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

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The polarity of the interplanetary magnetic field has been inferred by Svalgaard (1972) 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 (1969) have suggested that there may be an annual variation in the predominant polarity (toward or away from the sun) of the interplanetary field. The present analysis of 45 years of inferred field polarity clearly shows an annual variation and also a variation of about 20 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 ⅔ years after sunspot maximum, i.e., for about 10 consecutive years the predominant polarity of the interplanetary field is away from the sun during the 6-month interval in which the earth is at southern heliographic latitudes, and then a change of phase occurs such that for about the next 10 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 0.

On the basis of a few years of spacecraft observations of the interplanetary magnetic field, *Rosenberg and Coleman* [1969] have suggested that there should be an annual variation in the predominant polarity (toward or away from the sun) of the interplanetary field observed near the earth. During the 6-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 that 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 the effect now being discussed can be thought of as a small modulation of the sector pattern; i.e., when the southern polar region of the sun is tipped toward the earth, the interplanetary sectors having the polarity of the southern solar polar region have an increased observed width, and vice versa. The effect proposed by *Rosenberg and Coleman* [1969] was based on a few years of observation, and its limited statistical significance has been discussed by *Wilcox* [1970]. However, the present work appears to confirm the observational effect proposed by *Rosenberg and Coleman* [1969].

Recently *Svalgaard* [1968, 1972] discovered a method of inferring the polarity of the interplanetary magnetic field from observations of the polar geomagnetic field. This method has been confirmed by *Friis-Christensen et al.* [1971] with a prediction technique. The Danish Meteorological Institute has maintained observations of the geomagnetic field at Godhavn (77.5°N invariant latitude) 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 27 days long. For each Bartels' rotation the number of days with the inferred interplanetary field polarity directed toward the sun has been counted and is plotted in Figure 1. Also shown in Figure 1 is the heliographic latitude of the earth. We notice in Figure 1 that there are intervals 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 they 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 having a period equal to twice that of the sunspot cycle. During the present century the sunspot cycles have lasted about 10 years, and therefore the solar-magnetic cycle would be about 20 years. Although we have 45 years of inferred interplanetary field polarities for 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 polar regions of the sun changes near the times of sunspot maximum. On the basis of Babcock's model we have constructed a test function during the interval 1926–1971. During the approximately 10-year intervals from one sunspot maximum [*Waldmeier*, 1961] to the following maximum, when the polarity of the northern polar cap of the sun is south (into the sun), the test function is just equal to the heliographic latitude of the earth. During these intervals the points of inferred interplanetary field polarity in Figure 1 might be expected to be in phase with the heliographic latitude of the earth. During the remaining ~10-year intervals from sunspot maximum to maximum, when the polarity of the northern polar cap of the sun 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 ~1 year apart. The peak near

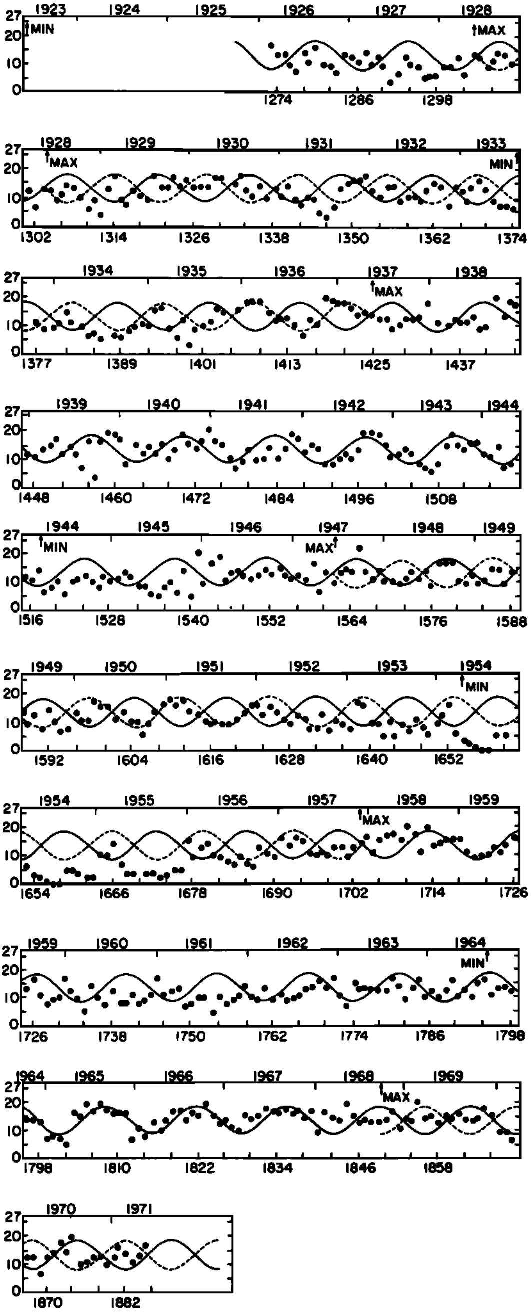

Fig. 1. (Opposite) The predominant polarity of the inferred interplanetary field. Each point represents the number of days within a Bartels' rotation 27 days long that have the inferred interplanetary magnetic-field polarity directed toward the sun. The ordinate is the number of days with polarity toward the sun in each Bartels' rotation. Solid curve, the heliographic latitude of the earth (with extremes at ±7.25°); dashed curve, the intervals in which the solar-magnetic-cycle test function described in the text is out of phase with the heliographic latitude of the earth.

the zero lag is the result of a comparison of the test function and the inferred field at the same times, whereas the peak near a lag of 3 years corresponds to a comparison of the test function with the inferred field displaced 3 years later. Thus the peak near a lag of 3 years would have the maximum amplitude if on the average the inferred field changed its phase ~3 years after sunspot maximum. As was 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 ⅔ 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 on December 7 and June 7, a peak in Figure 2 would be located exactly at the yearly marker, since the test function, which is by definition always either in 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 0. 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 3 years, have positions within a few days of their yearly markers. This finding 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 0. Actually, we might expect that the interplanetary field would change its predominant polarity on about December 11 and June 11 because of the 4-day transit time of the solar wind from near the sun to the earth.

We can only offer tentative comments on the

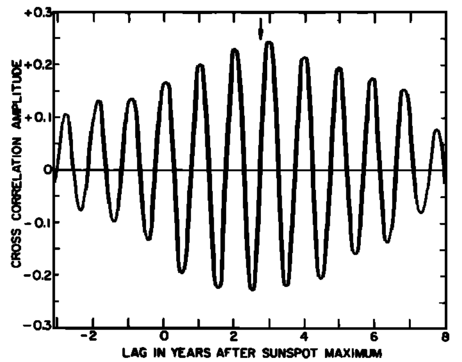

Fig. 2. Cross correlation as a function of lag of the test function described in the text and the points shown in Figure 1, i.e., the predominant polarity of the inferred interplanetary field. The meaning of the arrow is described in the legend for Figure 3.

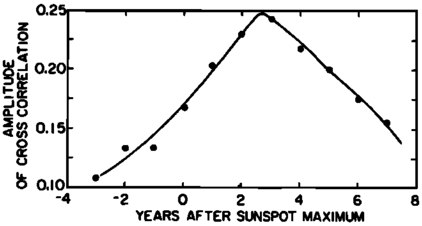

Fig. 3. The amplitude of each peak in Figure 2 plotted as a function of the years after sunspot maximum. By interpolation of the curve between the yearly points the maximum correspondence between the test function and the inferred interplanetary field would occur at a lag of about 2 ⅔ years, i.e., when the inferred interplanetary field changed phase about 2 ⅔ years after sunspot maximum. This position is indicated in Figures 2 and 4 with an arrow.

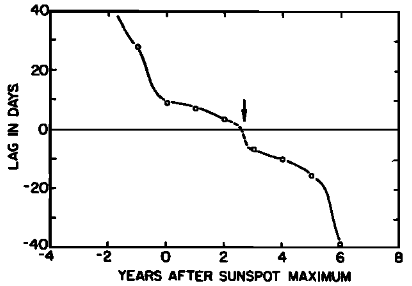

Fig. 4. The position of some of the peaks in Figure 2 with respect to the yearly markers. If a peak occurred exactly at the yearly marker, the predominant polarity of the inferred interplanetary field changed direction exactly when the heliographic latitude of the earth was equal to 0. The zero lag means the field changed phase on December 7 and June 7. 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 legend for Figure 3.

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 0 suggests that most of the inferred field designations are correct and 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 4 or 5 days later with spacecraft near the earth are very similar in polarity and that the magnitudes are consistent with a $1/R^2$ scaling from the sun to the earth. *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 6-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 ⅔ years in Figure 3 would mean that on the average the polarity of the solar polar regions changed about 2 ⅔ years after sunspot maximum. In 1957 and 1958 the polarity of the polar regions of the sun changed rather near sunspot maximum [*Babcock,* 1959], but the last sunspot maximum occurred in 1968, and the polarity of the sun's polar regions changed no earlier than the latter part of 1971 [*Howard,* 1972]. Thus our result appears to be consistent with the rather meager observations of changes in the large-scale predominant polarity of the polar regions of the sun.

Our result may also be related to a persistence of the solar polar polarities in the large-scale solar fields at lower latitudes. More definite information on this point must await further studies of the large-scale solar field and the manner in which the observed interplanetary field is formed from the solar field.

In any case, our result over a 45-year interval 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., ~20 years during this century.

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REFERENCES

Babcock, H. W., The sun's polar magnetic field, *Astrophys. J., 130,* 364–365, 1959.

Babcock, H. W., The topology of the sun's magnetic field and the 22-year cycle, *Astrophys. J., 133,* 572–587, 1961.

Friis-Christensen, E., K. Lassen, J. M. Wilcox, W. Gonzalez, and D. S. Colburn, Interplanetary magnetic sector polarity from polar geomagnetic field observations, *Nature Phys. Sci., 233,* 48–50, 1971.

Hale, G. E., Preliminary results of an attempt to detect the general magnetic field of the sun, *Astrophys. J., 38,* 27–98, 1913.

Howard, R., Polar magnetic fields of the sun: 1960–1971, submitted to *Solar Phys.,* 1972.

Rosenberg, R. L., and P. J. Coleman, Jr., Heliographic-latitude dependence of the dominant polarity of the interplanetary magnetic field, *J. Geophys. Res., 74,* 5611–5622, 1969.

Schatten, K. H., A 'source surface theory' corollary: The mean solar field–interplanetary field correlation, *Solar Phys., 15,* 499–503, 1970.

Severny, A., J. M. Wilcox, P. H. Scherrer, and D. S. Colburn, Comparison of the mean photospheric magnetic field and the interplanetary magnetic field, *Solar Phys., 15,* 3–14, 1970.

Svalgaard, L., Sector structure of the interplanetary magnetic field and daily variation of the geomagnetic field at high latitudes, *Geophys. Pap. R-6,* Danish Meteorolog. Inst., Charlottenlund, Denmark, August 1968.

Svalgaard, L., Interplanetary magnetic sector structure 1926–1971, *J. Geophys. Res., 77,* 4027–4033, 1972.

Waldmeier, M., *The Sunspot-Activity in the Years 1610–1960,* Zurich Schulthess & Co. AG, Zurich, Switzerland, 1961.

Wilcox, J. M., The interplanetary magnetic field: Solar origin and terrestrial effects, *Space Sci. Rev., 8,* 258–328, 1968.

Wilcox, J. M., Statistical significance of the proposed heliographic-latitude dependence of the dominant polarity of the interplanetary magnetic field, *J. Geophys. Res., 75,* 2587–2590, 1970.

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