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Abstract

The polarity of the interplanetary magnetic field has been inferred by Svalgaard from observations of the polar geomagnetic field during the interval 1926-1971. On the basis of a few years of spacecraft observations Rosenberg and Coleman have suggested that there may be an annual variation in the predominant polarity of the interplanetary field. The present analysis of forty-five years of inferred field polarity shows clearly an annual variation and also a variation of about twenty years, which we associate with the solar magnetic cycle. On the average the phase of the annual variation of the interplanetary field changes about 2-2/3 years after sunspot maximum, i.e. for about ten consecutive years the predominant polarity of the interplanetary field is away from the sun during the six-month interval in which the earth is at southern heliographic latitudes, and then a change of phase occurs such that for about the next ten years the predominant polarity is toward the sun while the earth is at southern heliographic latitudes. The annual variation changes its predominant polarity within a few days of the times when the heliographic latitude of the earth is zero.

Annual and Solar-Magnetic-Cycle Variations in the Interplanetary Magnetic Field, 1926-1971

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On the basis of a few years of observations by spacecraft of the interplanetary magnetic field, Rosenberg and Coleman (1969) have suggested that there should be an annual variation in the predominant polarity of the interplanetary field observed near the earth. During the six-month interval from December 7 to June 7 when the southern polar region of the sun is tipped toward the earth, the predominant polarity of the interplanetary field should be the same as the polarity of the southern solar polar region, and vice versa for the interval from June 7 to December 7. It should be emphasized that the sector structure (Wilcox, 1968) is nearly always present, and that the effect now being discussed can be thought of as a small modulation of the sector pattern. The effect proposed by Rosenberg and Coleman (1969) was based on a few years' observations, and its statistical significance has been discussed by Wilcox (1970).

Recently Svalgaard (1968, 1972) has discovered a method of inferring the polarity of the interplanetary magnetic field from observations of the polar geomagnetic field. This method has been confirmed using a prediction technique by Friis-Christensen, et al. (1971). The Danish Meteorological Institute has maintained observations of the geomagnetic field at Godhavn (invariant latitude 77.5°N) without interruption since 1926. Svalgaard (1972) has used this long series of observations to infer the polarity of the interplanetary magnetic field in the interval 1926-1971. We have used this inferred interplanetary magnetic field to look for an annual and also a solar-magnetic-cycle variation in the predominant polarity of the interplanetary field. The interval 1926-1971 has been divided into Bartels Rotations of length 27 days. For each Bartels Rotation the number of days with the inferred interplanetary field polarity directed toward the sun has been counted and plotted in Figure 1. Also shown in Figure 1 is a solid curve representing the heliographic latitude of the earth. We notice in Figure 1 that there are interevals of several years in which the inferred field polarity seems to be approximately in phase with the heliographic latitude of the earth, and that there are other intervals of several years in which the two appear to be out of phase.

Hale (1913) discovered that during one sunspot cycle (i.e. from minimum to minimum), in the northern solar hemisphere nearly all the preceding spots in a bipolar region will have north polarity and nearly all the following spots will have south polarity. During this same sunspot cycle in the southern solar hemisphere the polarities are reversed, i.e. the preceding spots will have south polarity and the following spots will have north polarity. During the next sunspot cycle all of these polarities are reversed. We thus arrive at the concept of a solar-magnetic-cycle whose period is equal to twice the period of the sunspot cycle. During the present century the sunspot cycles have lasted about ten years, and therefore the solar-magnetic cycle would be about twenty years. Although we have forty-five years of inferred interplanetary field polarities to use in the present investigation, this is still only a little more than two solar-magnetic cycles. We have therefore based our quantitative investigation of the results shown in Figure 1 on a model of the solar-magnetic cycle.

In the model of Babcock (1961), the magnetic polarity of the sun's polar regions changes near the times of sunspot maximum. Based on Babcock's model, we have constructed a test function during the interval 1926-1971. During the approximately ten-year intervals from one sunspot maximum (Waldmeier, 1961) to the following maximum in which the polarity of the sun's northern polar cap is south (into the sun), the test function is just equal to the heliographic latitude of the earth. During these intervals the inferred interplanetary field polarity points in Figure 1 might be expected to be in phase with the heliographic latitude of the earth. During the remaining approximately ten-year intervals from sunspot maximum to maximum during which the polarity of the sun's northern polar cap is north (out of the sun) the test function is equal to the negative of the heliographic latitude of the earth. Thus the test function has a 180° phase change at each sunspot maximum.

A cross-correlation has been computed as a function of lag between the test function described above and the inferred field points shown in Figure 1. The results of this cross-correlation are shown in Figure 2, which contains a regular series of peaks approximately one year apart. The peak near zero lag is the result of a comparison of the test function and the inferred field at the same times, while the peak near a lag of three years corresponds to a comparison of the test function with the inferred field displaced three years later. Thus the peak near a lag of three years would have the maximum amplitude if on the average the inferred field changed its phase approximately three years after sunspot maximum. As described above, by a phase change we mean a change in the predominant polarity of the inferred interplanetary field associated with a given algebraic sign of the heliographic latitude of the earth.

A plot of the amplitude of each peak in Figure 2 is shown in Figure 3. By interpolating in Figure 3 we see that the best resemblance between the test function and the inferred interplanetary field would come if the inferred field changed phase on the average about 2-2/3 years after sunspot maximum.

We may also compare the position of each peak in Figure 2 with respect to the yearly markers shown on the scale of the figure. For this purpose a centroid technique is used to define the position of each peak. If the predominant polarity of the inferred interplanetary field changed sign just at December 7 and June 7, then a peak in Figure 2 would be located exactly at the yearly marker, since the test function, which is by definition always either in phase or out of phase with the heliographic latitude of the earth, changes its algebraic sign on December 7 and June 7, when the heliographic latitude of the earth is equal to zero. The position of several of the peaks in Figure 2 with respect to their yearly markers is plotted in Figure 4. The peaks near the maximum shown in Figure 3 (i.e. near a lag of three years) have positions within a few days of their yearly markers. This indicates that on the average the inferred interplanetary field changed the direction of its predominant polarity within a few days of the times when the heliographic latitude of the earth was equal to zero. Actually we might expect that the interplanetary field would change its predominant polarity on about December 11 and June 11 because of the four-day transit time of the solar wind from near the sun to the earth.

We can only offer tentative comments on the physical interpretation of these results. The fact that on the average the predominant polarity of the inferred field changes direction within a few days of the times when the heliographic latitude of the earth is zero suggests that most of the inferred field designations are correct, and that the relation between the inferred field and our test function has considerable physical significance. Severny, et al. (1970) have shown that the mean solar field (i.e. the sun observed as a star) and the interplanetary field observed with spacecraft near the earth are very similar. Schatten (1970) has suggested that perhaps this result should be taken rather literally, i.e. that the interplanetary field observed near the earth is indeed some kind of average of the fields on the visible disk of the sun. This point of view is consistent with the results reported here, i.e. during the six-month interval in which a given solar pole is tipped toward the earth its polarity will influence the interplanetary magnetic field. On the basis of this interpretation we would say that the interpolated peak lag of about 2-2/3 years shown in Figure 3 would mean that on the average the polarity of the solar polar regions changed about 2-2/3 years after sunspot maximum. In 1957 and 1958 the polarity of the sun's polar regions changed rather near sunspot maximum (Babcock, 1959), but the last sunspot maximum occurred in 1968 and the polarity of the sun's polar regions did not change until the latter part of 1971 at the earliest (<u>Howard</u>, 1972). Thus our result appears to be consistent with the rather meager observations of changes in the large-scale predominant polarity of the sun's polar regions.

In any case, our result over an interval of 45 years is probably the most direct evidence for a continuing change of the predominant polarity of the large-scale solar magnetic field with a period equal to the sunspot magnetic cycle, i.e. approximately twenty years during this century.

We thank Robert Howard, Leif Svalgaard, and particularly Kenneth H. Schatten for helpful discussions. This work was supported in part by the Office of Naval Research under Contract N00014-67-A-0112-0068, by the National Aeronautics and Space Administration under Grant NGR 05-020-559, and by the National Science Foundation under Grant GA-31138.

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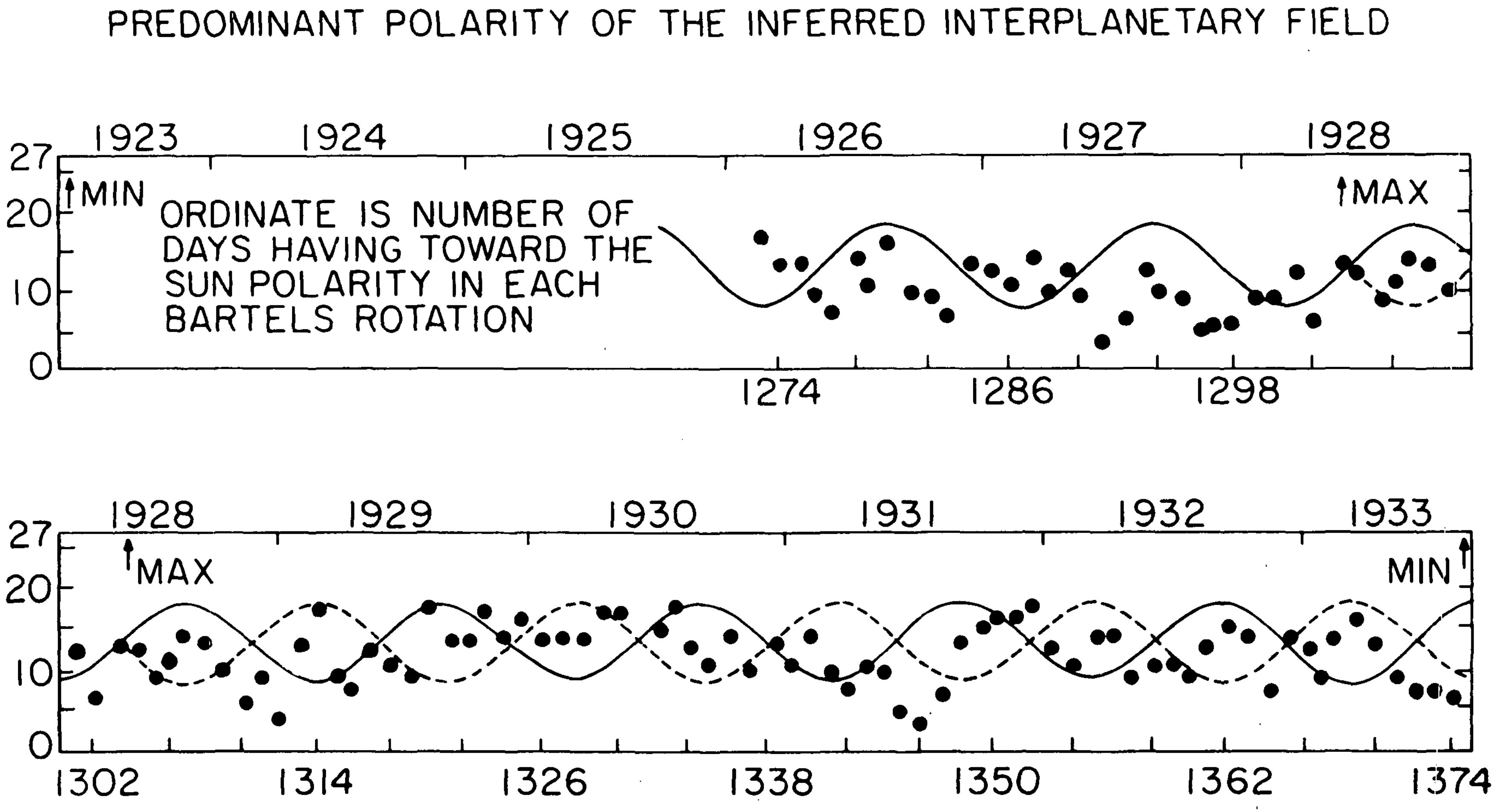
Figure Captions

Fig. 1. Each point represents the number of days within a Bartels Rotation of length 27 days that have the inferred interplanetary magnetic field polarity directed toward the sun. The solid curve is the heliographic latitude of the earth (with extrema at $\pm 7.25^{\circ}$), and the dashed curve represents the intervals in which the test function described in the text is out of phase with the heliographic latitude of the earth.

Fig. 2. Cross-correlation as a function of lag of the test function described in the text and the points shown in Figure 1, i.e. the predominant polarity of the inferred interplanetary field. The meaning of the arrow is described in the caption to Figure 3.

Fig. 3. The amplitude of each peak in Figure 2 plotted as a function of the years after sunspot maximum. By interpolation of the curve between the yearly points, the maximum correspondence between the test function and the inferred interplanetary field would occur at a lag of about 2-2/3 years, i.e. when the inferred interplanetary field changed phase about 2-2/3 years after sunspot maximum. This position is indicated in Figures 2 and 4 with an arrow.

Fig. 4. The position of some of the peaks in Figure 2 with respect to the yearly markers. If a peak occurred exactly at the yearly marker this would mean that the predominant polarity of the inferred interplanetary field changed direction exactly when the heliographic latitude of the earth was equal to zero. The curve is dashed between years 2 and 3 to indicate that the precise form of the interpolation is uncertain. The meaning of the arrow is described in the caption to Figure 3.



PREDOMINANT POLARITY OF THE INFERRED INTERPLANETARY FIELD

ORDINATE IS NUMBER OF DAYS HAVING TOWARD THE SUN POLARITY IN EACH BARTELS ROTATION

Figure 1a

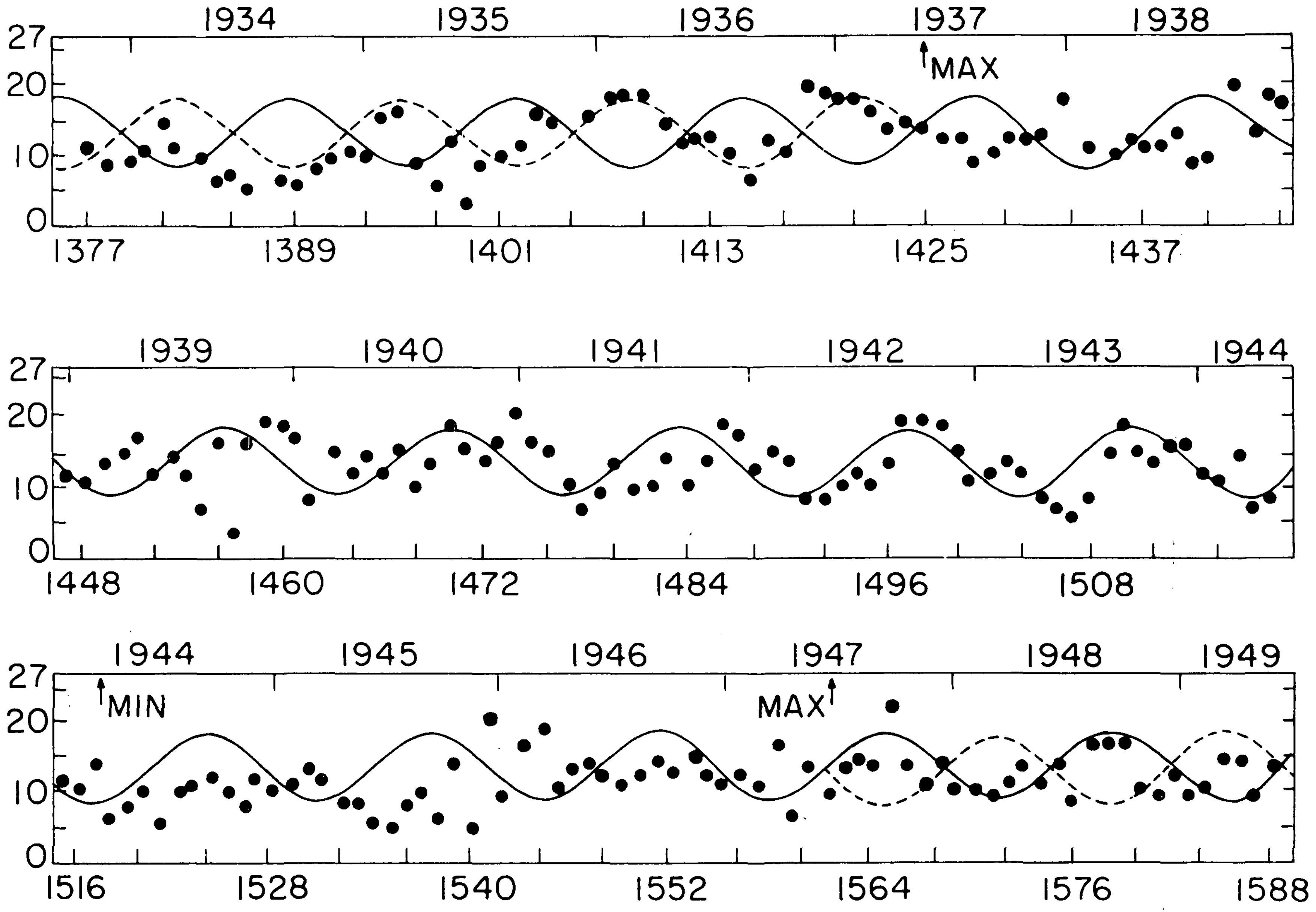

1934
1935
1936
1937
1938
MAX
27
20
10
0
1377
1389
1401
1413
1425
1437
1939
1940
1941
1942
1943
1944
27
20
10
0
1448
1460
1472
1484
1496
1508
1944
1945
1946
1947
1948
1949
MIN
MAX
27
20
10
0
1516
1528
1540
1552
1564
1576
1588

Figure 1b

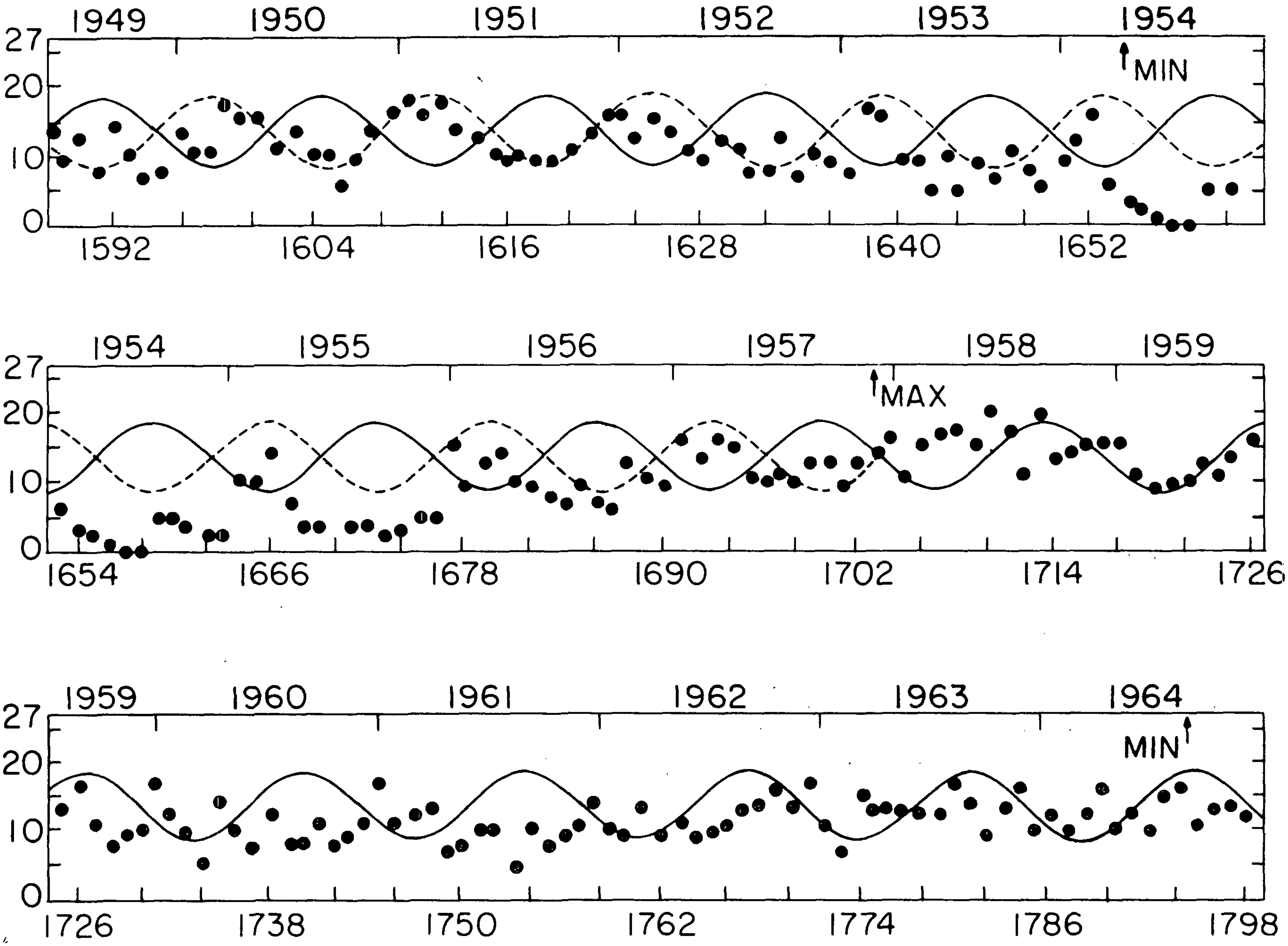

1949
1950
1951
1952
1953
1954
MIN
27
20
10
0
1592
1604
1616
1628
1640
1652
1954
1955
1956
1957
1958
1959
MAX
1654
1666
1678
1690
1702
1714
1726
1959
1960
1961
1962
1963
1964
MIN
1726
1738
1750
1762
1774
1786
1798

Figure 1c

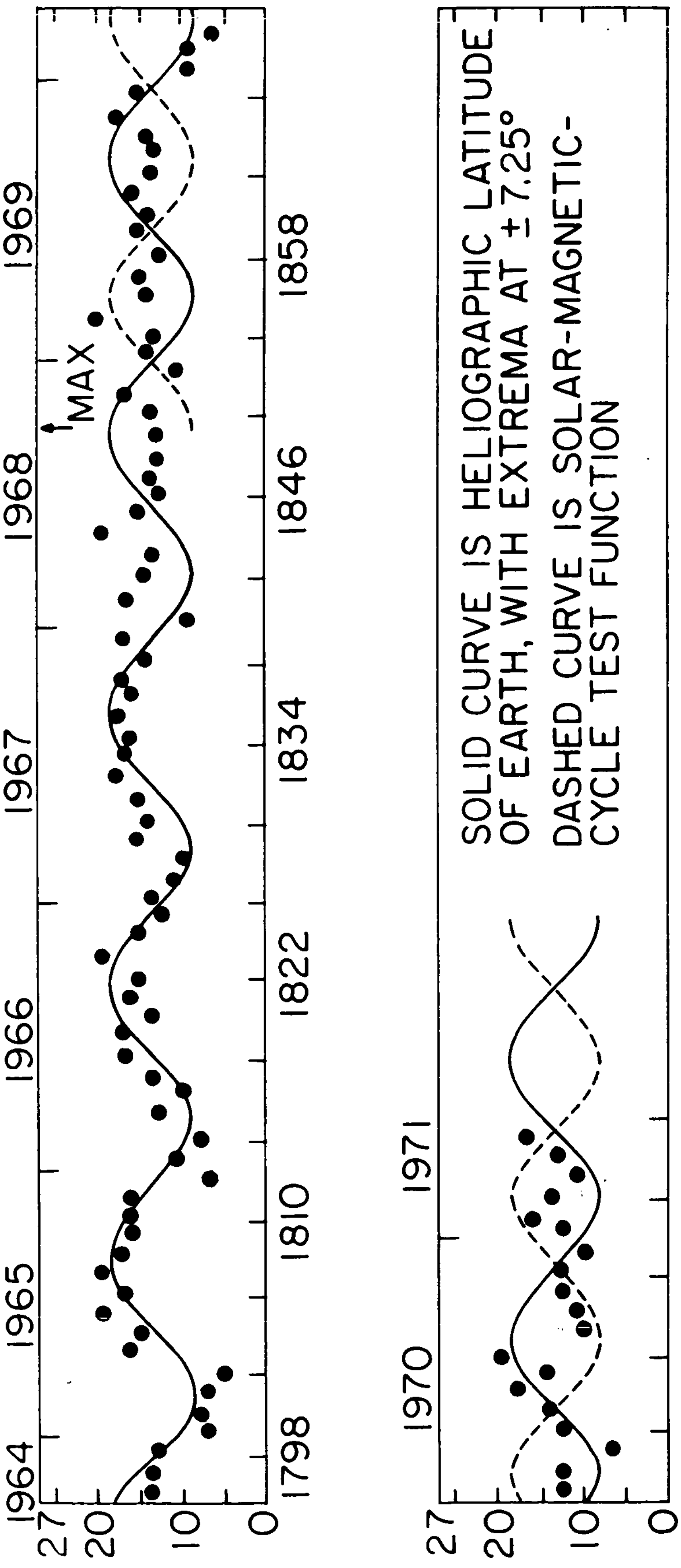
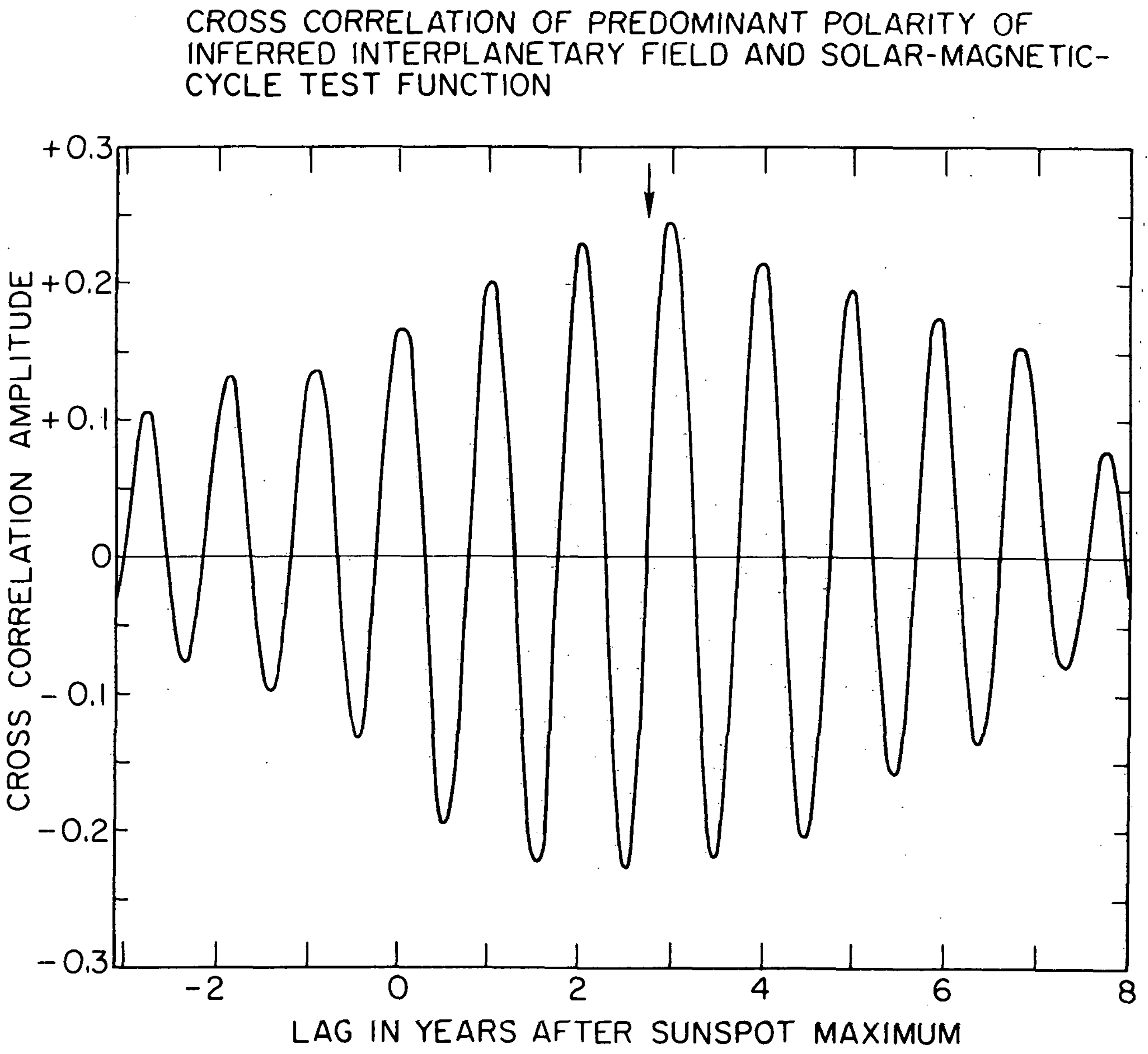
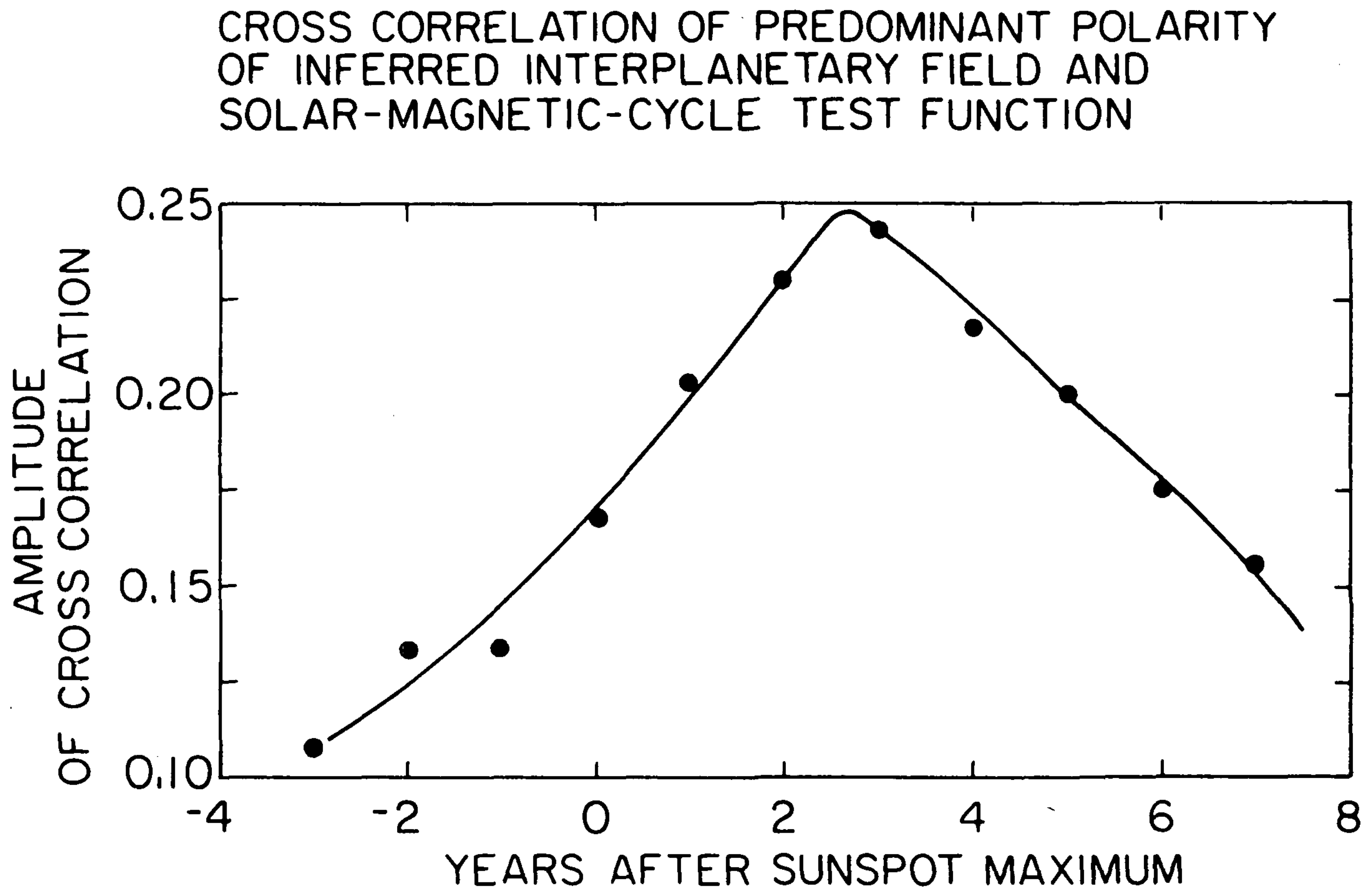

27
20
10
0
1964
1965
1966
1967
1968
1969
1798
1810
1822
1834
1846
1858
MAX
27
20
10
0
1970
1971
1870
1882
SOLID CURVE IS HELIOGRAPHIC LATITUDE
OF EARTH, WITH EXTREMA AT ± 7.25°
DASHED CURVE IS SOLAR-MAGNETIC-
CYCLE TEST FUNCTION

Figure 1d



CROSS CORRELATION OF PREDOMINANT POLARITY OF INFERRED INTERPLANETARY FIELD AND SOLAR-MAGNETIC-CYCLE TEST FUNCTION

Figure 2



CROSS CORRELATION OF PREDOMINANT POLARITY OF INFERRED INTERPLANETARY FIELD AND SOLAR-MAGNETIC-CYCLE TEST FUNCTION

Figure 3

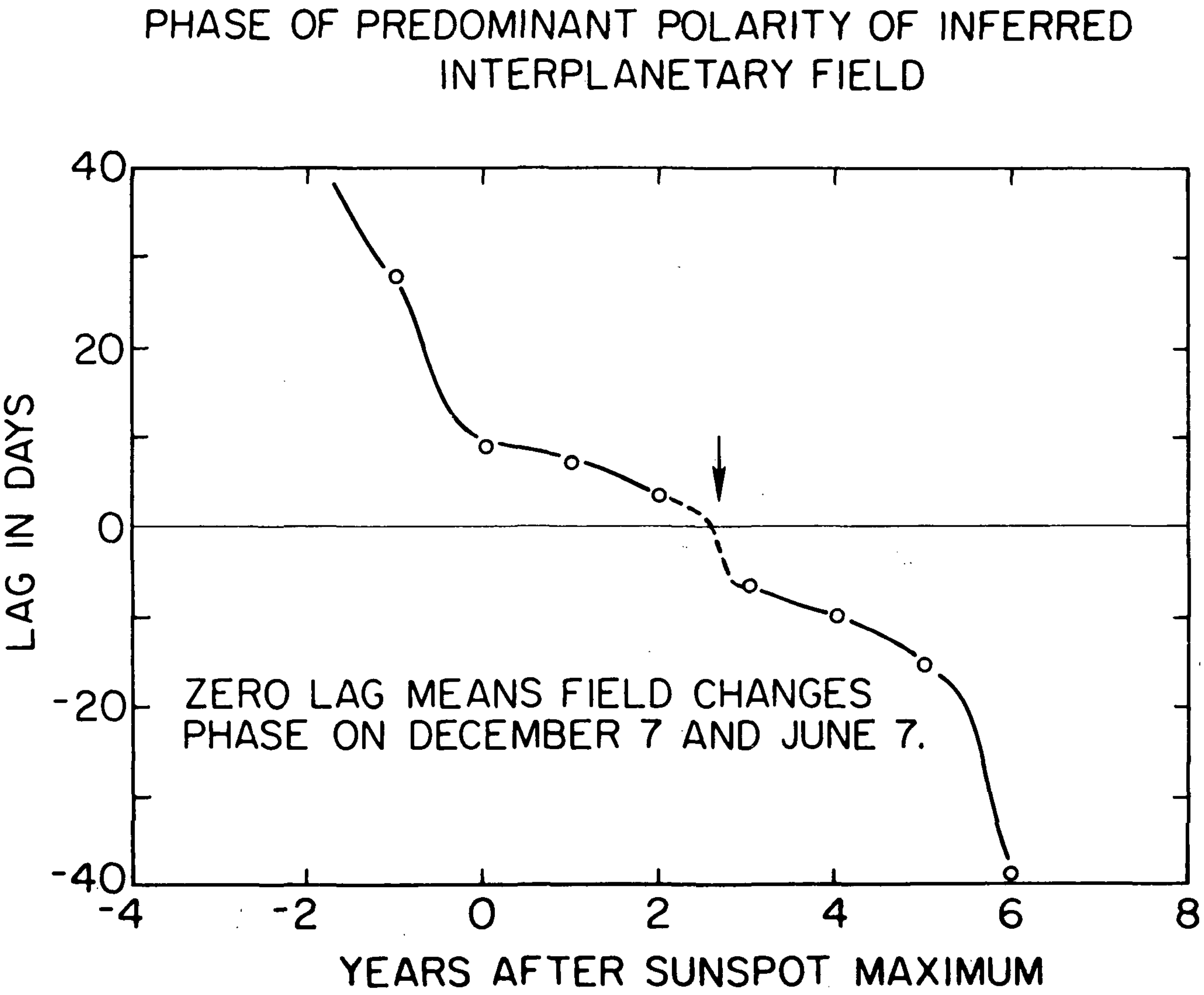

PHASE OF PREDOMINANT POLARITY OF INFERRED INTERPLANETARY FIELD
LAG IN DAYS
40
20
0
-20
-40
-4
-2
0
2
4
6
8
YEARS AFTER SUNSPOT MAXIMUM
ZERO LAG MEANS FIELD CHANGES PHASE ON DECEMBER 7 AND JUNE 7.

Figure 4

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13. ABSTRACT

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