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Solar Source of the Interplanetary Sector Structure

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Abstract

The interplanetary sector structure observed by the IMP-1 satellite during three solar rotations in 1963-4 is compared with the photospheric magnetic field structure observed with the solar magnetograph at Mt. Wilson Observatory. The interplanetary sector structure was most prominent on the sun in latitudes between 10^{o}N and 20^{o}N, although the average heliographic latitude of the satellite was 3 $1/2^{o}$S. A superposed-epoch analysis of the calcium plage structure obtained from the Fraunhofer Institute daily maps of the sun is used to discuss the relation between the structure of the plages and the interplanetary sector structure. A possible explanation for the observations is discussed in terms of a north-south asymmetry in the flow of the solar wind. It is suggested that these observations favor the "equinoctial" hypothesis as compared with the "axial" hypothesis for the explanation of the semiannual maxima in geomagnetic activity.

1. Interplanetary Sector Structure

The purpose of this paper is to compare observations of the photospheric magnetic field and plage structure with satellite observations of the interplanetary magnetic field. The IMP-1 satellite observed the interplanetary medium from November 27, 1963 to February 15, 1964, and its magnetometer experiment has been discussed by NESS et al. (1964). A quasi-stationary sector structure in the interplanetary medium was discussed by WILCOX and NESS (1965) and is shown in Figure 1. This structure corotates with the sun. A review of several properties of the solar and interplanetary magnetic fields observed at this time has been given by WILCOX (1966). NESS and WILCOX (1966) have discussed the extension of the photospheric magnetic field into the interplanetary space, and suggested that the latitude of the photospheric source of the interplanetary field observed by IMP-1 was within 10^{o} or 15^{o} of the center of the visible disk. In the present work it is suggested that this latitude was on the average about 10^{o}N to 20^{o}N.

The solid line in Figure 2 shows an autocorrelation of the direction of the interplanetary magnetic field observed by IMP-1. (This direction is indicated by the + and - signs at the periphery of Figure 1.) In addition to the prominent recurrence peak at a lag of about 27 days, subsidiary structure is present in the form of a secondary maximum at about 13 1/2 days and minima at about 7 days and at about 20 days. The sector structure shown in Figure 1 can be idealized to consist of three equal sectors, each occupying 2/7 of the circumference, and one smaller sector occupying 1/7 of the circumference. The dashed line in Figure 2 shows an autocorrelation of this idealized sector structure, which is very similar to the envelope of the solid line representing the actual observations. It can thus be seen that the signature of the IMP-1 sector structure appears in an autocorrelation in the form of a recurrence peak at about 27 days together with a centered secondary maximum surrounded by the two minima.

2. Photospheric Magnetic Field Structure

IMP-1 observed the interplanetary medium during portions of three solar rotations during the winter of 1963-4. As has been mentioned by NESS and WILCOX (1966), weather conditions at Mt. Wilson caused several gaps in the photospheric data totaling about 25 days, and thus limited the possibility for detailed analysis. For this reason the present work uses photospheric field observations for seven solar rotations, centered on the three rotations observed by IMP-1. In the course of an extended study of the large-scale characteristics of the photospheric magnetic field during the decline of the last 11-year sunspot cycle being conducted by R. Howard and J. Wilcox, the autocorrelation of the direction of the photospheric field as a function of latitude shown in Figure 3 was obtained. Details of the methods used to obtain these autocorrelations have been described by NESS and WILCOX (1966). The format of Figure 3 is as follows. For the autocorrelation for 35°N, the top line of Figure 3 represents an autocorrelation value of 1.0, the horizontal line labeled 35° represents a value of 0.0, and the next lower line (labeled 30°) represents a value of -1.0. Within these limits the autocorrelation for 35° is shown approximately centered about the horizontal line labeled 35°. Each other latitude is overlayed using the same format.

It can be observed in Figure 3 that the autocorrelation for 15°N is a good approximation to the signature of the interplanetary sector structure discussed previously in connection with Figure 2. The autocorrelations for

10°N and for 20°N also display a fairly prominent representation of the sector-structure signature. At 5°N and 25°N only a slight suggestion of the signature appears, while at 0° and at 30°N the signature has completely disappeared. The other heliographic latitudes displayed in Figure 3 do not show the sector signature, with the possible exception of 20°S. However, the adjacent latitudes, 15°S and 25°S, do not show any trace of the sector signature, which suggests that the apparent signature at 20°S is likely a result of chance. Thus a comparison of Figure 2 and Figure 3 suggests that heliographic latitudes between about 10°N and 20°N had a large-scale structure most similar to the interplanetary sector structure observed by IMP-1. It should be noted that the average heliographic latitude of the earth (and of IMP-1) during these interplanetary observations was 3 $1/2^{\circ}$S.

3. Calcium Plage Structure

HOWARD (1959) has shown that photospheric magnetic features have a close relation to calcium plage regions, such that plages are outlined very nearly by a 10-gauss contour line. It would therefore be of interest to compare the results derived from photospheric magnetic field observations with an analysis of the location of calcium plages at this time. For this purpose the Fraunhofer Institute daily maps of the sun are utilized. Using the satellite observations, a date is selected on which one of the large sectors shown in Figure 1 is approximately centered, i.e. half of the sector has rotated past the earth. A previous cross-correlation of photospheric and interplanetary magnetic field directions by NESS and WILCOX (1966) has shown that the average time lag from the appearance of a magnetic feature at central meridian on the sun to the observation of the feature by the satellite at 1 AU is approximately 4 1/2 days. Therefore

4 1/2 days are subtracted from the date on which a large sector is approximately centered at the earth to obtain the date on which this sector was approximately centered at central meridian on the sun. The Fraunhofer Institute solar map for this day is selected. The process is repeated for each of the large sectors observed by IMP-1 during three solar rotations, resulting in eight Fraunhofer Institute maps, each of which should represent a day on which a large sector was approximately centered on the sun. From each of these maps a tracing is prepared in which the areas of all plages are colored a uniform gray. The eight tracings are then overlayed to give the result shown in Figure 4. In areas where several plages overlap an increased darkening of the image is visible. Since the large sectors each occupy approximately 2/7 of the total circumference of 360°, each sector should occupy approximately 100°. Since they are approximately centered on central meridian, the preceding boundary of the sector should be located near 50°W longitude and the following boundary of the sector should be near 50°E longitude. In Figure 4 it can be observed that the densest concentration of plages occurs in latitude range 10°N to 20°N, which was earlier discussed as the region most similar to the interplanetary sector structure. In this range of latitudes the preceding boundary of the sector (50°W) is relatively free of plages, while the most dense concentration of plages occurs approximately 1/4 of the distance into the sector. In the trailing portions of the sector there are considerably less plages.

It is of interest to compare this distribution of plages within the sectors with the average structure within the sectors as observed by the satellite and discussed in WILCOX and NESS (1965). The abscissa of Figure 5 represents the days as an average large sector rotates past the earth, with the preceding boundary passing at 0 days and the following boundary passing near 8 days. The ordinate shows the average value of an observed quantity obtained from a superposed-epoch analysis. It is seen that the solar wind velocity reaches a peak in the early portion of the average sector and then declines in the following portion. The peak in the solar wind velocity occurs at approximately the same position within the sector as the maximum density of the plages shown in Figure 4. The considerable increase shown in Figure 5 in the solar wind density in the trailing portion of the sector is different from the decrease shown in Figure 4 of plage density in the trailing portions of sectors. Thus the distribution in longitude of plages seems to be more similar to the distribution of solar wind velocity than to the distribution of solar wind density.

Figure 6 has been constructed in the same manner as Figure 4 except that in this case sector boundaries are near central meridian. In order to improve the averaging process all observed sector boundaries have been utilized, so that in some cases a small (1/7) sector is located near central meridian. In Figure 6 the preceding boundary of a large sector has just rotated off the western limb, and the preceding boundary of the following sector is just east of central meridian, with the following boundary of such a sector just off the eastern limb. It is again apparent that the concentration of plages in the preceding portion of the sectors is considerably greater than in the following portion of the sectors, and that the sector boundary near central meridian is relatively free of plages.

4. North-South Asymmetry

The fact that the average heliographic latitude of IMP-1 during these observations was 3 1/2°S whereas the solar structure most similar to the interplanetary sector structure was at latitudes around 10°N to 20°N requires an explanation. One possibility is a north-south asymmetry in the flow of the solar wind. WILCOX (1965) suggested that the observation by BELL (1961) that "northern flares of a given type are far more likely to produce significant geomagnetic disturbances than are corresponding southern flares" might be understood on the basis of an asymmetric solar wind flow. At the time observed by IMP-1, solar activity and the photospheric magnetic field (R. HOWARD, private communication) were predominant in the northern solar hemisphere, which could cause a greater coronal heating and temperature in the north as compared with the south. With a higher coronal temperature it would be expected (PARKER, 1963) that a greater efflux of solar wind would occur. The resulting imbalance in lateral pressure between a larger solar wind efflux in the north and a smaller efflux in the south might provide a qualitative explanation for a north-south asymmetry in the flow of the solar wind.

The possibility that a north-south asymmetry in the flow of the solar wind may be a reasonably persistent feature is raised by the observation of BELL (1962) that the northern solar hemisphere contributed over 50% of the spottedness in cycles 8 and 9 (1833-1866) and in cycles 14-19 (1901-1965), while the southern hemisphere contributed over 50% of the spottedness in cycles 10-13 (1856-1901).

5. Axial-Equinoctial Hypotheses

The cause of the semiannual maxima in geomagnetic activity has been a matter of some controversy over the years. Some authors (BARTELS, 1932, 1963) argue for the "equinoctial" hypothesis in which the varying inclination of the geomagnetic axis is the primary causal agent. Other authors (CORTIE, 1912) favor the "axial" hypothesis in which the variation in the heliographic latitude of the earth by $\pm 7.2^{\circ}$ is held to be the primary cause. For a recent discussion of this controversy see CURRIE (1966).

The suggestion in the present paper that during an interval in which the average heliographic latitude of the earth was 3 1/2°S the source of the nearby interplanetary magnetic field was nevertheless between 10°N and 20°N is a substantial argument against the axial theory, since this theory assumes that as the heliographic latitude of the earth changes from 7.2°N to 7.2°S the heliographic latitude of the solar source of the nearby interplanetary field changes in a corresponding manner.

NESS (1965) found that the position of the neutral sheet in the earth's magnetic tail is best described in a coordinate system that includes the direction of the geomagnetic axis. This demonstration of the influence of the geomagnetic axis on the configuration of the magnetosphere is a substantial argument in favor of the equinoctial hypothesis.

Acknowledgement

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Figure Legends

Fig. 1. The interplanetary sector structure observed by IMP-1. The + signs (away from the sun) and - signs (toward the sun) at the circumference of the figure indicate the direction of the measured interplanetary magnetic field during successive 3-hour intervals.

Fig. 2. Autocorrelation of the observed direction of the interplanetary magnetic field. The solid line is from the observations, and the dashed line is the autocorrelation of the idealized sector structure shown in the center of Figure 1. The large positive peak at about 27 days lag indicates that the interplanetary magnetic field structure corotates with the sun.

Fig. 3. Autocorrelations of the photospheric magnetic field direction for heliographic latitudes from 35°N to 35°S in intervals of 5°. Seven solar rotations centered on the three rotations observed by IMP-1 are included. The format is explained in the text.

Fig. 4. Superposed-epoch analysis of calcium plage structure obtained from the daily Fraunhofer Institute maps of the sun. The large sectors shown in Figure 1 are approximately centered at central meridian, so that the leading edge of the sector is at about 50°W and the trailing edge of the sector is about 50°E longitude.

Fig. 5. Schematic representation of the average solar wind velocity and solar wind density as a function of position within the large sectors. Range of velocity, 280 to 340 km/sec; density, 7 to 14 protons/cc. The

position labeled 0 days would correspond to about 50°W in Figure 4, the position labeled 4 days would correspond to central meridian in Figure 4, and the position labeled 8 days would correspond to about 50°E in Figure 4.

Fig. 6. Same as Figure 4 except that the sector boundaries are near central meridian.

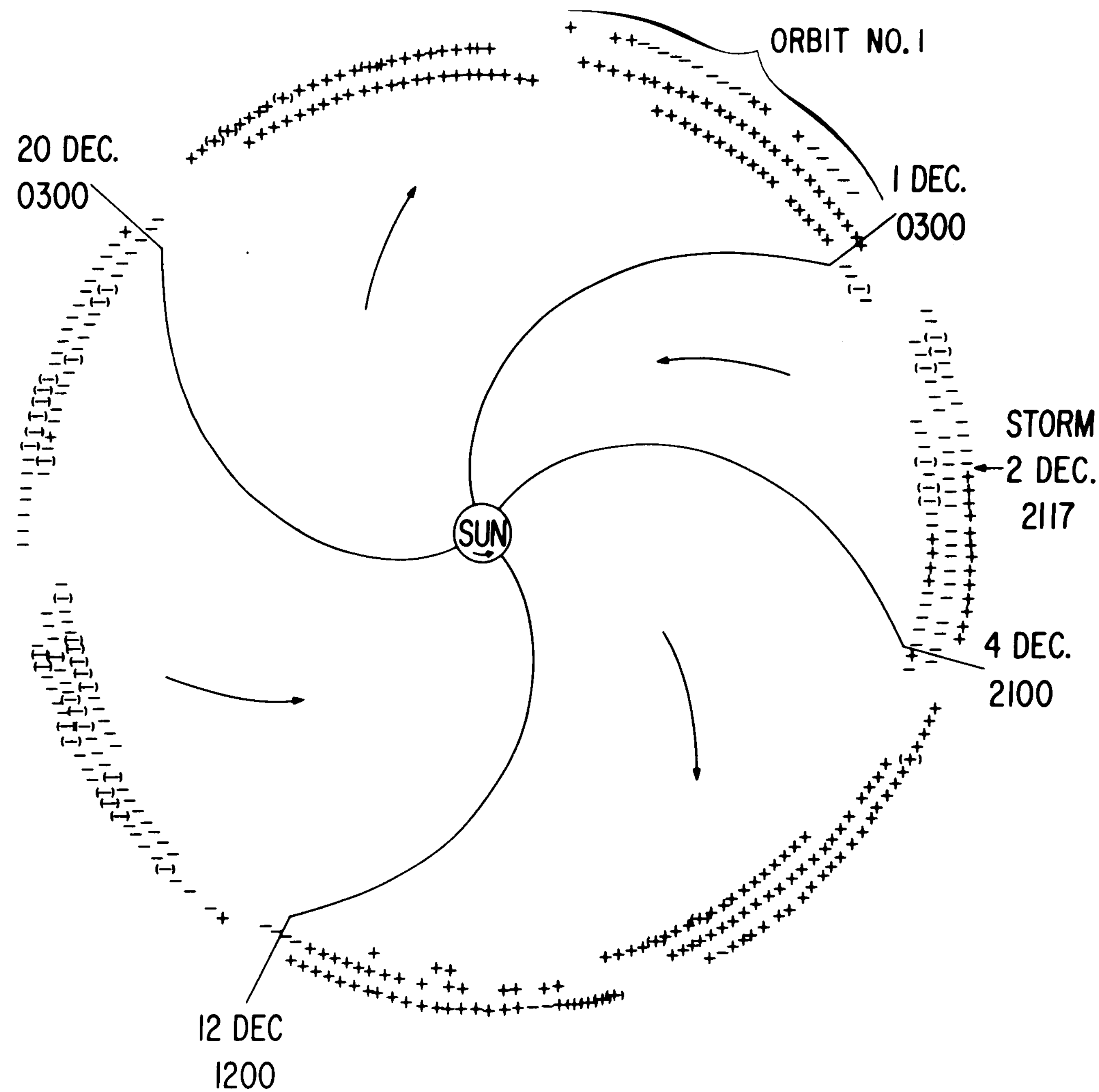

ORBIT NO. I
I DEC.
0300
STORM
2 DEC.
2117
4 DEC.
2100
12 DEC
1200
20 DEC.
0300
SUN

Fig. 1

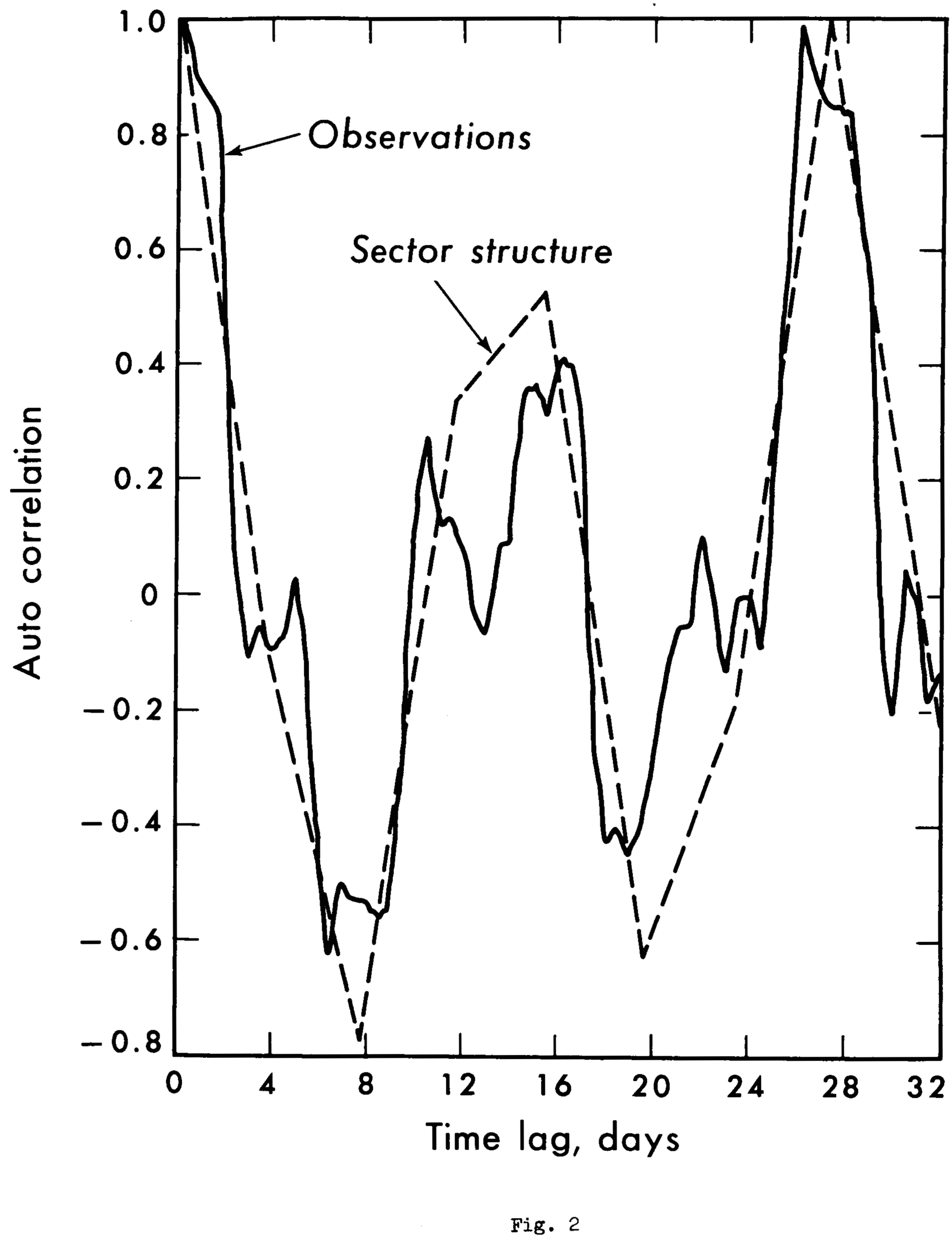

Observations
Sector structure
Auto correlation
Time lag, days
1.0
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
0
4
8
12
16
20
24
28
32

Fig. 2

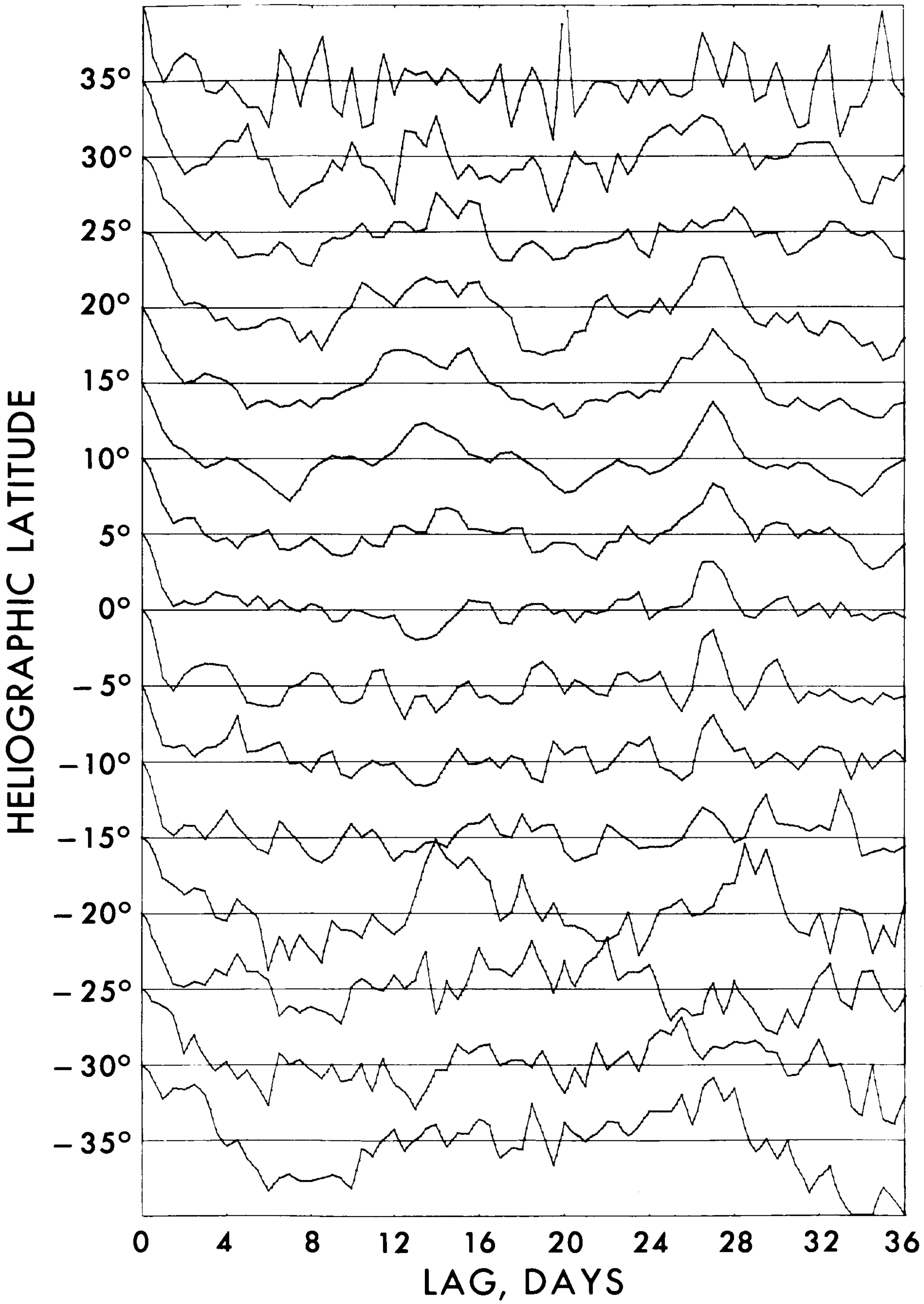
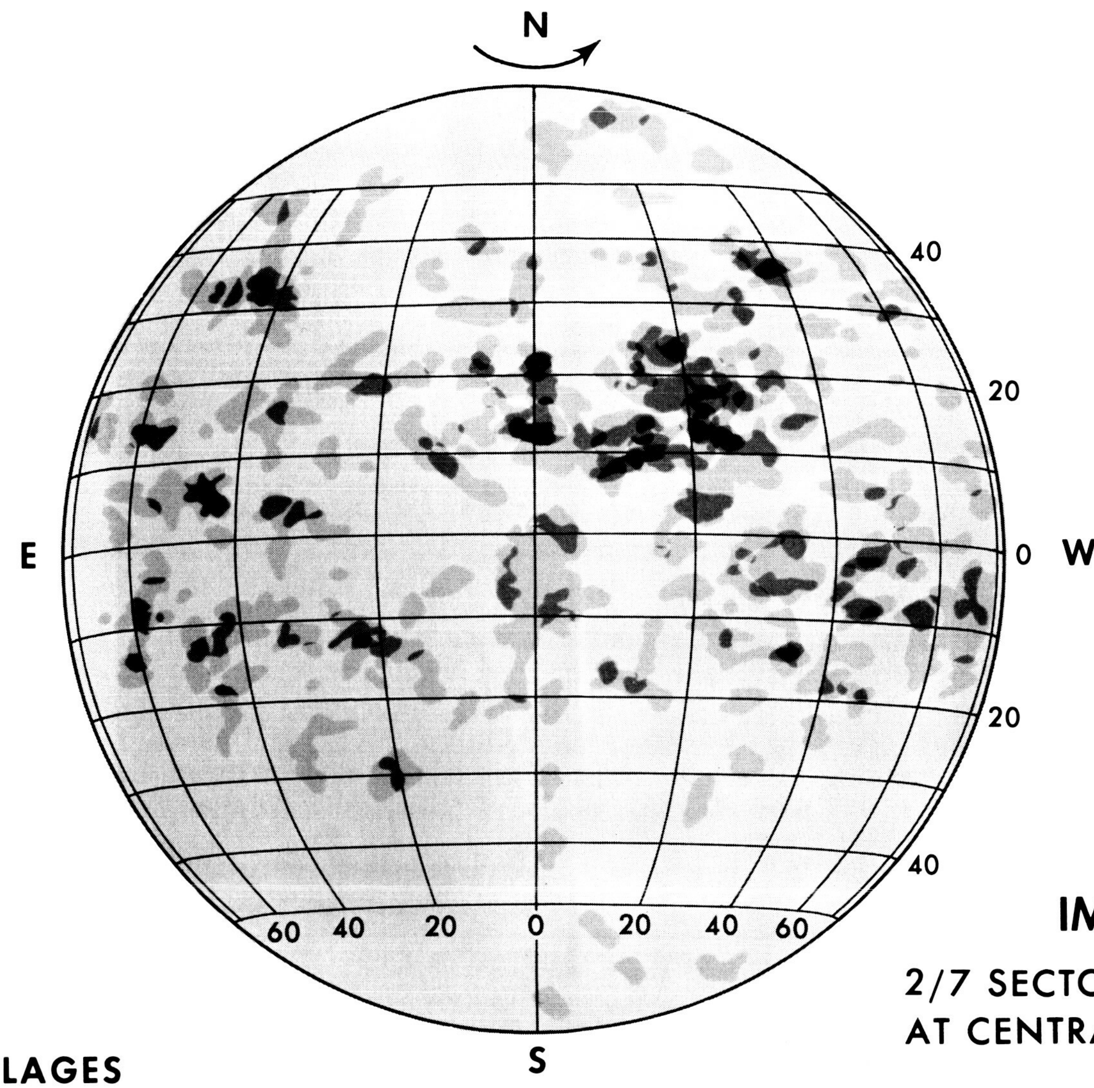

HELIOGRAPHIC LATITUDE
35°
30°
25°
20°
15°
10°
5°
0°
-5°
-10°
-15°
-20°
-25°
-30°
-35°
0
4
8
12
16
20
24
28
32
36
LAG, DAYS

Fig. 3



IMP-1

2/7 SECTORS CENTERED AT CENTRAL MERIDIAN

SECTORS EXTEND FROM ~50°W TO ~50°E

PLAGES
FRAUNHOFER INSTITUT

Fig. 4

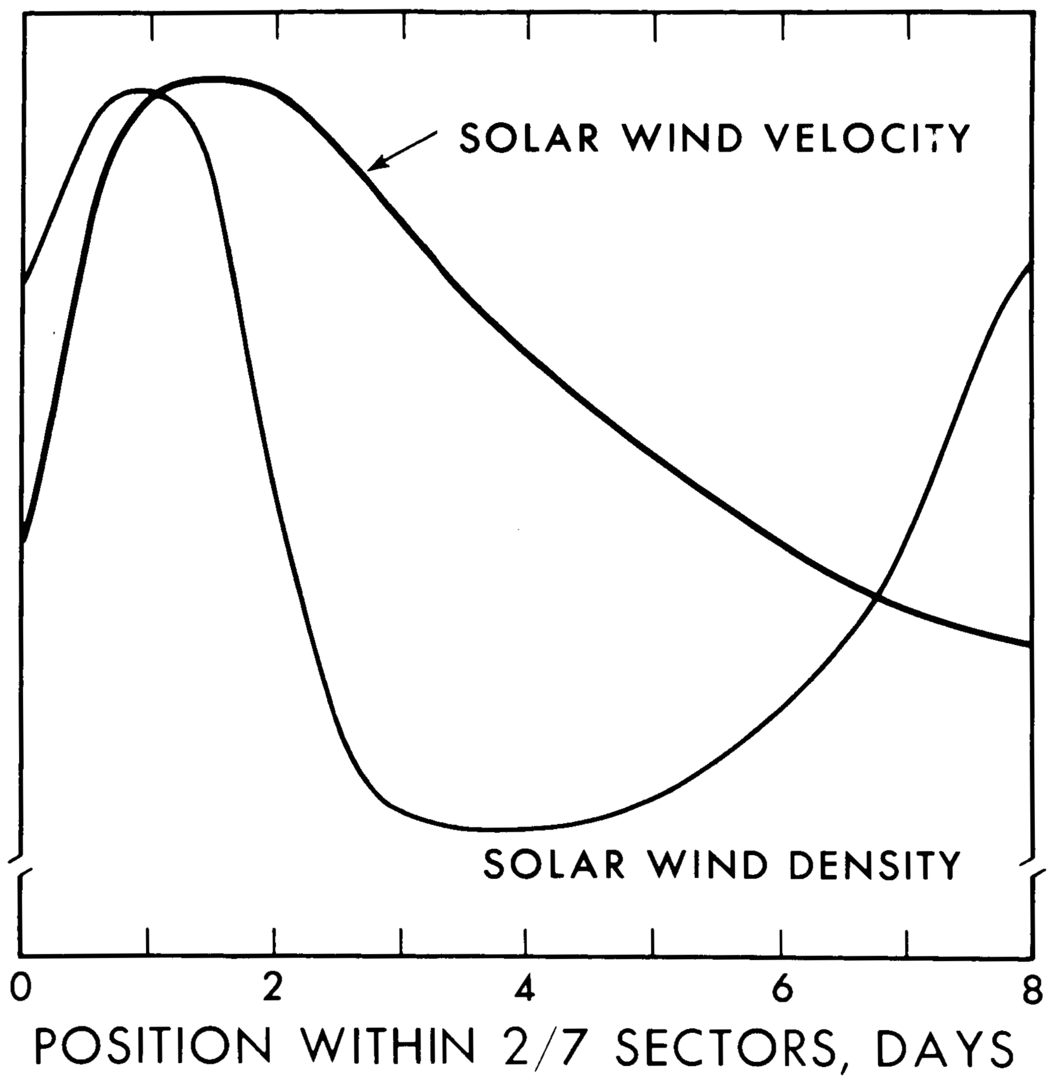
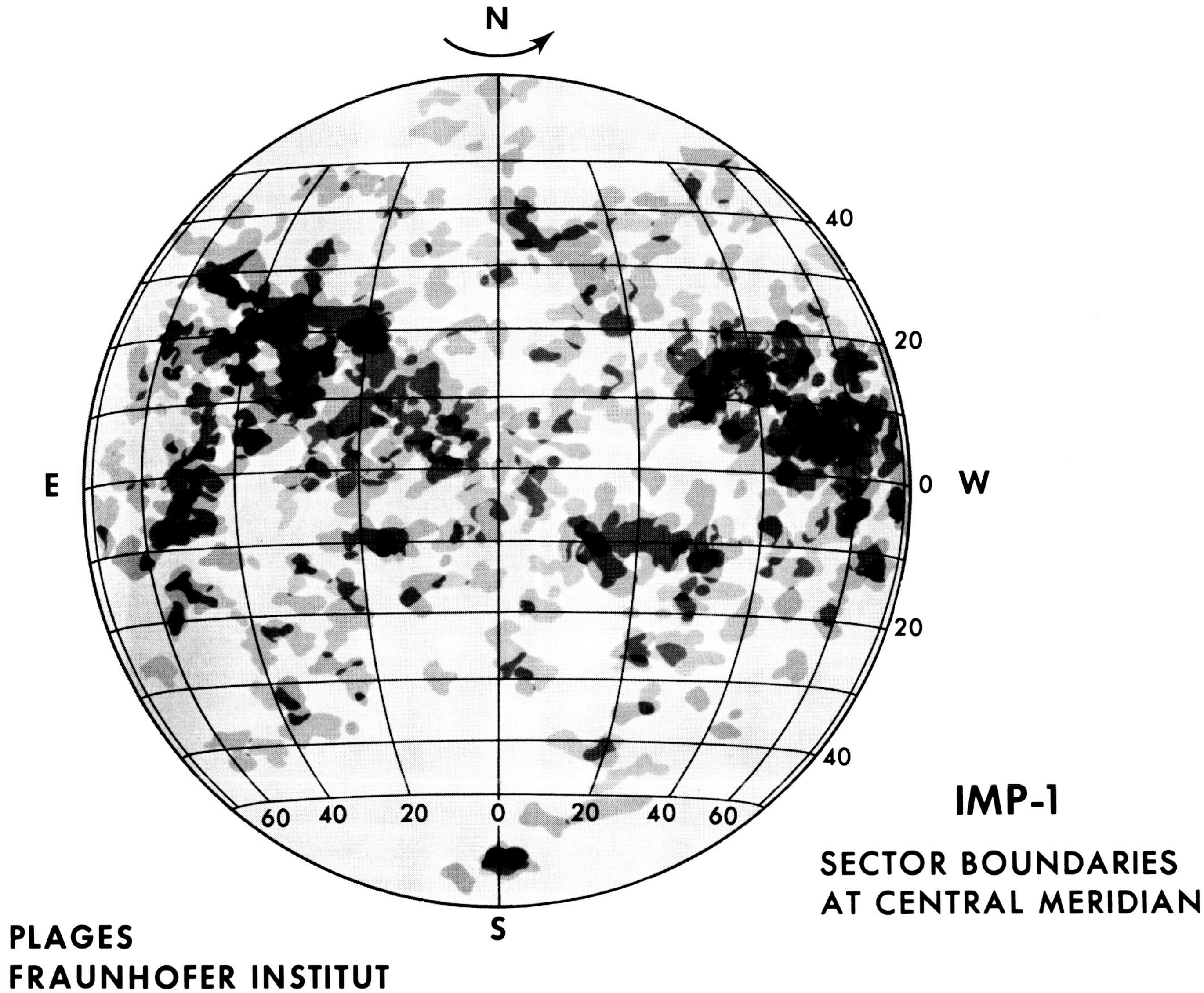

SOLAR WIND VELOCITY
SOLAR WIND DENSITY
0
2
4
6
8
POSITION WITHIN 2/7 SECTORS, DAYS

Fig. 5



N
E
W
S
40
20
0
20
40
60
40
20
0
20
40
60
IMP-1
SECTOR BOUNDARIES
AT CENTRAL MERIDIAN
PLAGES
FRAUNHOFER INSTITUT

Fig. 6

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13. ABSTRACT

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Calcium plages						

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