The Solar Magnetic Field Since 1976

An Atlas of Photospheric Magnetic Field Observations
and Computed Coronal Magnetic Fields from the
John M. Wilcox Solar Observatory at Stanford
(Minimally revised from UAG-94, WDC-A, 1985)

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Abstract

Daily magnetogram observations of the large-scale photospheric magnetic field have been made at the John M. Wilcox Solar Observatory at Stanford since May of 1976. These measurements provide a homogeneous record of the changing solar field through Solar Cycles 21 and 22.

Using the photospheric data, the configuration of the coronal and heliospheric fields can be calculated using a Potential Field -- Source Surface model. This provides a 3-dimensional picture of the heliospheric field evolution during the solar cycle.

In this report we describe the complete set of synoptic charts of the measured photospheric magnetic field, the computed field at the source surface, and the coefficients of the multipole expansion of the coronal field that are available on the WSO home page: URL http://quake.stanford.edu/~wso. The general underlying structure of the solar and heliospheric fields, which determine the environment for solar - terrestrial relations and provide the context within which solar activity related events occur, can be approximated from these data.

1. Introduction

The large-scale magnetic field of the sun evolves slowly but dramatically during the 11 years of a sunspot cycle. Because the changes occur relatively slowly, much can be learned about the ambient environment within which activity related events occur by studying the large scale field configuration over longer periods of time.

Full disk measurements of the mean solar magnetic field began at Stanford in 1975. Observations of the photospheric field with a resolution of three arc minutes began in May 1976 and have continued through the present time. Synoptic charts of the photospheric field have been published monthly in the Prompt Reports of *Solar Geophysical Data* beginning with the data from January, 1979. The data now span an entire 22-year sunspot cycle, beginning with solar minimum in 1976.

One important use of this data is in determining the configuration of the coronal and interplanetary magnetic field (IMF) by means of a Potential Field -- Source Surface model. With this model, described below, the three-dimensional polarity structure of the interplanetary medium can be calculated. Comparisons with IMF measurements and coronameter data suggest a good level of agreement with the actual coronal and interplanetary field configurations (e.g. Wilcox & Hundhausen, 1983, Hoeksema, 1984 or Bruno *et al.*, 1984). Synoptic charts of the heliospheric field configuration are also presented on the pages labeled as "classic line-of-sight boundary condition." A more modern version of the computation that uses a radial field boundary condition at the photosphere is also presented.

Finally, one intermediate result of the potential field calculation is a description of the coronal field in terms of its multipole components: dipole, quadrupole, etc. From these components the three-dimensional field near the sun can be calculated. The relative contributions of the multipoles to the total field vary with height above the photosphere and with time during the solar cycle. Because the field is constantly changing, the values of the components are available for each 180° of Carrington Longitude.

Short descriptions of the observing instrument, the method of observation, data reduction, and model computation are provided below. More detailed descriptions may be found in the referenced reports.

2. Method of Observation -- Photospheric Field

Daily magnetograms with three arc-minute resolution are taken at the John M. Wilcox Solar Observatory at Stanford every day that the weather is good. Plots of many individual magnetograms are available in the WWW atlas. WSO's Babcock solar magnetograph measures the line-of-sight component of the photospheric magnetic field using the Zeeman splitting of the 5250.2 Å Fe I spectral line. This method accurately measures large-scale, weak field regions, but only crudely shows regions of strong or complex fields. The noise level of each measurement is less than 10 μT and the zero level error is less than 5 μT. [1 Gauss is 100 μT.] Because of the saturation of the magnetic signal in the magnetograph, the measured values reported here are smaller than the actual field strengths by about a factor of two. A detailed description of the instrument can be found in Scherrer et al. (1977), Duvall (1977), or Hoeksema (1984).

The magnetograms are obtained by scanning boustrophedonically along east-west lines. The aperture moves 90 arc seconds between points in the east-west direction and 180 arc seconds north or south between scan lines. The entire procedure, including calibrations and an auxilliary scan using the 5247 Å Fe I line, takes approximately 2 hours; the integration time for each of the 195 points on the solar disk is 15 seconds. The daily magnetograms are interpolated onto a finer grid based on the Carrington coordinate system by fitting a parabolic surface to the nearest observed points. The synoptic chart is constructed by combining all the values for each Carrington coordinate. Data from all magnetograms for which the Carrington longitude of interest is within 55° of central meridian contribute. The individual values are weighted for central meridian distance and the quality of the measurement to provide the best determination of the solar field. Because of the large aperture size the regions from 70° to the poles lie entirely within the last aperture and are not resolved. In the final plotted grid there are 29 points equally spaced in latitude from 70° north to 70° south at 5° intervals. The resolution in longitude is also 5°.

3. Synoptic Chart Format -- Photospheric Field

The synoptic charts are available on the WSO home page. They are presented as contour maps of the photospheric magnetic field over the entire surface of the sun and as tables. The first map is for Carrington Rotation 1641. The contour levels have the magnitudes indicated and are the same for every photospheric field chart. The thinner solid lines identify positive field regions, where the field is directed out of the sun; the broad solid contour is the neutral line; and dashed contours show regions of negative magnetic field polarity. With the large aperture size the field strength rarely exceeds 2000 μT. The solar field are presented for Carrington Rotations 1641 through the present.

The Carrington coordinate system specifies the central meridian longitude, thus time goes from right to left on the Carrington grid simulating the rotation of the sun. The dates of central meridian passage are labeled. The scale is the standard 8mm/day. The inverted carets indicate the times of magnetograms contibuting to the field data. An extra 30° are shown at each end of the rotation for continuity. Note that the opposite ends of a rotation differ because of field evolution and differential rotation.

The top panel of the chart shows the mean magnetic field of the sun as measured in integrated sunlight for each day. This is the result of a separate observation taken at the solar observatory. Dotted lines are linear interpolations over missing days. The mean field is also available on the web.

4. Data Coverage

Because of weather and equipment problems, magnetograms are not available every day. Sometimes gaps of 8 or more days occur which produce gaps in the magnetic field record. The data are generally of uniform quality, though near gaps data as much as 55° from central meridian was used. Magnetograms were taken on 63% of the days from 1976 - 1985.

5. Method of Computation -- Source Surface Field

Much work has been accomplished since this report was originally written in 1985, however the summary below will suffice for now.

Under the assumptions that the coronal field is approximately a potential field and that the field at some height above the photosphere is completely radial (as suggested by eclipse pictures and energy density considerations) the field configuration can be calculated from the photospheric measurements. While some changes in the field configuration undoubtedly occur above the radius where the field lines are assumed to become radial, called the source surface radius, we assume that the polarity structure is essentially locked in at that point and advected radially outward by the solar wind into the heliosphere. These are simplifying assumptions and although none of these assumptions is strictly true, the overall picture which emerges conforms quite well to the available data.

This model was first developed independantly by Schatten et al. (1969) and by Altschuler & Newkirk (1969). Later investigations (e.g. Adams & Pneuman, 1976; Altschuler et al., 1976; Schulz et al., 1978; Levine, 1982; Hoeksema, 1984; and references therein) demonstrated the basic validity of the model for predicting the large scale structure and suggested improvements for looking at the finer scale. The results presented in this report are extensions of the calculations of Hoeksema et al. (1982, 1983) and Hoeksema (1984). The source surface radius has been located at 2.5 solar radii because it gives the best overall agreement with the polarity pattern observed at Earth.

Calculation of the coronal field requires a knowledge of the photospheric field over the entire solar surface. It takes about 27 days to measure the entire solar surface because of solar rotation. During that time there can be substantial field evolution, especially in strong field regions. Furthermore, a magnetic region on the sun would not be observed at the same Carrington coordinates on the following rotations because of differential rotation. To minimize these effects which are most important near the "edges" of the Carrington Rotation, the source surface field has been calculated for 360° data windows stepping just 10° between calculations and only the center 30° are used to construct the final dataset.

Three corrections have been applied to the data: elimination of the zero offset, or monopole component; addition of a strong polar field; and reconstruction of missing data in the synoptic charts.

The zero offset of the instrument is very small; much of the problem comes from the effects near the edges of the data window described above. In addition, with the large aperture the strong sunspot fields are not fully measured because they are relatively dim. Since most of the zero offset comes from small local effects it has been subtracted from the final field values.

Because the magnetograph measures only the line-of-sight projection of the field and because of the large aperture, the polar regions are not accurately measured. From the changes in the measured field strength at the polar caps during the year as the Earth moves between $\pm 7.25^o$ in solar latitude, the magnitude of the polar field can be inferred (Svalgaard *et al.*, 1978). The derived 6.4 $\cos^8\theta$ G radial field has been added to the data near solar minimum; θ is the colatitude. [This 6.4 G field is the same as the 11.7 G field discussed in Hoeksema et al., (1982, 1983) when corrected by the 1.8 saturation factor.] The correction changes as the polar field strength changes during the solar cycle (Hoeksema et al., 1983) and reverses sign at solar maximum late in 1979. While the magnitude of the correction is rather large, it is sharply peaked and significantly affects only the most poleward values. At lower latitudes it has the primary effect of moving the neutral line toward the equator.

When computing the coronal field using the 'radial' boundary condition, the polar field is more accurately represented, or at least accounted for more properly in the computation of the coronal structure. As a result no correction for the polar field is made when computing the "radial boundary condition" potential field model. The HCS is typically flatter when using the "radial" boundary condition.

Missing data in the synoptic charts would cause large gaps in the computed source surface fields. To minimize the effects of missing data we have filled the gaps by using the average of the photospheric field measurements at the same location from the preceeding and following rotation. Because the large scale field changes relatively slowly this is a reasonable approximation to the field.

The "preliminary" charts of various sorts are computed in the same way, but observations extending 55° east of central meridian on the magnetograms are used as they are observed.

6. Source Surface Field Format

Contour maps of the source surface field are shown with the same layout as the photospheric field charts, with the grid once again showing slightly more than one Carrington rotation. The broad solid neutral line divides the negative polarity regions, shown by dashed contours, from the positive areas, indicated by solid lines. The field strength is about 1% that found at the photosphere.

Since we assume this field is carried radially outward by the motion of the solar wind, these graphs show the predicted three-dimensional polarity structure of the heliospheric field. It should be pointed out that much beyond 1 AU the interaction of various streams with different velocities will distort this structure (Suess & Hildner, 1985). The solar latitude of the Earth is shown by the small '>' and '<' symbols at the edges of each graph. To compare with the IMF polarity observed at Earth, the travel time of the solar wind must be taken into account. Near the neutral line the transit time is about 4.5 to 5 days. Thus to find the field extrapolated to Earth, look 60° to 65° west (i.e. right) of the desired date's central meridian longitude.

Warning: one cannot directly infer the *strength* of the field much above the source surface. Observations of IMF strength at 1 AU show a very different pattern from that observed on the source surface. At the source surface the field strength increases in magnitude away from the neutral line, while at 1 AU the field reaches its highest value near the neutral sheet and is roughly constant through the rest of a sector. Suess et al. (1977) modelled the field in a polar coronal hole. From $2R_o$ to $5R_o$ to 1 AU the field strength profile changed from one with a maximum field strength near the center and a minimum near the coronal hole boundaries to a profile having an almost uniform field across the hole to one with an enhanced magnitude near the boundaries.

7. The Multipole Expansion

To summarize the mathematical solution: using the observed line-of-sight photospheric field as one boundary condition and the requirement of a purely radial field at the source surface as the other, a solution is found to LaPlace's equation (the potential field assumption) in terms of the Legendre polynomials:

$$P_l^m(\theta) = \left\{ q_m \frac{(l-m)!}{(l+m)!} \right\}^{1/2} \times$$

$$\frac{(2l)!}{2^l\, l!(l-m)!} \sin^m\theta \left\{ \cos^{l-m}\theta - \frac{(l-m)(l-m-1)}{2(2l-1)} \cos^{l-m-2}\theta \right.$$

$$\left. + \frac{(l-m)(l-m-1)(l-m-2)(l-m-3)}{2\cdot 4\cdot (2l-1)(2l-3)} \cos^{l-m-4}\theta - \cdots \right\}$$

where $q_m = 2$ for $m > 0$ and 1 for $m = 0$.

In this normalization the polynomials have the same order of magnitude for the various degrees, m, and can be compared directly (see the discussion in Chapman and Bartels, 1940). The mean square value of these functions over the sphere is given by:

$$\frac{1}{4\pi} \int_0^{\pi} \int_0^{2\pi} \left[P_l^m(\theta) \left\{ \begin{matrix} \cos \\ \sin \end{matrix} \right\} m\,\phi \right]^2 \sin\theta\, d\theta\, d\phi = \frac{1}{(2l+1)} \,.$$

Using this form for the Legendre polynomials the solution for the three components of the field between the photosphere and the source surface can be written:

$$B_r = -\frac{\partial \Psi}{\partial r} = \sum_{lm} P_l^m(\cos\theta)\,(g_{lm} \cos m\,\phi + h_{lm} \sin m\,\phi) \left\{ (l+1) \left(\frac{R_o}{r} \right)^{l+2} - l \left(\frac{r}{R_s} \right)^{l-1} c_l \right\}$$

and

$$B_\theta = -\frac{1}{r} \frac{\partial \Psi}{\partial \theta} = -\sum_{lm} \left\{ \left(\frac{R_o}{r} \right)^{l+2} + c_l \left(\frac{r}{R_s} \right)^{l-1} \right\} (g_{lm} \cos m\,\phi + h_{lm} \sin m\,\phi) \frac{\partial P_l^m(\cos\theta)}{\partial \theta}$$

and

$$B_\phi = -\frac{1}{r \sin\theta} \frac{\partial \Psi}{\partial \phi} = \sum_{lm} \left\{ \left(\frac{R_o}{r} \right)^{l+2} + c_l \left(\frac{r}{R_S} \right)^{l-1} \right\} \cdot \frac{m}{\sin\theta} \cdot P_l^m(\cos\theta) \cdot (g_{lm} \sin m\,\phi - h_{lm} \cos m\,\phi),$$

where $c_l = -\left(\frac{R_o}{R_s} \right)^{l+2}$, R_o is the solar radius and R_s is the source surface radius. The g_{lm} and h_{lm} are tabulated in the harmonic coefficients pages for each Carrington longitude.

8. Conclusions

It is our hope that the provision of a homogeneous dataset of the solar magnetic field over two sunspot cycles in a convenient, inclusive package will stimulate the studies of the large-scale structures of the solar and heliospheric magnetic field, encourage others to consider the relationship of the large scale, ambient field structures to activity on short time scales and smaller spatial scales, and enable the inclusion of the heliospheric field in analyses of solar-terrestrial relations.

It is our intention to promote the use of these synoptic observations as primary data and for use in correlative studies in solar physics and solar-terrestrial physics research. We ask only that the source of the data be acknowledged and that we receive a copy of resulting research reports and papers. Inquiries concerning extended analyses should be directed to J. Todd Hoeksema Center for Space Science and Astrophysics, HEPL Annex B213, Stanford, CA 94305-4085.

9. Acknowledgements

The existence of this data and the John M. Wilcox Solar Observatory would not have been possible without the foresight and persistence of John M. Wilcox.

Without long term funding such records can not be compiled. Over the years this work has been faithfully supported by the Office of Naval Research, by the National Aeronautics and Space Administration, by the Atmospheric Sciences Section of the National Science Foundation. In earlier years support was provided by the Max C. Fleischman Foundation.

We would also like to thank the observers who have worked hard to provide the data presented in this report with as few gaps as possible: Eric Gustavson, Steve Bryan, Todd Hoeksema, Phil Duffy, John Foster III, Harald Henning, Dave Fernandez, Sarah Gibson, Bernard Gelly, Luiz Sa, Rakesh Nigam, Peter Giles, and Thornton (Jack) Kline III.

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