USING DYNAMO THEORY TO PREDICT THE SUNSPOT NUMBER DURING SOLAR CYCLE 21

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Abstract. On physical grounds it is suggested that the sun's polar field strength near a solar minimum is closely related to the following cycle's solar activity. Four methods of estimating the sun's polar magnetic field strength near solar minimum are employed to provide an estimate of cycle 21's yearly mean sunspot number at solar maximum of 140 ± 20. We think of this estimate as a first order attempt to predict the cycle's activity using one parameter of physical importance based upon dynamo theory.

Introduction

A variety of methods have been used by many scientists to predict solar activity (Sargent, 1978 and references contained therein). Often they rely on time series analyses which assume implicitly that the solar dynamo has basic periodicities. These methods are questionable in that the basic periodicities, if any exist other than the 11-year cycle, can not be determined with the current uncertain set of sunspot numbers (Mayaud, 1977).

Other methods, such as that of Ohl (1968), are based upon some apparent precursor of sunspot number which the author has noted fits past solar cycles. These methods will work if some underlying, but as yet obscure, physical connection exists in these quantities. The method may not work, or may break down some time in the future, if it depends only upon the researcher's ability to notice an apparent high statistical but not necessarily physical correlation.

We would like to discuss a method based upon the solar dynamo mechanism. One aspect which is central to the solar activity cycle is that the magnetic flux from sunspots in a given cycle cancels the existing polar magnetic flux causing the polar fields to reverse (Babcock, 1961; Leighton, 1969; Parker, 1977 and Howard, 1977). Furthermore, it is the polar flux, wound by differential rotation into a subsurface toroidal flux, which emerges as the next cycle's sunspots Thus, on physical grounds, we believe the strength of the sun's polar magnetic field at minimum is related to the next cycle's sunspot activity. In this paper we test this hypothesis by several graphs which are basically a plot of the polar field strength (measured at solar minimum in various ways) versus the next cycle's maximum sunspot number, as determined during the past several sunspot cycles. These graphs provide a crude test of the Babcock dynamo model. We then use these graphs with our estimate of the polar field strength during the present sunspot minimum to ascertain a best estimate of this cycle's sunspot maximum.

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Polar Field Strength

Estimates of the polar magnetic field strength near sunspot minimum may be obtained from the shape of the corona at the time of solar eclipses, or by the amount of flattening of the "warped current sheet" at 1AU as obtained from interplanetary magnetic field measurements analysed in accordance with the methods of Rosenberg and Coleman (1969). A further and more direct estimate of polar field strength is obtained by observing the number of polar faculae.

The shape of the corona at eclipses may be used to obtain a measure of polar field strength in the following two ways. The Ludendorf index (Billings, 1966) may be used as a measure of coronal flattening and hence of polar field strength. Figure 1a shows the mean sunspot number versus the Ludendorf index. Each point represents the Ludendorf index for an eclipse near sunspot minimum (listed) versus the yearly mean sunspot number at the following solar maximum. The straight line through the origin is chosen as a best fit to the observations with the theoretical assumption that if there is a zero polar field at solar minimum corresponding to a zero Ludendorf index, the next solar maximum will have few, if any, sunspots. The June 1954 solar eclipse was remarkable in the flattening of the corona due to the symmetrical plumes over each pole and the huge equatorial streamers. It was also marked by a very high amount of solar activity the next cycle, suggestive that these ideas for predicting solar activity may have some validity.

It should also be noted that some of the scatter of the points near Ludendorf index 0.23 may be related to the possibility (Svalgaard, 1978) that the interplanetary and coronal fields may have increased progressively by a factor of two from 1900 to the present time The Ludendorf flattening would not reflect an overall change in solar field strengths, thus the rise in R_m from 1900 to 1922, to 1933, and to 1944 along nearly the same flattening index could be due to an increase in polar field strengths, not reflected in the flattening index. This can occur because the flattening index only measures the polar magnetic pressure relative to low latitude field and plasma pressure. The October 23, 1976 solar eclipse (Waldmeier and Weber, 1977) with a Ludendorf index equal to 0.36 (see arrow in Figure 1a) was used to estimate a maximum yearly mean sunspot number of 155 ± 25, with the uncertainty based upon the spread of the points near the index 0.23.

A second similar measure of polar field strength and subsequent solar activity may be obtained from the bending of high latitude polar plumes. This assumes that a higher polar field strength will bend the high latitude plumes more

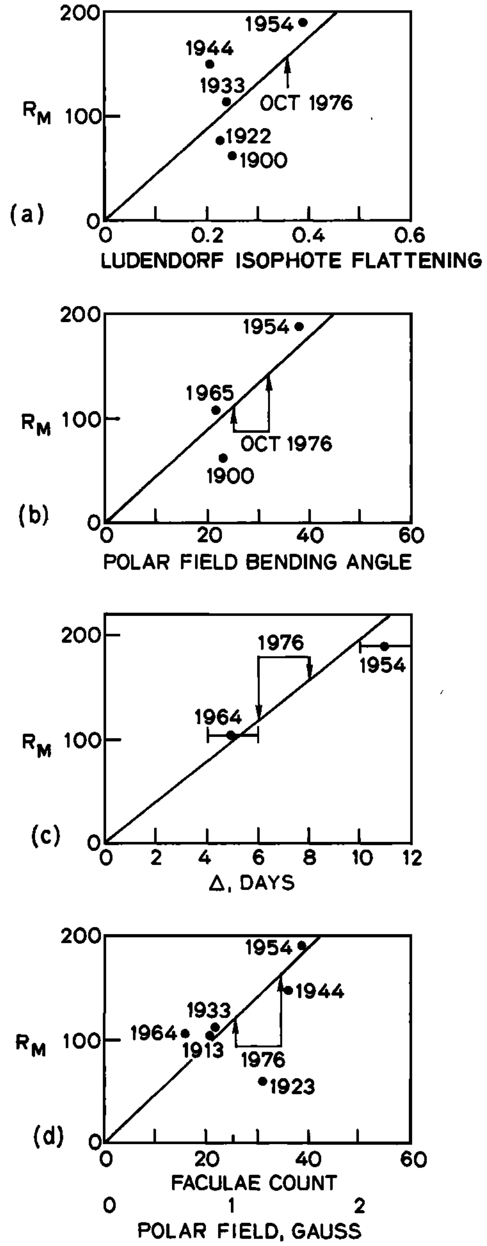

Fig. 1. (a) Sunspot number at maximum vs. the Ludendorf isophote flattening index at an eclipse near the preceding solar minimum. The arrow in this graph indicates cycle 21's Ludendorf index from which the cycle's sunspot maximum is estimated. (b) Sunspot number at maximum vs. Δ, a measure of the yearly variation of the predominant polarity of the interplanetary field near earth, a measure of polar magnetic field strength. The arrows as above. (c) Sunspot number at maximum vs. facular count in polar regions, and related polar field strength, at the preceding solar minimum. The arrows as above.

toward the solar equator (where the polar magnetic field pressure is balanced by low latitude field and coronal plasma pressure). The bending of the polar plumes was obtained by taking an average of the angle of the coronal plumes from the radial just above the photosphere at 60° latitude in the four quadrants seen at solar eclipses. Only those eclipse drawings near solar minimum where these angles could be determined were used in this study. In Figure 1b, the bending angle is plotted against the mean sunspot number of the following maximum. The line shows a best linear fit, again through the origin, assuming a zero bending angle corresponds to a zero following sunspot cycle. One can see a relation emerging between polar field strength (as determined by the bending angle) and the subsequent maximum's mean sunspot number. The value for the October 23, 1976 eclipse bending angle was obtained directly from eclipse photos and also from Waldmeier's (1977) eclipse drawing. These two estimates shown in Figure 1b provide an estimate for the next maximum's mean yearly sunspot number of 110-140.

The third estimate of polar field strength utilizes the model of a "warped current sheet" in interplanetary space, whose geometry depends upon the polar field strength (see Svalgaard and Wilcox, 1976). For a few years prior to and spanning sunspot minimum the dominant polarity of the interplanetary magnetic field as observed at the earth - which through the year is traveling ± 7° out of the solar equatorial plane - shows an annual variation. This is due to the fact that the sector boundary in interplanetary space is very nearly in the east-west direction. This flattening of the current sheet results from strong solar polar fields controlling coronal and interplanetary field configurations. Thus the stronger the flattening the stronger the polar fields and hence the ensuing sunspot maximum.

The flattening, Δ, may be obtained from interplanetary field measurements near solar minimum by determining the number of days per Bartels' rotation of toward-the-sun field polarity throughout one or more years. The amplitude of this curve, in days, throughout the year (as the earth swings between ± 7° heliographic latitude) is Δ. The interplanetary field observations are obtained from Svalgaard (1976). For a discussion of the relation between the number of days per Bartels' rotation of toward-the-sun polarity and the heliographic latitude of the earth see Schatten (1971). As the sun's polar field grows, the current sheet is flatter. Thus more variation exists in the number of days per Bartels' rotation of toward-the-sun field as the earth swings north and south of the solar equatorial plane. In Figure 1c, Δ near solar minimum is graphed with the following sunspot maximum yearly mean sunspot number, R_m. The curve is assumed to go through zero as with the previous graphs. The range of Δ near 1976 (shown as arrows) provide an estimate for the next sunspot maximum's mean yearly sunspot number of 135 ± 20. Again, the ability of the 1964 and 1954 data to fit a line through the origin is seen as supporting the view that subsequent sunspot peaks are related to polar field strengths.

Sheeley (1964, 1966, 1976) has suggested that the sun's polar field strengths may be estimated by a fourth method - counting the numbers of faculae at the poles. Annual averages of the polar fields from Mt. Wilson synoptic magnetic charts for the years available (1967 through 1975) confirm Sheeley's results. Sheeley also points out that the polar field magnitude tends to lag the sunspot number and that this is consistent with the model that the polar fields are produced by the poleward transport of flux that originates in bipolar magnetic regions in the lower latitude zones of solar activity. In Babcock's model, the polar fields near sunspot minimum are the source of the fields to generate the next activity maximum. We have compared the sum of north and south polar faculae counts (from Sheeley, 1976, Figure 1 but without his polarity determination) with the sunspot number. We found a better correlation between the polar faculae counts and the following sunspot maximum than with the preceding one. This supports the idea that the polar fields near minimum (when the polar fields are usually the greatest) predict the peak of the following cycle. To attempt a numerical estimate we have computed 3-year averages of the polar faculae counts centered about sunspot minimum and plotted them with the maximum yearly mean sunspot number of the next cycle. Figure 1d shows the result. The faculae count was a maximum at sunspot minimum for all minima except 1923 and 1954 when it was the largest in the declining phase of the cycle. The faculae count for the 1923 minimum may be biased by an unusually large count just after the 1917 maximum. As a rough estimate of the coming maximum we estimate a sunspot number of 120-160 by this method. It should be noted that analyzing the solar hemispheres separately would be interesting.

Further suggestion of a fairly high sunspot cycle comes from the work of Brown (1976) who noticed a correlation between solar activity at solar minimum with the following maximum. Utilizing such a correlation, with the added fact that this past minimum had the highest ever recorded value for mean sunspot number (13), suggests the new cycle could have a mean value of 150 ± 25, near solar maximum.

Sunspot Number of Solar Cycle 21

Utilizing the previous estimate of polar magnetic field strength obtained near solar minimum, we have four estimates of cycle 21's maximum mean yearly sunspot number. These are 155 ± 25, 125 ± 15, 135 ± 20, and 140 ± 20. Averaging these four together we get a value of 140 ± 20 for the mean yearly maximum sunspot number of cycle 21. We have kept the ± 20 uncertainty rather than reducing its value because the four methods are based on the same physical principles, and any uncertainties in the four methods may not be independent.

An estimate of the time of rise of the solar activity cycle may be found from Waldmeier's (1935) formulae, which gives the rise time as 3.4 ± 0.5 years. Placing the solar minimum in July 1976 gives the time of maximum to be December 1979, to within half a year.

Figure 2 shows our estimate of sunspot number for cycle 21 as a solid line with dashed lines around it to indicate the limits of our estimate. The mean of cycles 8-20, shown as a dotted line, indicates that we predict cycle 21 to be significantly larger than average.

It is important to add that we are making a prediction of the size of solar cycle 21 using estimates of the polar field strength together with our assumption that this relates to the size of the next cycle's activity. We also believe that more than just this one parameter governs the behavior of the solar activity cycle. We would thus like to think of this paper as a first order attempt to predict the cycle's activity using one parameter of physical importance. If this method succeeds to some degree, it may be possible to establish other solar parameters which will improve the prediction.

The prediction of cycle 21's yearly mean sunspot maximum to be 140 ± 20 is close to Sargent's (1978) prediction of 154 but significantly larger than most other predictions listed in Sargent's paper. It we err in the prediction, we feel we have erred on the side of being too conservative. Waldmeier and Weber (1977) point out that this cycle had the largest value of sunspot number at solar minimum ever recorded. Thus it is possible that solar maximum may exceed our stated limits.

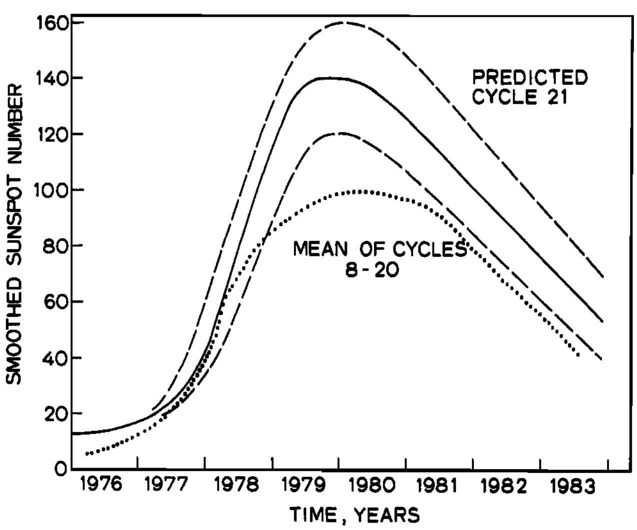

Fig. 2. Predicted smoothed sunspot number from 1976 to 1983 (solid curve). A maximum of 140 ± 20 near December, 1979 is significantly above the mean of cycles 8-20 (dotted curve).

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References

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

Billings, D.E., A Guide to the Solar Corona, Academic Press, N.Y. 226, 1966.

Brown, C.M., What determines sunspot maximum?, M.N.R.A.S., 174, 185-190, 1976.

Howard, R., Large-scale solar magnetic fields, Ann.Rev. of Astron. and Astrophys., 15, 153-174, 1977.

Leighton, R.B., A magneto-kinematic model of the solar cycle, Astrophys.J., 156, 1-26, 1969.

Mayaud, P.N., On the reliability of the Wolf number series for estimating long-term periodicities, J. Geophys. Res., 82, 1271-1272, 1977.

Ohl, A.I., Forecast of the maximum Wolf number for the current eleven-year cycle, Problems of the Arctic and Antarctic, No. 28, 137-139, 1968.

Parker, E.N., The origin of solar activity, Ann. Rev. of Astron. and Astrophys., 15, 45-68, 1977.

Rosenberg, R.I., and P.J. Coleman, Jr., Heliocentric latitude of the dominant polarity of the interplanetary magnetic field, J. Geophys. Res., 74, 5611, 1969.

Sargent III, H.H., A prediction for the next solar cycle, IEEE Vehicular Technology Conference, in press, 1978.

Schatten, K.H., Large-scale properties of the interplanetary magnetic field, Rev. Geophys. and Space Phys., 9, 773-802, 1971.

Sheeley, N.R., Jr., Polar faculae during the sunspot cycle, Ap.J., 140, 731, 1964.

Sheeley, N.R., Jr., Measurements of solar magnetic fields, Ap.J., 144, 728, 1966.

Sheeley, N.R., Jr., Polar faculae during the interval 1906-1975, J. Geophys. Res., 81, 3462-3464, 1976.

Svalgaard, L., Geomagnetic activity: dependence on solar wind parameters, Coronal Holes, ed. Zirker, Colorado Assoc. Univ. Press, 371, 1978.

Svalgaard, L., Interplanetary sector structure 1947- 1975, Stanford University Institute for Plasma Research Report No. 648, 1976.

Svalgaard, L., and J.M. Wilcox, Three-dimensional structure of the extended solar magnetic field and the sunspot cycle variation in cosmic ray intensity, Nature, 262, 766, 1976.

Waldmeier, M., Astron.Mitt.Zurich, 14, No. 133, 1935.

Waldmeier, M., Predicted and observed coronal structure, Nature, 265, 611, 1977.

Waldmeier, M. and S.E. Weber, Shape and structure of the corona at the solar eclipse of Oct. 23, 1976, Astron.Mitt.Zurich, No. 353, 1-24, 1977.

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