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THE EXTENDED CORONAL MAGNETIC FIELD

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THE EXTENDED CORONAL MAGNETIC FIELD*

John M. Wilcox

Technical Report

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THE EXTENDED CORONAL MAGNETIC FIELD

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Abstract. The coronal magnetic field should contain many field lines connecting the photosphere to interplanetary space. A sharp boundary separates two adjacent sectors of opposite polarity. The large-scale structure of the corona is related to the photospheric sector pattern. The corona may frequently contain transient magnetic loops reaching out to five to ten solar radii.

As has already been mentioned in the introductory talk there is a good correspondence between the large-scale photospheric magnetic field and the large-scale interplanetary magnetic field observed with spacecraft near the earth. This situation means that the coronal magnetic field problem is bounded, although the outer bound is perhaps at a rather large distance from the region of the corona most often discussed. In the first portion of this paper we shall indicate the nature of the large-scale patterns in the photospheric field and then indicate some implications and related observations for the extended coronal field.

The classical Babcock (1961) model of solar magnetism utilizes the stretching and field amplication effects of differential rotation to explain a number of the observed solar magnetic phenomena, including the observation that the polarity of a bipolar magnetic region in the northern solar hemisphere is opposite from the polarity of a bipolar region in the southern hemisphere. An additional large-scale pattern in the photospheric magnetic field having rather different properties has recently been discovered (Wilcox and Howard, 1968). Figure 1 is a schematic showing some of the main properties of this solar sector pattern. A boundary exists approximately in the north-south direction. On one side of the boundary the large-scale weak photospheric field is predominantly directed out of the sun, and on the other side of the boundary this field is predominantly directed into the sun. This pattern exists over a wide range of latitudes on both sides of the equator. The boundary rotates in an approximately rigidly rotating coordinate system, since it is very little influenced by the shearing effects to be expected from differential rotation. The solar sector pattern thus differs from the Babcock model in two fundamental respects: 1) The solar sector pattern rotates in an almost rigidly rotating coordinate system while the Babcock model depends on differential rotation to produce the observed effects, and 2) the solar sector pattern has the same polarity on both sides of the equator while the Babcock model (and observations) show that bipolar magnetic regions have opposite polarities on either side of the equator. Yet the two patterns coexist on the sun.

The solar sector pattern is the source (Wilcox and Ness, 1965) of a corresponding interplanetary sector pattern, an example of which is shown in Figure 2. Some of the solar magnetic field lines are carried outward by the radially flowing solar wind plasma. The combination of the radial plasma flow and the solar rotation leads to an Archimedes spiral shape for an average interplanetary field line. Thus a solar sector boundary is transported into interplanetary space in the form of an Archimedes spiral. The interplanetary sector pattern rotates with the sun so that a complete pattern sweeps past the earth every 27 days (the solar rotation period). The pattern shown in Figure 2 was approximately stationary in time for one year (1964) near the minimum of the 11-year sunspot cycle.

The evolution with time of the sector pattern (Wilcox and Colburn, 1970) is shown in Figure 3, which is basically a 27-day calendar. The top row represents the first 27-day rotation, the second row is the next 27-day rotation and so on. The shaded regions indicate the polarity of the interplanetary magnetic sector pattern. The stationary pattern with four sectors per solar rotation can be seen during the year 1964. With the rise of solar activity in 1965 the sector pattern begins to change. Usually one solar rotation is quite similar to the preceding rotation, but in the course of several rotations an appreciable change in the sector pattern may occur. From the discussion so far we see that the coronal magnetic field should contain many field lines connecting the photosphere to interplanetary space. A sharp boundary separates two adjacent sectors of opposite polarity.

We will next establish that the region to the west of a sector boundary (before the boundary in the sense of solar rotation) is a quiet region while the region just east of the boundary (after the boundary) is an active region. First we may examine the location of flares. Do they occur at random with respect to sector boundaries? We see in Figure 4 that the region close to a sector boundary is the most likely site for a flare. Figure 4 is a histogram of flare occurrence as a function of distance from a sector boundary, where distance is measured in terms of days of rotation (one day equals 13° longitude). The results by Bumba and Obridko (1969) have been extended by

Vladimirsky (private communication) using a larger body of observations. Vladimirsky confirms these results and shows that the most likely position for a flare is just eastward of (after) a sector boundary. Is this a particular property of flares or does it extend to other solar activity? Figure 5 shows the average position of plages in the sectors observed near solar minimum (Wilcox and Ness, 1967). In Figure 5 the preceding boundary of a sector is at about 50°W and the following sector boundary is at about 50°E. We can see that the plages are more numerous in the areas just after the sector boundary.

Does this same property exist in the extended coronal field near the earth? To answer this question we may use the earth's magnetic field as a probe, since this field is influenced by interplanetary conditions. Figure 6 shows the average response of geomagnetic activity as a sector boundary sweeps past the earth (Wilcox and Colburn, 1970). The abscissa labeled zero represents the time at which a sector is observed near the earth and the graph shows the situation four days before and four days after this time. We see that in the days before the sector boundary geomagnetic activity is monotonically decreasing, with an almost discontinuous increase near the boundary and a peak shortly thereafter. Thus we see again that the region just before the boundary is quiet and the region after the boundary is active.

Having established this boundary situation in the photosphere and at the distance of the earth we may inquire if the same effect exists in the corona. The vertical hatched regions in Figure 7 (Couturier and Leblanc, 1970) represent coronal enhancements observed with the Nancay radio interferometer at 169 MHz (1.77m). These are regions of enhanced electron density and temperature at altitudes between 0.2 and 0.5 solar radii above the photosphere. At the bottom of Figure 7 the interplanetary sector polarity is indicated. It can be seen that just after each sector boundary a coronal enhancement occurs. Thus we see that the large-scale structure of the corona is related to the photospheric and interplanetary sector patterns.

We examine now some unique observations of the coronal magnetic field in the regions 5 to 10 solar radii that were obtained when the Pioneer 6 spacecraft was occulted by the sun. The Faraday rotation of the microwave telemetry signal from the spacecraft was observed (Stelzried et al., 1970) during the time in which the line-of-sight from earth to Pioneer had its closest approach to the sun in this region. The positions of Pioneer, sun and earth are shown in Figure 8. The Faraday rotation observation gives the product of the line-of-sight magnetic field multiplied by the density along the column from earth to Pioneer. Most of the rotation occurs near the shortest distance to the sun where the densities and field magnitudes are largest. Occasionally the observed Faraday rotation showed a change of 30° within a time interval of 2 hours, as shown in Figure 9. This observation has been interpreted (Schatten, 1970) in terms of loops of magnetic field transported outward from the sun by plasma ejected from flares. The three sketches in Figure 10 show the situation before, during and after the event shown in Figure 9. The Faraday observations in Figure 9 agree in direction and in magnitude with observations of an active region in the photosphere assumed to be the source of the flare. The flares producing events of this kind are not particularly large, and we may therefore assume that often the corona contains such magnetic loop structures. It is rare to find evidence of such loops in the observations of the interplanetary field near the earth. It therefore seems that most of the loops return to the sun after having reached perhaps a distance of 10 solar radii.

Thus the corona may frequently contain transient magnetic loops reaching out five to ten solar radii.

Acknowledgements

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Wilcox, J. M., Severny, A. and Colburn, D. S.: 1969, Nature 224, 353.

Figure Captions

Figure 1. A schematic of the average position of a solar sector boundary during 1965. On each side of the boundary the weak background photospheric magnetic field is predominantly of a single polarity in equatorial latitudes on both sides of the equator (after Wilcox et al., 1969).

Figure 2. The plus signs (away from the sun) and minus signs (toward the sun) at the circumference of the figure indicate the direction of the measured interplanetary magnetic field during successive 3-hour intervals. The inner portion of the figure is a schematic representation of a sector structure of the interplanetary magnetic field that is suggested by these observations. The deviations about the average streaming angle that are actually present are not shown (after Wilcox and Ness, 1965).

Figure 3. 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 indicate an interpolated quasi-stationary structure during 1964 (after Wilcox and Colburn, 1970).

Figure 4. Histograms of frequency distribution of the time difference between the central meridian passage of spot groups and the position of solar sector boundaries for the groups: (a) with flares of importance 1 + or greater; (b) with a number of flares equal or greater than 10 (after Bumba and Obridko, 1969).

Figure 5. Superposed-epoch analysis of calcium plage structure obtained from the daily Fraunhofer Institute maps of the sun. The sectors 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 about 50°E longitude (after Wilcox and Ness, 1967).

Figure 6. Superposed epoch analysis of the magnitude of the planetary magnetic 3-hour-range indices Kp as a function of position with respect to a sector boundary. The abscissa represent position with respect to the sector boundary, measured in days, as the sector pattern sweeps past the earth. The solid line represents similar results obtained near solar minimum, the dots represent results in 1967 and the Xs represent results during 1968 (after Wilcox and Colburn, 1970).

Figure 7. Solar wind activity during solar rotation 1768. The vertical hatched regions represent CMP of coronal enhancements. a, solar wind velocity, b, proton density, c, temperature (upper and lower limits), d, interplanetary magnetic field magnitude, and e, sector polarity pattern (after Couturier and Leblanc, 1970).

Figure 8. Positions of the Pioneer 6 spacecraft, the sun and the earth at the time of observations of the Faraday rotation of the spacecraft telemetry signal.

Figure 9. Observed polarization of the telemetry radio signal from Pioneer 6 as a function of time (after Stelzried et al., 1970).

Figure 10. View from the north of the magnetic field model proposed to explain the transient events observed with Pioneer 6. The line-of-sight between Pioneer 6 and the earth is shown to the right of each panel (after Schatten, 1970).

AVERAGE SOLAR SECTOR BOUNDARY - 1965

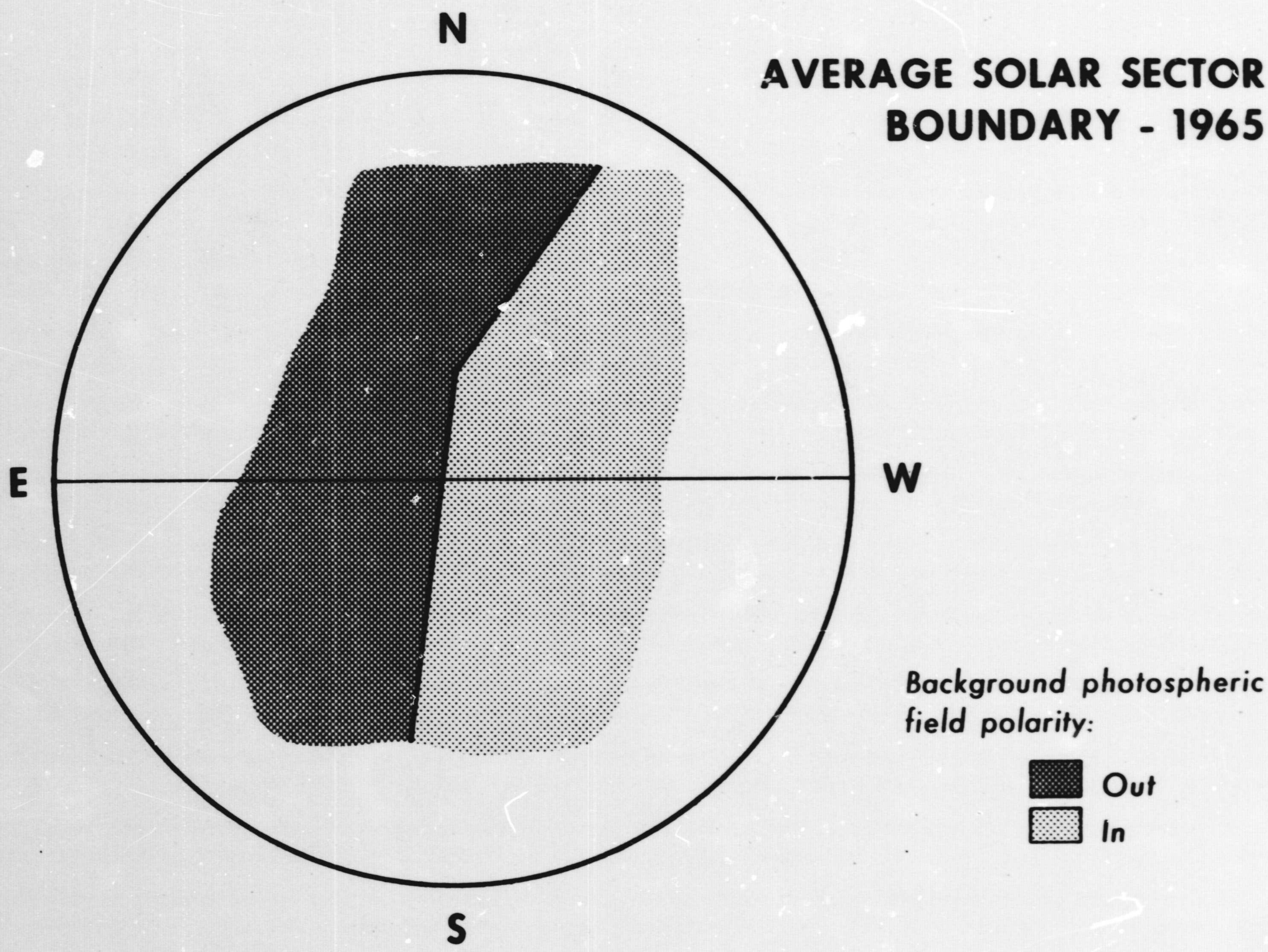
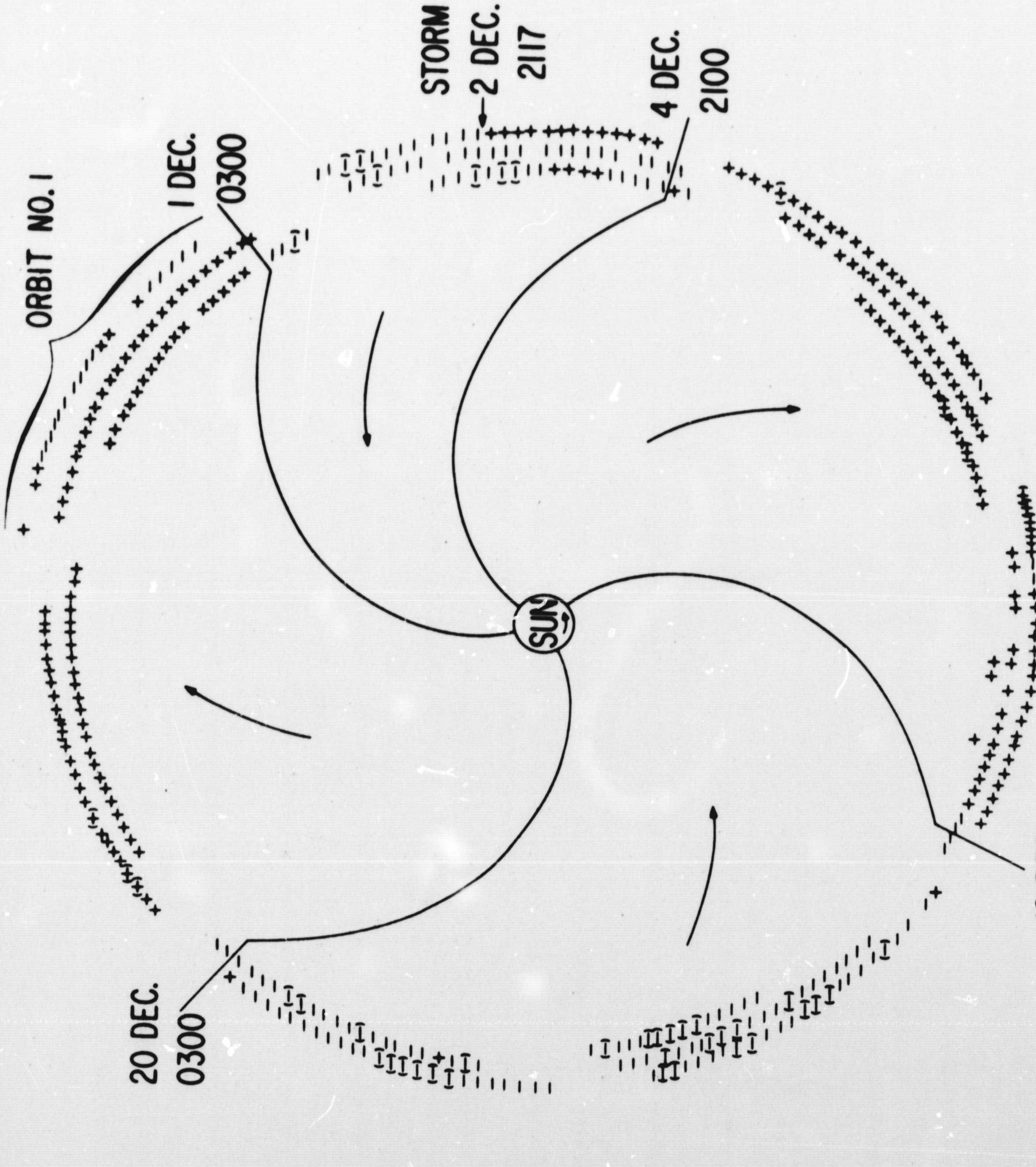


Figure 1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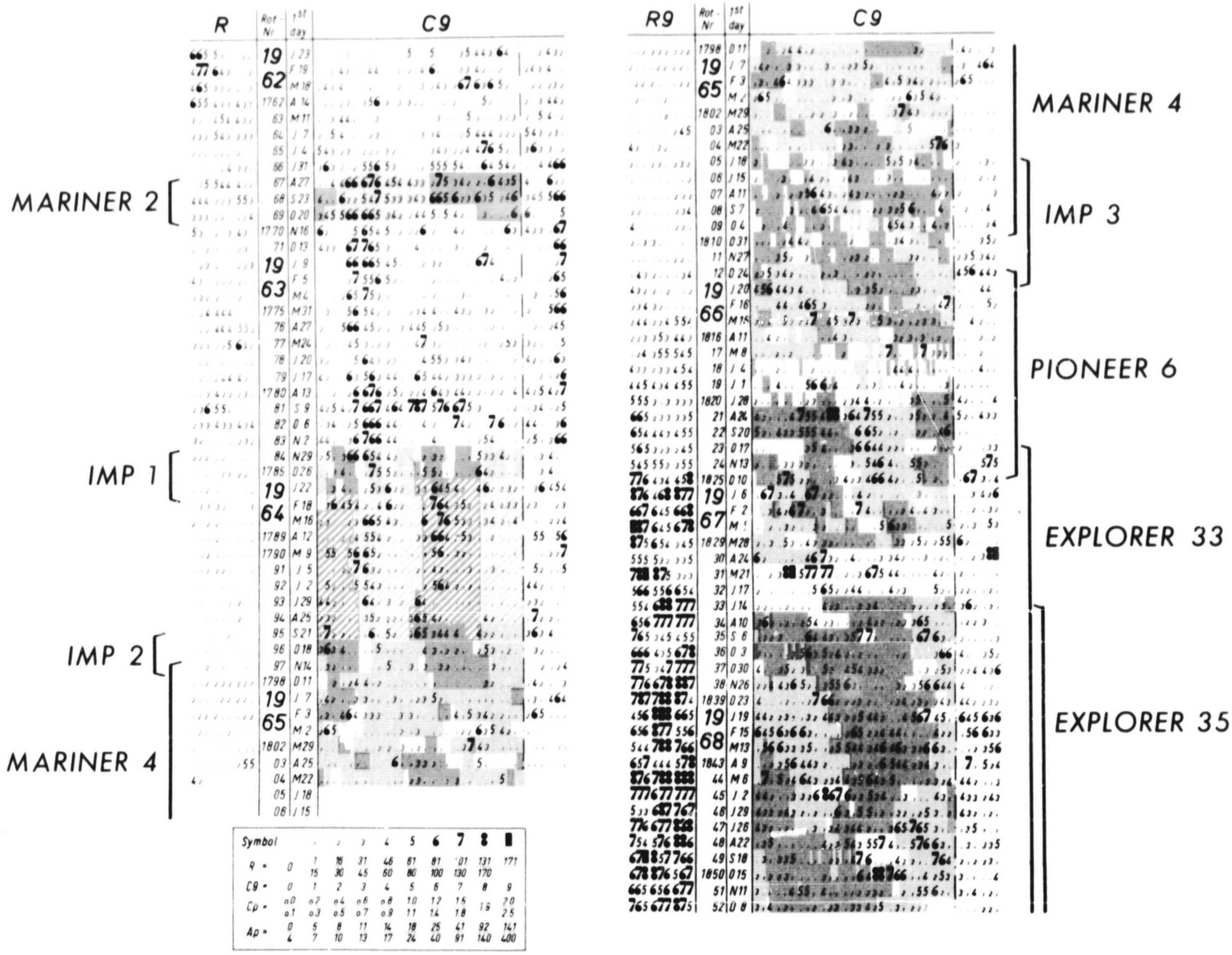
1 DEC.
0300
STORM
2 DEC.
2117
4 DEC.
2100
SUN
12 DEC
1200
20 DEC.
0300

Figure 2



Symbol		.	2	3	4	5	6	7	8	█
Q =	0	1 15	16 30	31 45	46 60	61 80	81 100	101 130	131 170	171
C9 =	0	1	2	3	4	5	6	7	8	9
Cp =	0.0 0.1	0.2 0.3	0.4 0.5	0.6 0.7	0.8 0.9	1.0 1.1	1.2 1.4	1.5 1.8	1.9	2.0 2.5
Ap =	0 4	5 7	8 10	11 13	14 17	18 24	25 40	41 91	92 140	141 400

Figure 3

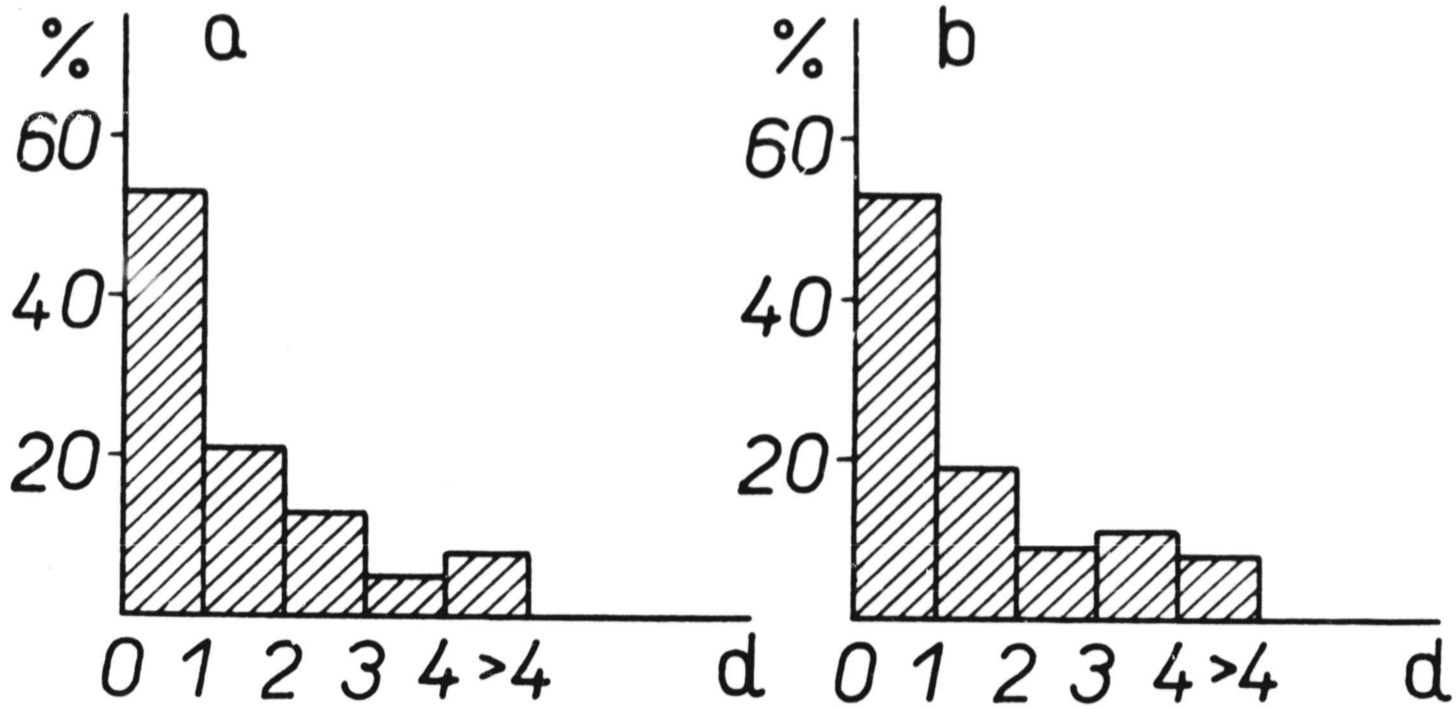
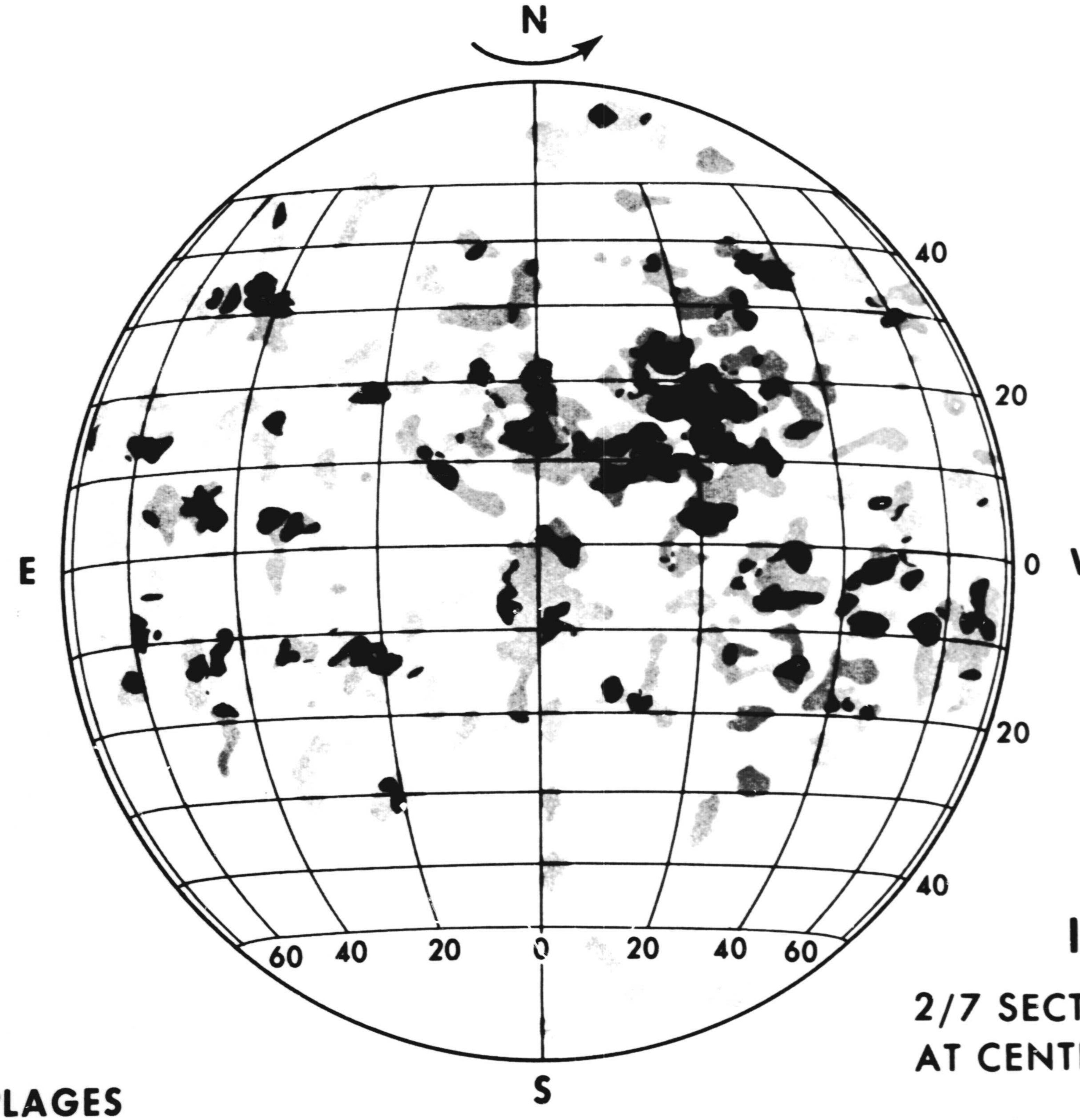


Figure 4



IMP-1

2/7 SECTORS CENTERED AT CENTRAL MERIDIAN

SECTORS EXTEND FROM ~50°W TO ~50°E

PLAGES
FRAUNHOFER INSTITUT

Figure 5

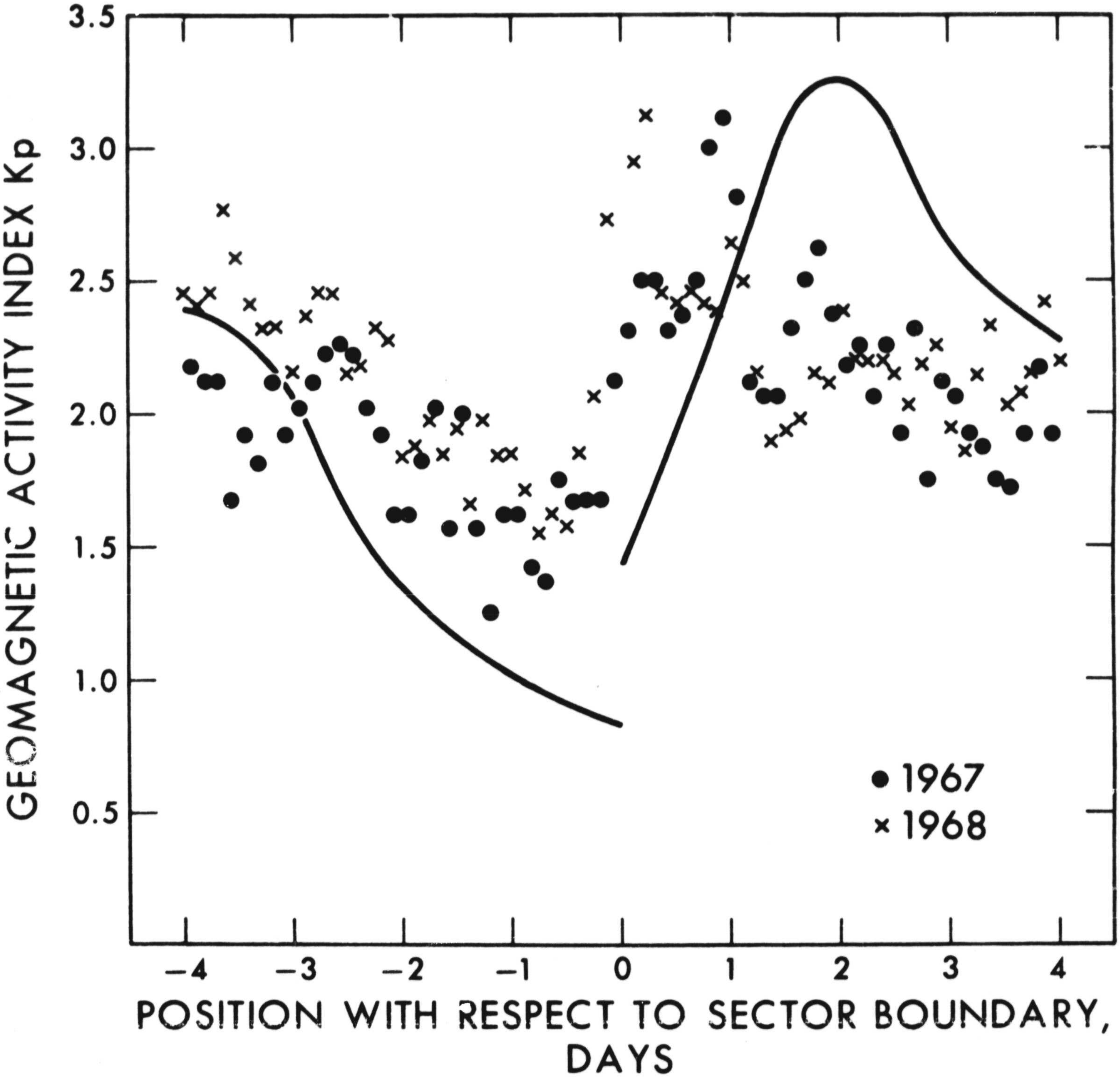
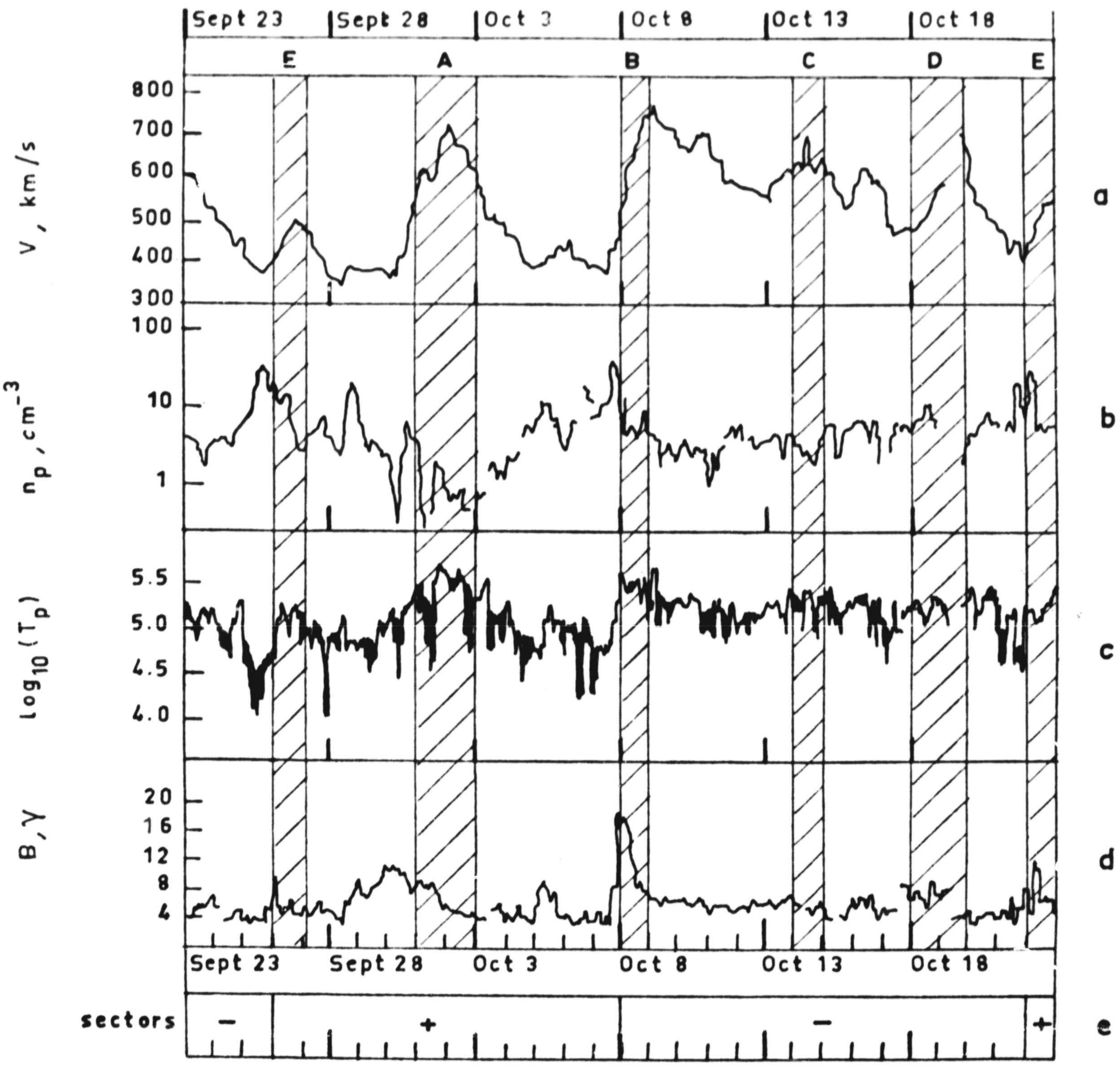

3.5
3.0
2.5
2.0
1.5
1.0
0.5
GEOMAGNETIC ACTIVITY INDEX Kp
−4
−3
−2
−1
0
1
2
3
4
POSITION WITH RESPECT TO SECTOR BOUNDARY, DAYS
● 1967
× 1968

Figure 6



Sept 23
Sept 28
Oct 3
Oct 8
Oct 13
Oct 18
E
A
B
C
D
E
V, km/s
800
700
600
500
400
300
a
n_p, cm^{-3}
100
10
1
b
$\log_{10}(T_p)$
5.5
5.0
4.5
4.0
c
B, γ
20
16
12
8
4
d
Sept 23
Sept 28
Oct 3
Oct 8
Oct 13
Oct 18
sectors
−
+
−
+
e

Figure 7

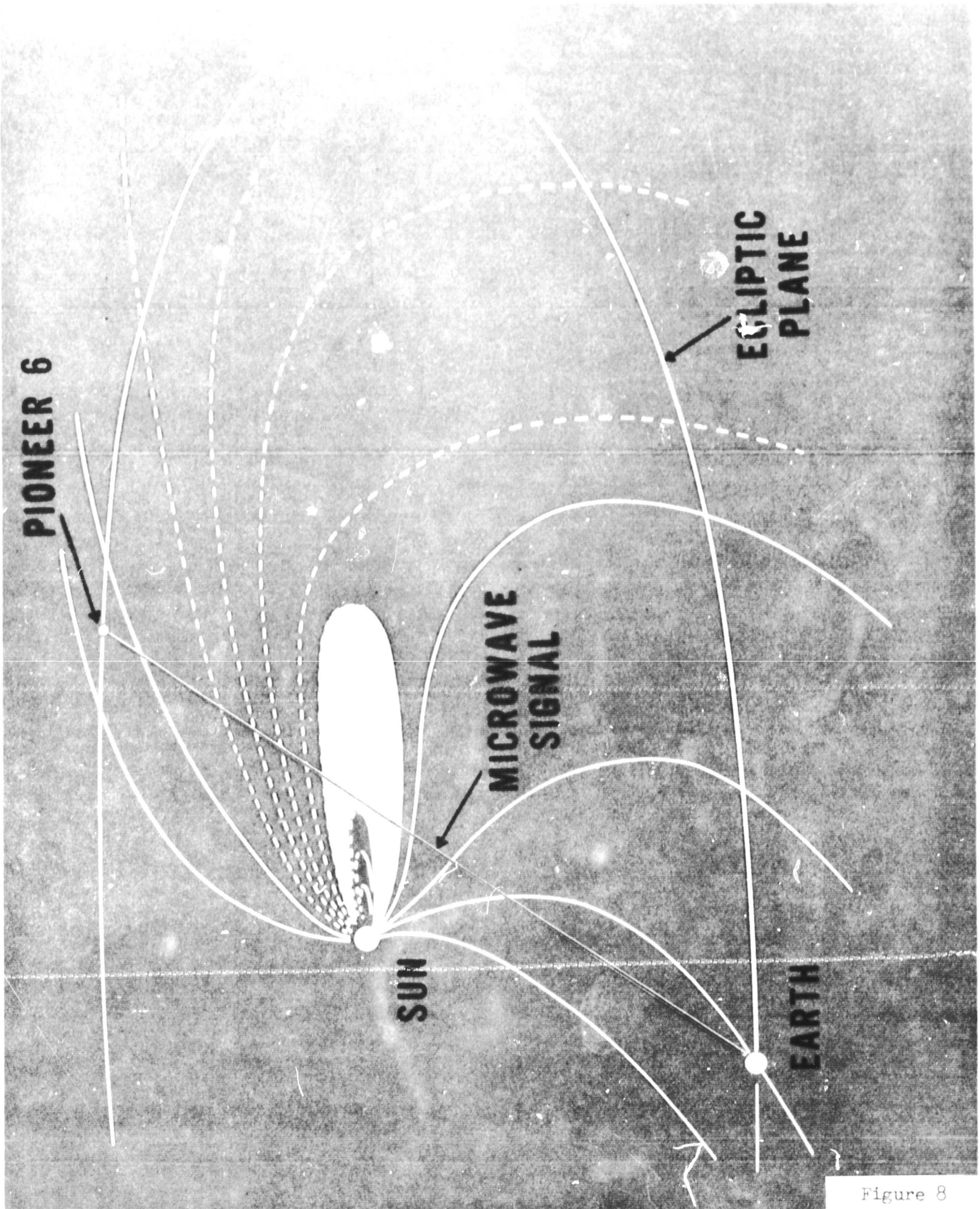
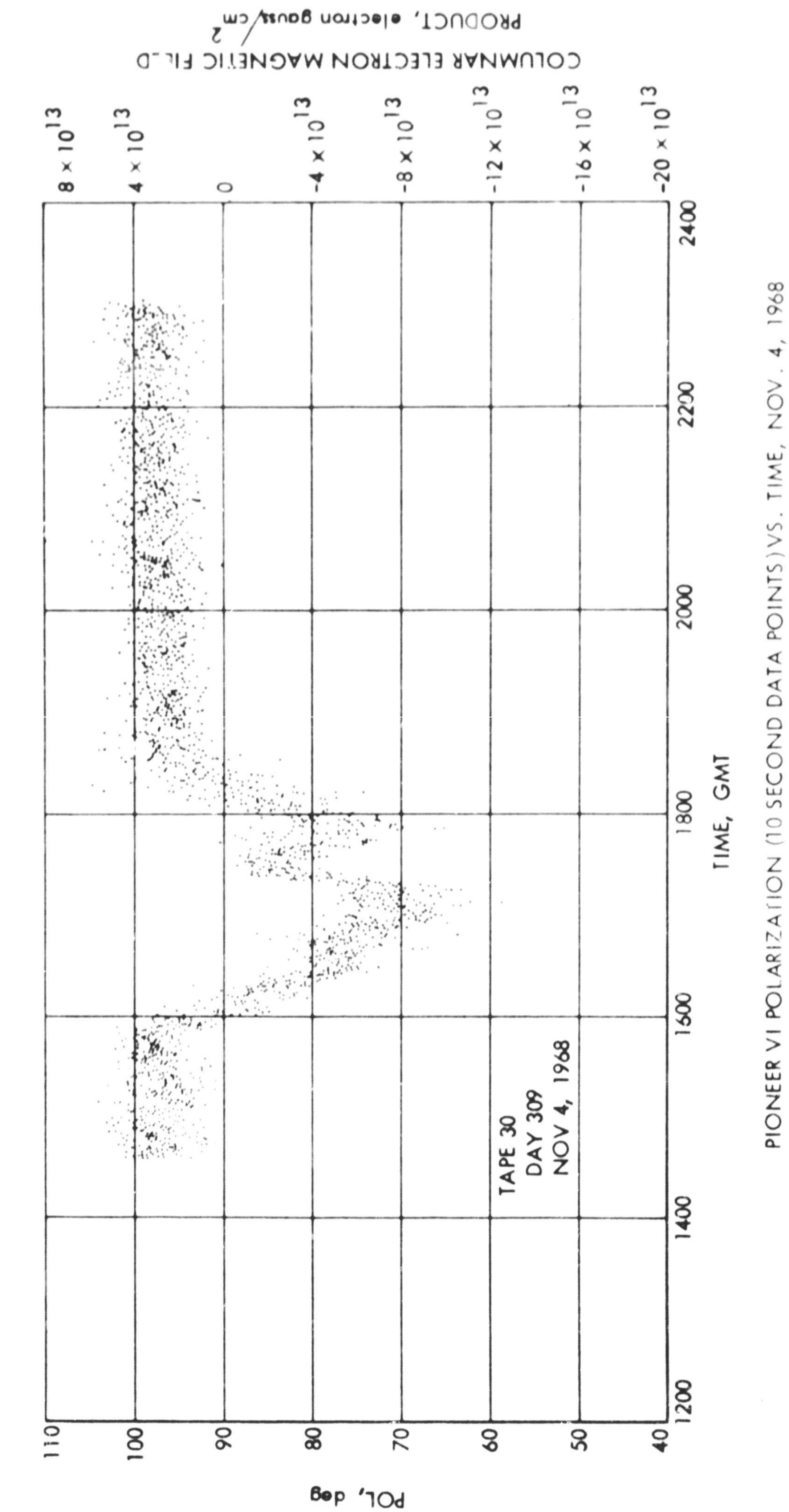


Figure 8



POL, deg
110
100
90
80
70
60
50
40
1200
1400
1600
1800
2000
2200
2400
TIME, GMT
TAPE 30
DAY 309
NOV 4, 1968
8 × 10^13
4 × 10^13
0
-4 × 10^13
-8 × 10^13
-12 × 10^13
-16 × 10^13
-20 × 10^13
COLUMNAR ELECTRON MAGNETIC FIELD
PRODUCT, electron gauss/cm^2
PIONEER VI POLARIZATION (10 SECOND DATA POINTS) VS. TIME, NOV. 4, 1968

Figure 9

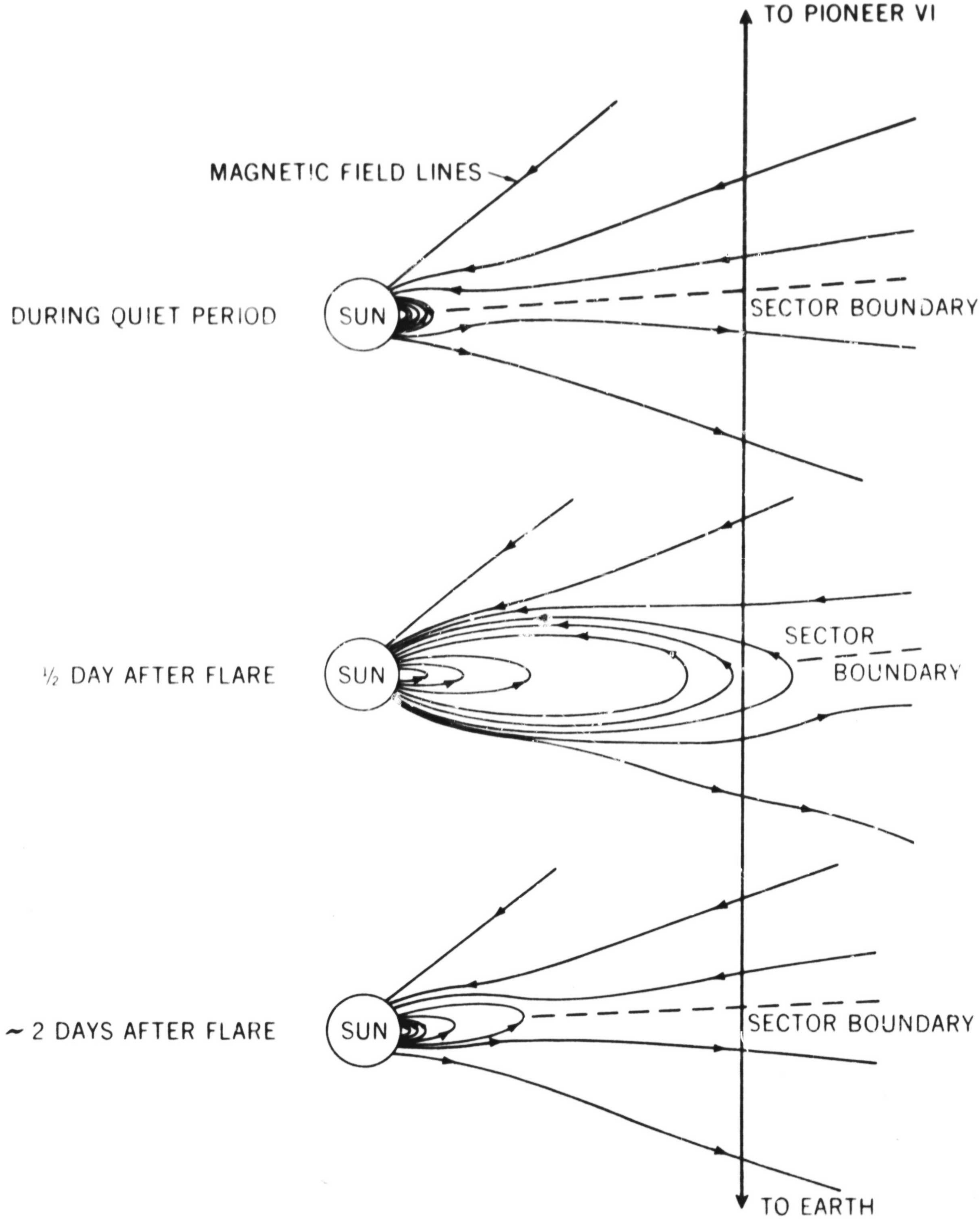

TO PIONEER VI
MAGNETIC FIELD LINES
DURING QUIET PERIOD
SUN
SECTOR BOUNDARY
½ DAY AFTER FLARE
SUN
SECTOR BOUNDARY
~ 2 DAYS AFTER FLARE
SUN
SECTOR BOUNDARY
TO EARTH

Figure 10

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Solar sector pattern						