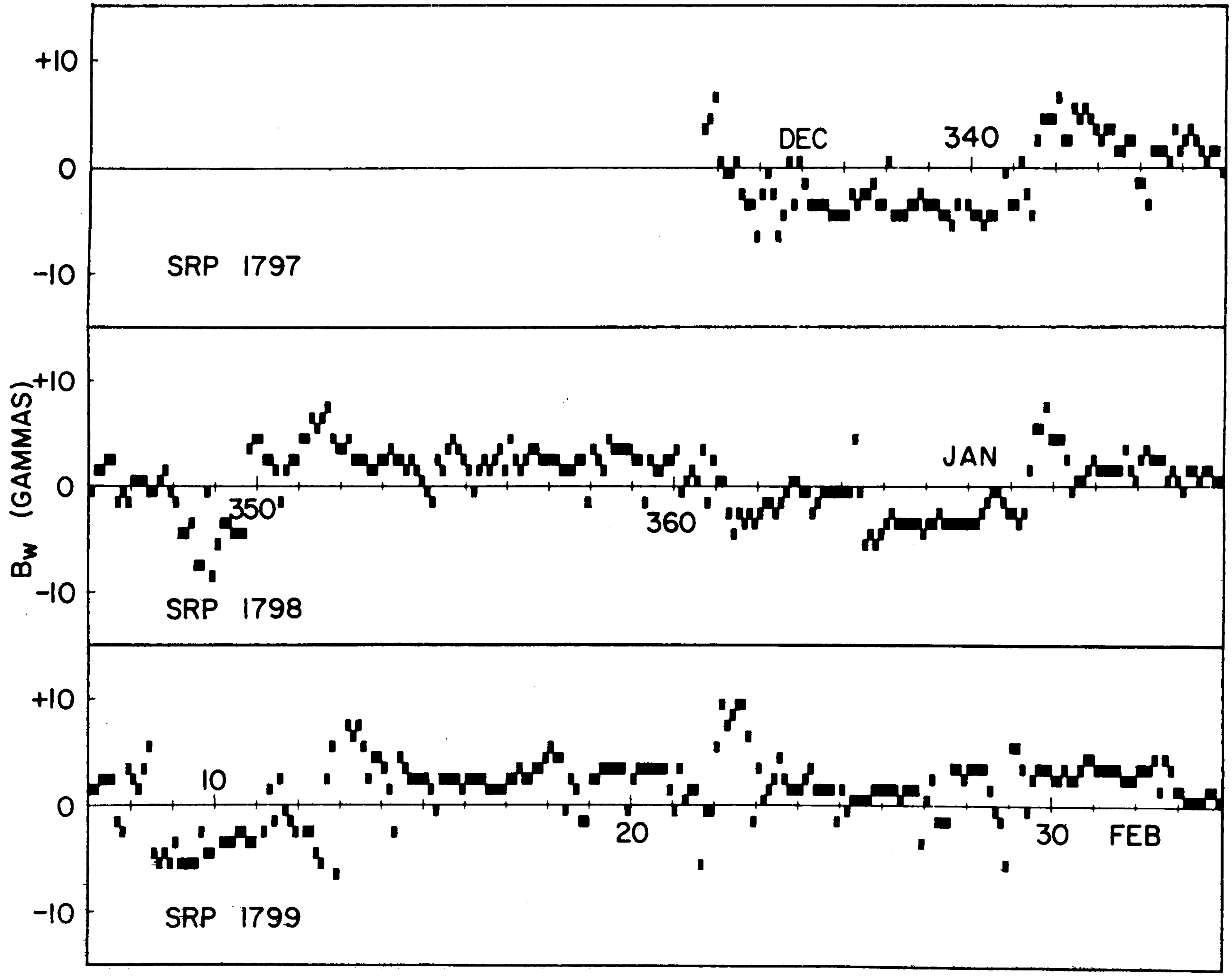

+10
0
-10
SRP 1797
DEC
340
B_W (GAMMAS)
SRP 1798
350
360
JAN
SRP 1799
10
20
30
FEB

Figure 2

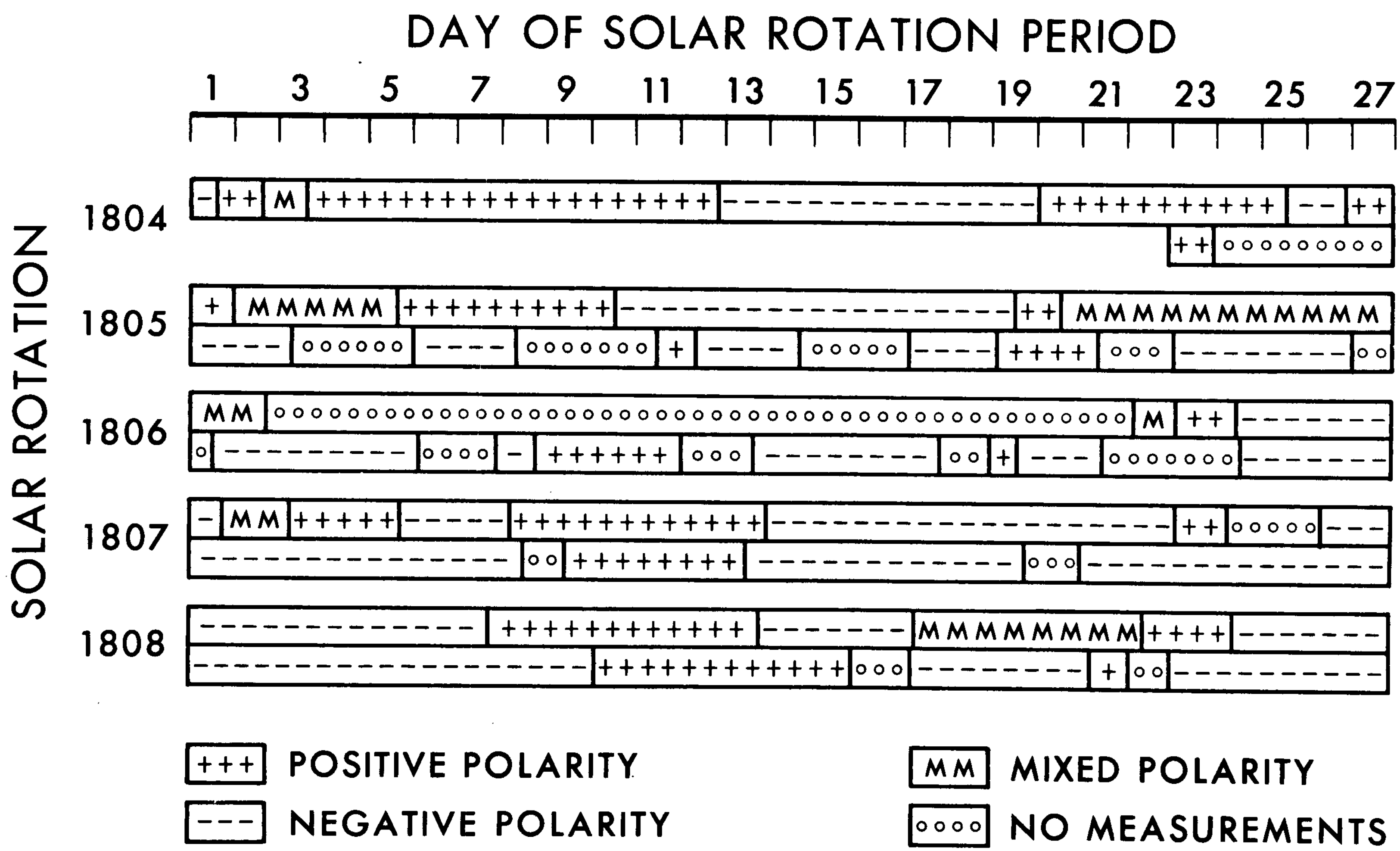
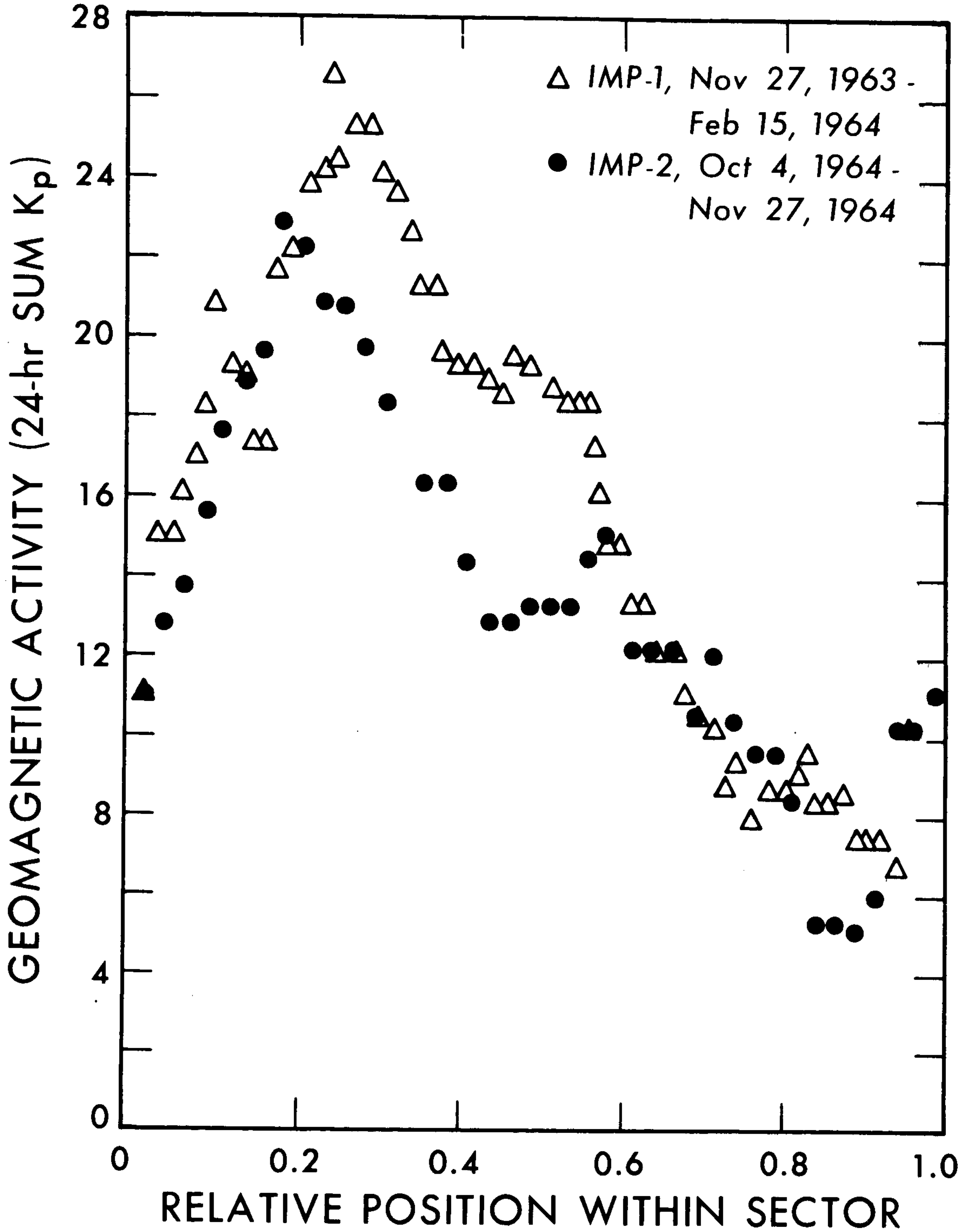

DAY OF SOLAR ROTATION PERIOD
1
3
5
7
9
11
13
15
17
19
21
23
25
27
SOLAR ROTATION
1804
1805
1806
1807
1808
POSITIVE POLARITY
NEGATIVE POLARITY
MIXED POLARITY
NO MEASUREMENTS

Figure 3



IMP-1, Nov 27, 1963 - Feb 15, 1964
IMP-2, Oct 4, 1964 - Nov 27, 1964
GEOMAGNETIC ACTIVITY (24-hr SUM K_p)
RELATIVE POSITION WITHIN SECTOR
0
4
8
12
16
20
24
28
0.2
0.4
0.6
0.8
1.0

Figure 4

AUTOCORRELATION OF INTERPLANETARY MAGNETIC FIELD DIRECTION, DAYS 157-1965 to 22-1966 (IMP-3)

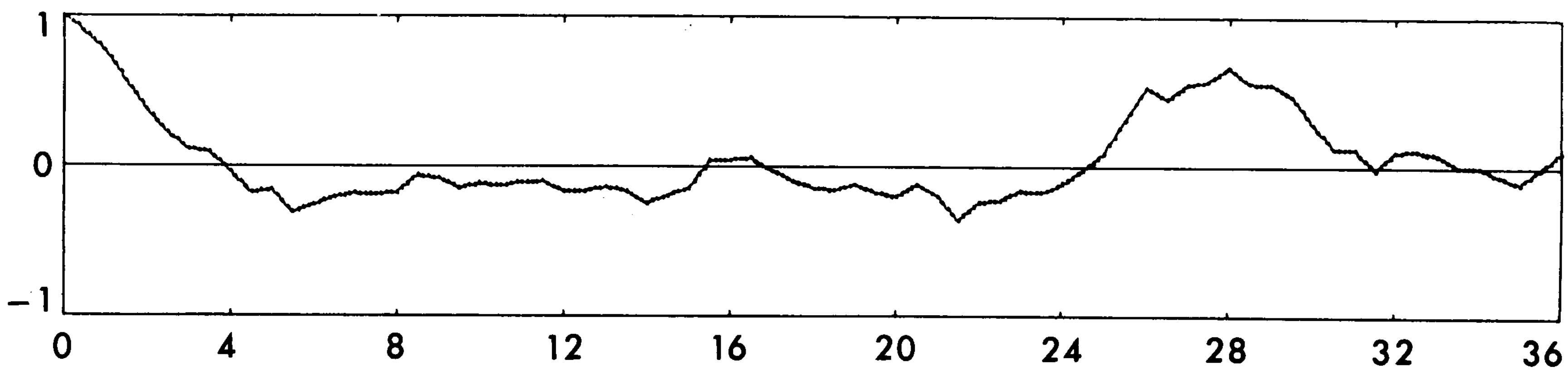
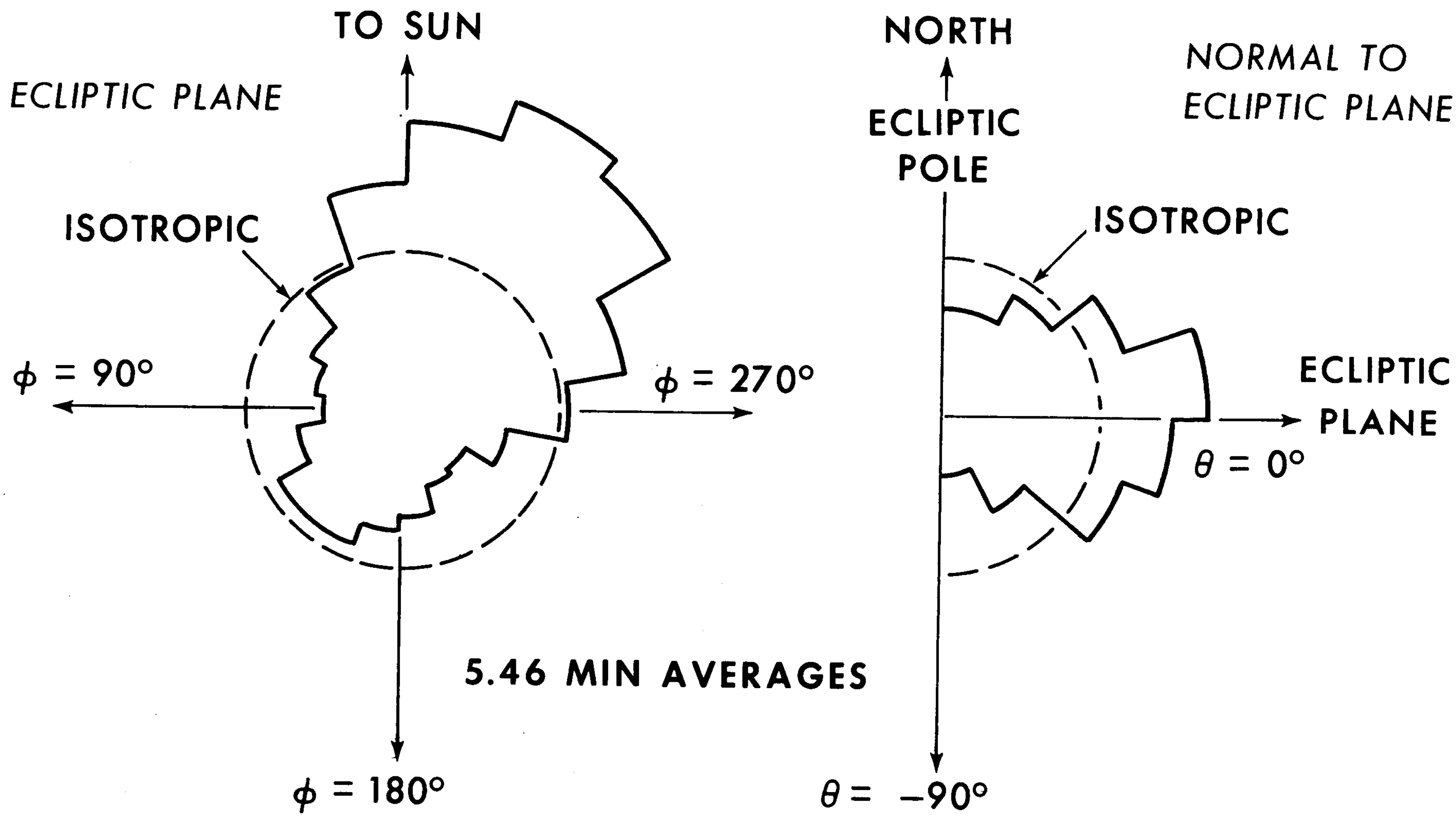


Figure 5



DISTRIBUTION OF INTERPLANETARY MAGNETIC FIELD DIRECTION

Figure 6

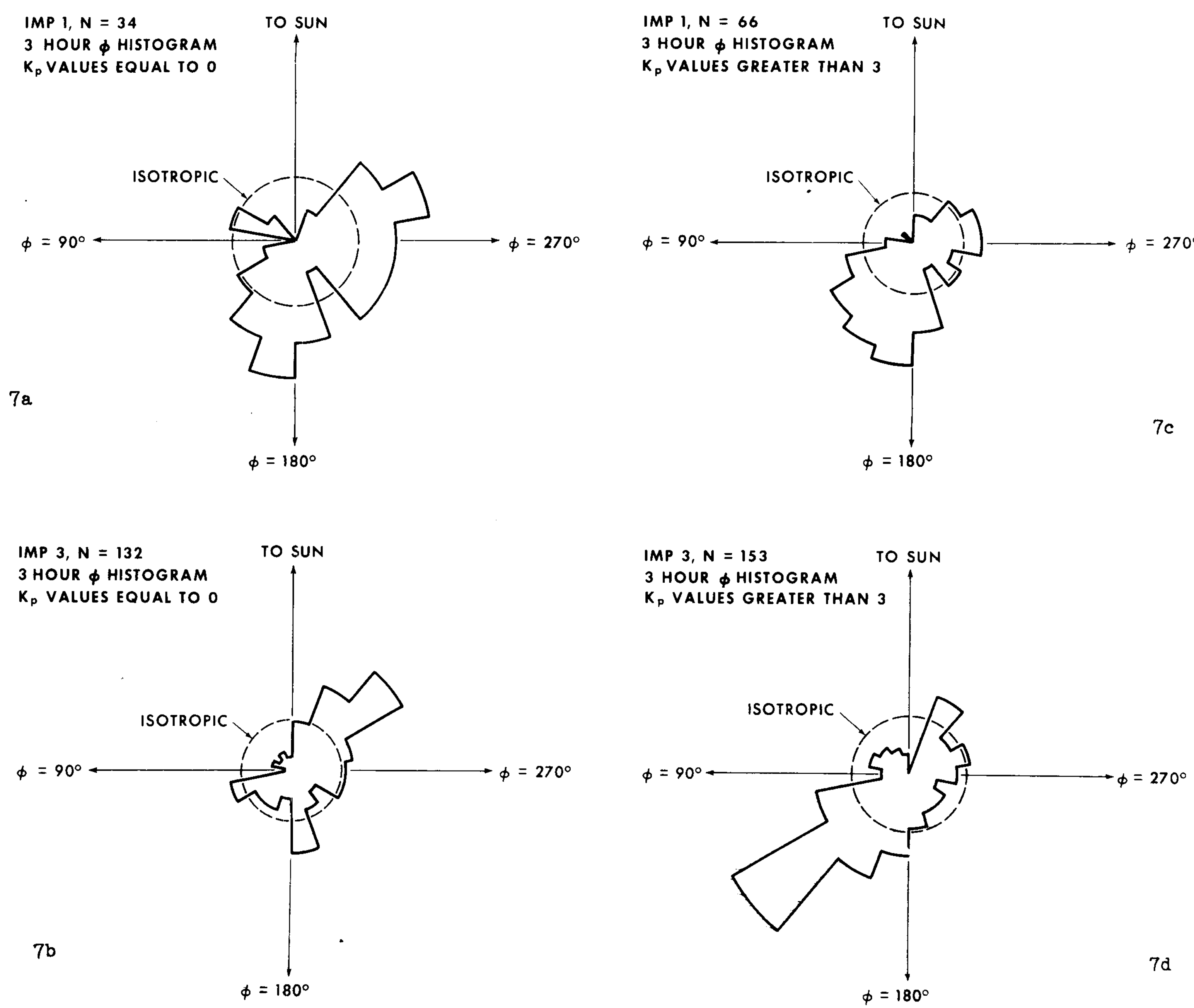

IMP 1, N = 34
3 HOUR φ HISTOGRAM
Kp VALUES EQUAL TO 0
TO SUN
ISOTROPIC
φ = 90°
φ = 270°
φ = 180°
7a
IMP 1, N = 66
3 HOUR φ HISTOGRAM
Kp VALUES GREATER THAN 3
TO SUN
ISOTROPIC
φ = 90°
φ = 270°
φ = 180°
7c
IMP 3, N = 132
3 HOUR φ HISTOGRAM
Kp VALUES EQUAL TO 0
TO SUN
ISOTROPIC
φ = 90°
φ = 270°
φ = 180°
7b
IMP 3, N = 153
3 HOUR φ HISTOGRAM
Kp VALUES GREATER THAN 3
TO SUN
ISOTROPIC
φ = 90°
φ = 270°
φ = 180°
7d

Figure 7

UNCLASSIFIED
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13. ABSTRACT

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