

THE MEAN MAGNETIC FIELD OF THE SUN: OBSERVATIONS AT STANFORD

PHILIP H. SCHERRER, JOHN M. WILCOX, LEIF SVALGAARD,
THOMAS L. DUVALL, JR., PHIL H. DITTMER, and ERIC K. GUSTAFSON

Institute for Plasma Research, Stanford University, Stanford, Calif., U.S.A.

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Abstract. A solar telescope has been built at Stanford University to study the organization and evolution of large-scale solar magnetic fields and velocities. The observations are made using a Babcock-type magnetograph which is connected to a 22.9 m vertical Littrow spectrograph. Sun-as-a-star integrated light measurements of the mean solar magnetic field have been made daily since May 1975. The typical mean field magnitude has been about 0.15 G with typical measurement error less than 0.05 G. The mean field polarity pattern is essentially identical to the interplanetary magnetic field sector structure (see near the Earth with a 4 day lag). The differences in the observed structures can be understood in terms of a 'warped current sheet' model.

1. Introduction

A solar telescope has been built at Stanford University to study the organization and evolution of large-scale solar magnetic fields and velocities. The primary objective of building the new observatory is to permit dedicated synoptic observations of the large-scale structures. The main observing program to date has been sun-as-a-star integrated light observations of the mean solar magnetic field. The instrument and mean field observations will be described in this paper.

2. The Instrument

The need for a solar observing instrument designed specifically to study large-scale structure of magnetic fields and velocities has been clear for several years. For such observations an instrument should be able to measure the average magnetic field and velocity over large regions (arc-minutes to full disk resolution) with negligible magnetic zero level errors and sensitivity which does not vary for many rotations. The design emphasis should be for precision rather than spatial resolution and for stability rather than temporal resolution. The instrument at Stanford was designed with these goals in mind. The goal for magnetic observations was (for a several minute observation) and error of less than 0.1 G. The goal for velocity observations was a sensitivity in the m s^{-1} range. To achieve these goals mechanical and electrical stability was considered to be of greatest importance.

The preliminary design of the instrument was begun in the summer of 1972 with the detailed design and construction beginning in 1973. The installation of the telescope was complete in the fall of 1974 and the daily observing program commenced May 16, 1975. The instrument was designed and built by the authors

and the Special Projects Group led by Jack Franck at the Lawrence Berkeley Laboratory of the University of California at Berkeley. The solar telescope and magnetograph is currently installed at the Stanford Solar Observatory which is located in the foothills about 2 km south of the Stanford University campus center.

A schematic layout of the optics is shown in Figure 1. The sunlight is directed into the telescope by 33 cm coelostat and 25 cm second flat mirrors. There are two objective lens positions. The north one is presently used to produce an image for a guiding system which controls the second flat angle. There is a choice of two lenses which can be mounted at the south position depending on the observation to be

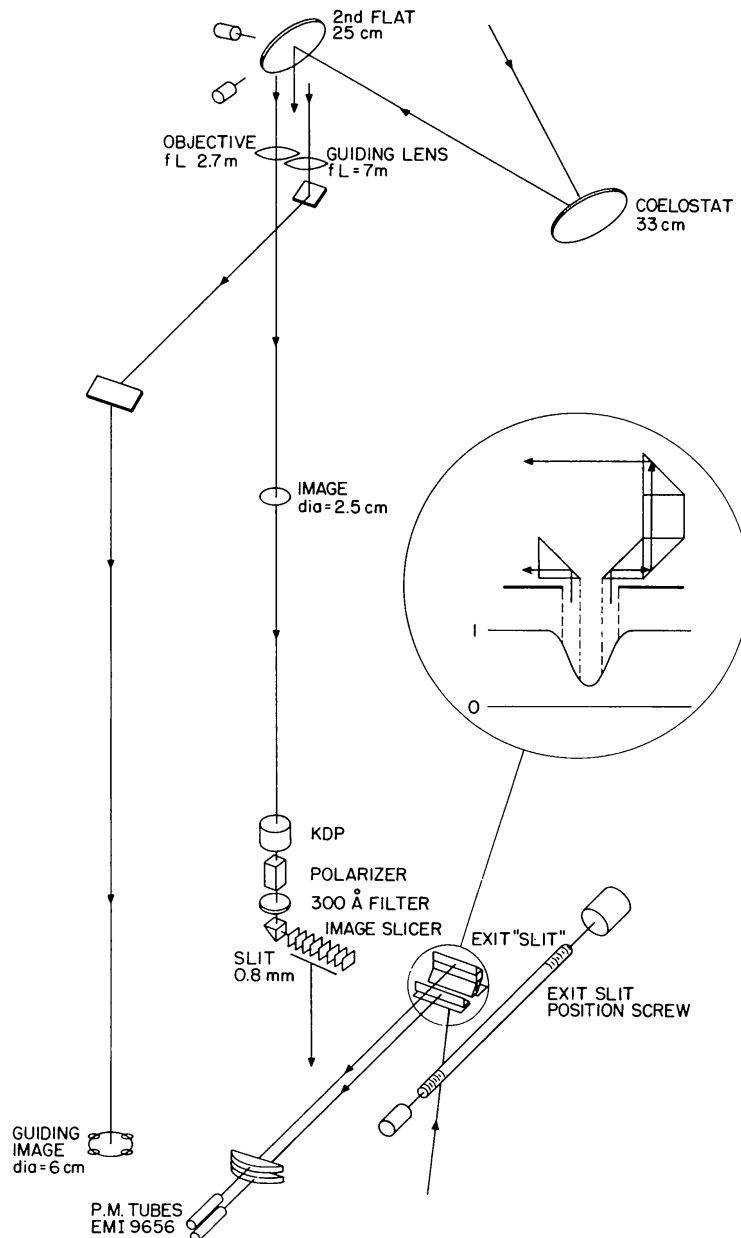


Fig. 1. A schematic layout of the solar telescope optical system. The 23 m vertical Littrow spectrograph is not shown.

made. The mirrors and lenses are mounted on a rigid steel structure attached to the concrete pyramid building and protected with a rotating dome. The lenses are mounted 6.5 m above the spectrograph entrance aperture. The spectrograph is located in a 2 m pit 23 m deep. The diffraction grating (33 cm by 15 cm with 632 rulings per mm) and Littrow lens (15 cm with 22.9 m focal length) are mounted in a steel frame attached to a 2 m by 3 m concrete block at the bottom of the pit. The spectrograph entrance aperture, exit slit assembly, phototubes, and magnetograph optics are mounted at 'table top' height in the observing room (Figure 2).

The spectrograph entrance aperture is an image slicer followed by a slit. The image slicer has a 9 mm by 9 mm aperture and is followed by a 0.8 mm by 100 mm slit. The individual mirrors in the image slicer are slightly tilted to eliminate the need for a field lens. The spectrograph exit slit assembly (as is the rest of the spectrograph) is similar to that at the Mt. Wilson 150 ft Tower Telescope. The slits consist of prisms and blinds mounted on ways and positioned with a lead screw. The exit slits are 100 mm long and are each 65 mÅ wide with a separation of 18 mÅ. The screw moves the slits in the direction of dispersion (Figure 1 insert). When the slits are positioned on a line (the position is maintained by a servo system) the angle of the screw is a measure of the doppler shift. The computer (see below) can control the grating angle and slit assembly position so the observing line can be automatically selected.

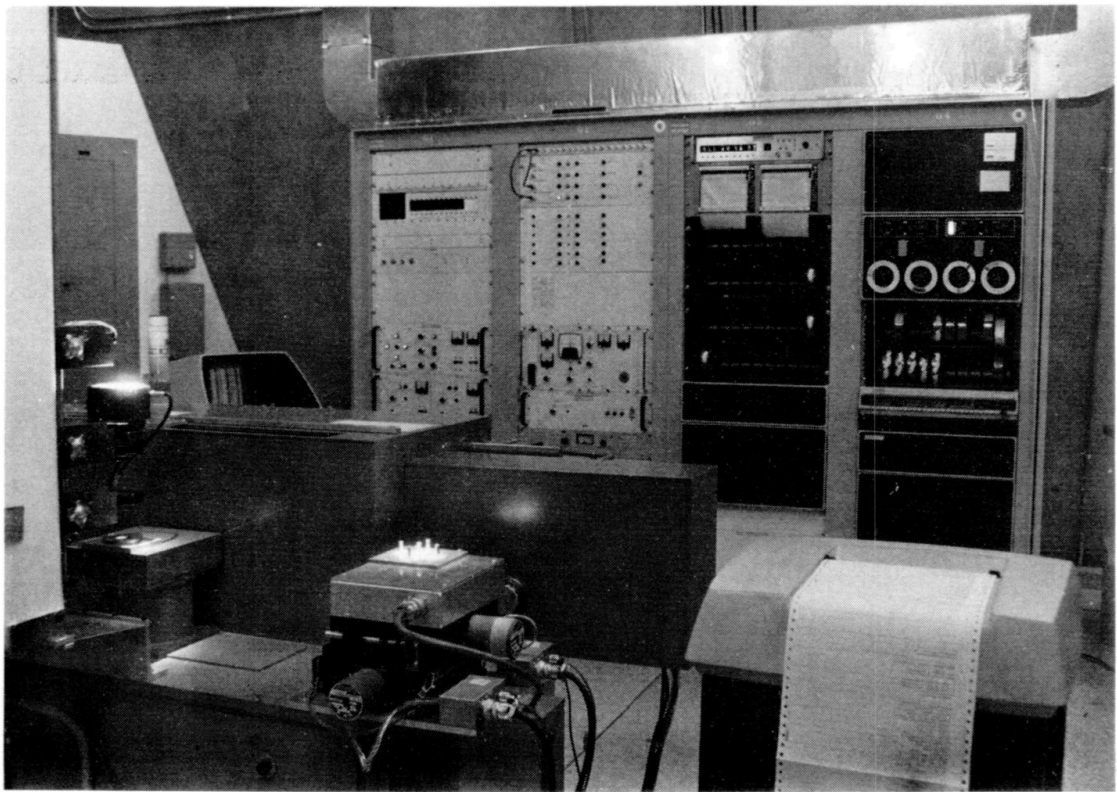


Fig. 2. The telescope observing area. The main observing beam is near the vertical optical bench (front, left). The guiding beam and X-Y positioner is displaced 61 cm to the east (front, center). The image slicer, exit slits, photomultiplier tubes, and pre-amplifiers are contained in spectrograph head while the magnetograph and control electronics are in the racks in the background.

The magnetograph is of the Babcock type. The line-of-sight component of the magnetic field is observed by measuring the amount and sense of circulation polarization in the wings of an absorption line (e.g. Beckers, 1968). The arrangement is similar to that at the Mt. Wilson 150 ft Tower Telescope described by Howard (1974) and Howard *et al.* (1968). The magnetic signal is the amplitude of the 110 Hz (KDP modulation frequency) square wave which is the difference in intensity in the Blue and Red wings of the line. The signal is calibrated by placing a right circular polarizer in front of the KDP and introducing a known artificial line shift using the exit slit positioning screw.

As mentioned above there are two main objective lenses for different observing modes. One is for observing the Sun as a star in integrated light. It has a focal length of 2.7 m which results in a 2.5 cm image located 3.8 m above the spectrograph slit. This makes a 2 cm diameter region at the entrance aperture which is evenly illuminated by all parts of the Sun's image. The purpose of this lens is essentially to match the angular size of the sun to the acceptance angle of the $f/150$ spectrograph. Various apertures and polarizers can be placed at the 'mean field image' to study large scale magnetic fields or velocity oscillations.

The other main objective lens which can be used has a 6.5 m focal length to make a 6.1 cm image of the Sun at the spectrograph entrance aperture. Since the second flat guiding detector head is mounted on an x - y positioning table, the second flat and thus the image can be moved to scan the sun. Low resolution magnetograms and velocitygrams can be made in this way. At present a 3' square aperture is used to make daily magnetograms.

All optics between the objective lens and spectrograph entrance slit are mounted on an optical bench which is attached with flexible couplings to the lens mount and spectrograph head. This means the optics (primarily the KDP) will remain aligned even if the top of the building shifts a few mm due to differential heating through the day. Presently these optics consist of the KDP crystal and polarizer for the magnetograph, a circular polarizer for magnetic calibration and a 300 Å bandpass interference filter to remove overlapping spectral orders.

Essentially all telescope functions except coarse mirror positioning are controlled by a PDP11/10 computer. The computer, magnetograph, and servo electronics are located near the spectrograph in the observing room. In addition to controlling the instrument the computer reduces and records data from the magnetograph. The computer operates as an interpreter for a locally defined 'telescope control language'. The interpreter was written in assembly language but the operators need to know only the telescope language. The instrument operates unattended during most of the day. An operator is needed only to begin separate observations when lenses need to be changed, analog electronics adjusted, data tapes changed, and so forth.

3. Mean Field Observations

The Sun-as-a-star mean magnetic field is observed by a procedure that is a combina-

tion of the methods used at Mt. Wilson and the Crimean Astrophysical Observatory as described by Scherrer *et al.* (1977). The field is observed by measuring the Zeeman splitting in the line Fe I $\lambda 5250 \text{ \AA}$ and the instrument zero offset in the magnetically insensitive line Fe I $\lambda 5124 \text{ \AA}$. We have found that even with very stable electronics and optical alignment of the circular polarization analyzer (KDP crystal and linear polarizer), the magnetic zero level must be determined for each observation. To minimize zero level errors and to investigate their sources we determine two zero references for each observation.

A complete observation consists of four three-minute integrations as follows: First the exit slits are positioned on $\lambda 5250$ and the magnetograph magnetic signal is integrated with the KDP modulation turned off. This gives an indication of the offsets in the amplifiers and analog to digital converters. Next we move the slits and grating to the zero reference line $\lambda 5124$ and integrate the magnetic signal. This yields the total magnetograph zero offset at that time. Next we move back to $\lambda 5250$ and measure the un-corrected solar mean field. Finally we go back to $\lambda 5124$ and repeat the zero offset integration. The electronic offset is first subtracted from each of the other three integrations, then the mean field is computed as the difference between the $\lambda 5250$ integration and the average of the $\lambda 5124$ measurements.

The reasons for this rather lengthy procedure can be seen in Figure 3. This plot shows individual integrations for both $\lambda 5250$ and $\lambda 5124$ for one day. The $\lambda 5124$ signal is separately calibrated assuming the same magnetic 'sensitivity' as $\lambda 5250$. Note that as the instrumental offset varies through the day the two curves follow each other. The vertical distance between the two curves is interpreted as the solar mean field. With three-minute integrations, the average formal statistical uncertainty in the observations is 0.04 G. The entire observation takes about twenty minutes and is repeated several times each day. A daily average mean field is computed as a

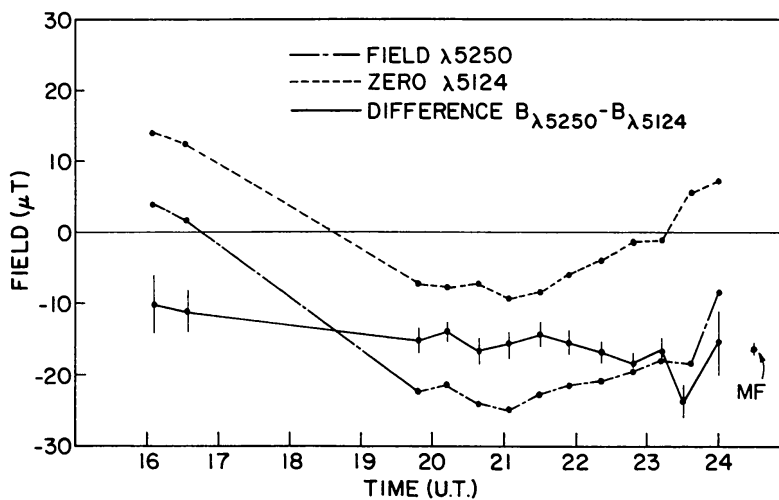


Fig. 3. The daily variation of the magnetic (light solid line) and zero reference (dashed line) signals are shown for 27 December, 1976 ($1 \mu T = 0.01 \text{ G}$). The mean solar magnetic field is taken to be the difference between the observed quantities (heavy solid line). The weighted average for the day is shown on the right as MF.

weighted average of the individual observations. The weighting includes both the statistical uncertainty and the magnitude of the zero offset as measured in $\lambda 5124$. The average standard deviation of all the observations in one day is 0.05 G. The daily averages are published by NOAA in *Solar-Geophysical Data*, Prompt Reports.

Figure 4 is a plot of all mean field observations through 1976. The plot is organized as 27^d Bartels rotations with a 5-day shift to facilitate comparison with interplanetary and geomagnetic quantities measured at the Earth. Each individual observation is shown as a vertical bar with length equal to twice the estimated uncertainty. The daily averages are shown as horizontal bars with length one day and centered about local noon. Careful inspection of Figure 4 shows that while some of the daily variation is of solar origin, much of it is probably from still uncorrected instrumental drifts. We feel, however, that we can see any variations of solar origin at the 0.1 G level.

The smoothness of the curves is consistent with a stable large-scale rotating structure. Severny (1971) has suggested that there might be rather large (about 1 G) variations in the mean field from one day to the next. However, with the possible exception of 12 August 1975, we do not see any short-term variation not due to measurement noise or solar rotation. There appears to be a long term drift in the data with approximately an annual period. This variation is consistent with the expected contribution to the mean field from the solar polar fields as the heliographic latitude of the observatory changes through the year. There is also a consistent small positive offset to the data of about 0.04 G. This may be of solar origin or some as yet unrecognized instrumental weighting.

The $\lambda 5124$ zero offset signal has also been examined for long-term trends. There is a slow variation in the signal with an amplitude of 0.1 G. This may be from instrumental polarization changes as suggested by Stix (1974) although it is of smaller magnitude and varies with a shorter period than suggested.

A comment should be made about the observed magnitude of the mean field. The average magnitude of the mean field observed at the Mt. Wilson and Crimean observatories for the years 1970 through 1974 was 0.5 G while the average magnitude of the Stanford mean field for 1975 and 1976 was 0.12 G. We feel, however, that the rather small value now observed is probably not in error. A preliminary comparison of the mean field observed at Stanford and the Crimea for the summer of 1975 shows substantial agreement in both the variation and magnitude of the field. Also, a preliminary comparison of the Stanford low-resolution daily magnetograms with averages of Mt. Wilson magnetograms (May and June 1975) show no significant differences in magnetograph calibration. The small mean field magnitude may simply be an indication of the small amount of net magnetic flux in the large-scale structure at solar minimum. Due to the weighting inherent in the Sun-as-a-star observing method there is still some uncertainty in using mean field magnitudes as a measure of actual photospheric net flux over large regions. The observed mean field should be proportional to the net weighted line-of-sight component of the solar field but will be an underestimate of the magnitude by a factor of perhaps 2 to 5.

MEAN SOLAR MAGNETIC FIELD

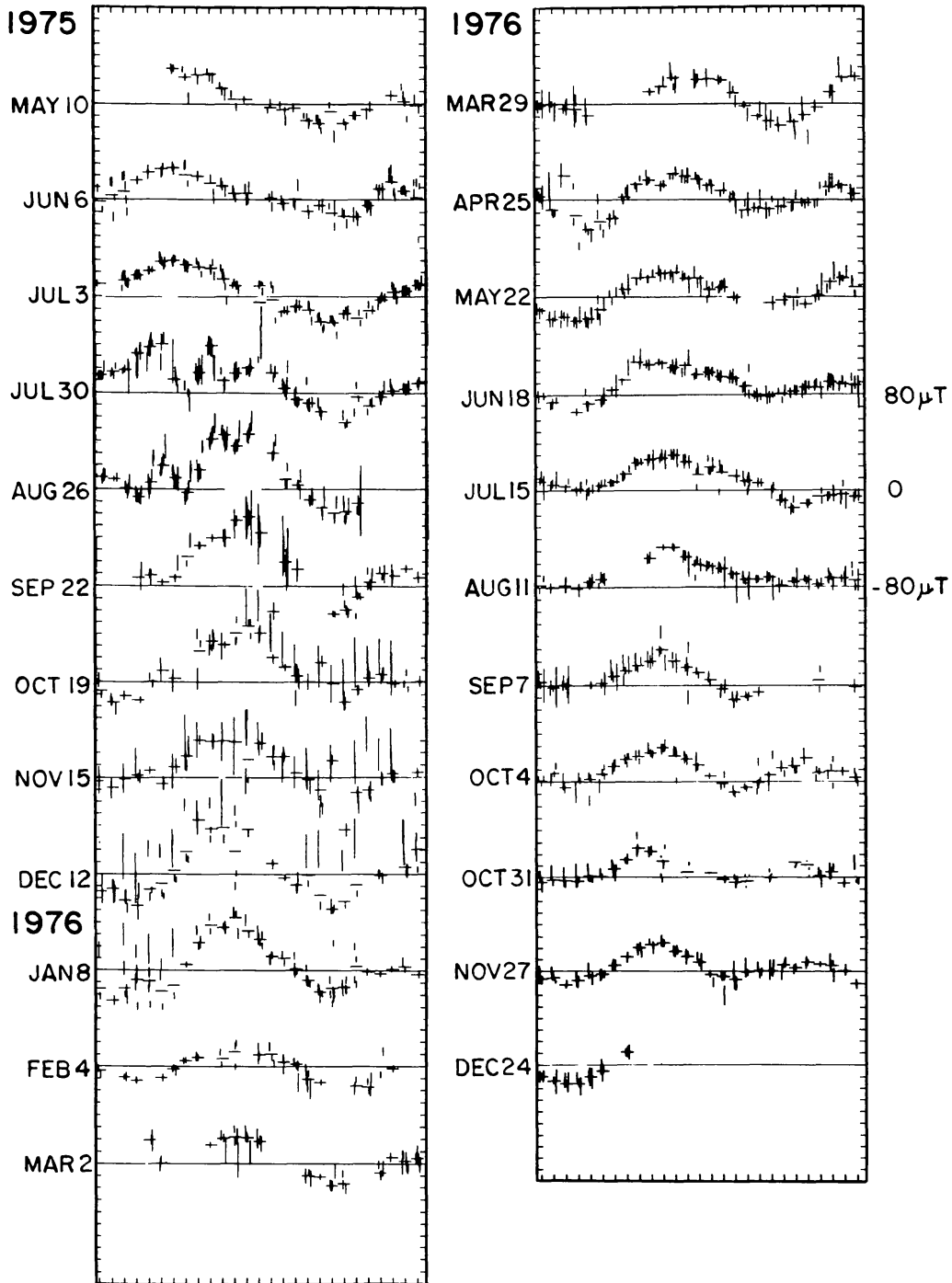


Fig. 4. The mean solar magnetic field for May 1975 through 1976 in μT (0.01 G). Individual measurements are shown as vertical bars. The horizontal bars are weighted daily averages as described in the text. The data are plotted in 27^d Bartels rotations with a 4.5^d displacement. The actual date of the observation for the first day in each rotation is shown.

4. Interpretation

Severny *et al.* (1970) and Scherrer *et al.* (1977) have reported that the mean solar field shows the same polarity pattern as the interplanetary magnetic field. Figure 5 shows the interplanetary magnetic field polarity as inferred from geomagnetic variations and the polarity of the solar mean field in Bartels rotation plots. The solar field is shown with the usual delay for solar wind transit time. The mean field is shown as zero when the magnitude is comparable to the uncertainty in measurement. Note first that the large-scale pattern is remarkably similar in both data. The large positive sector in the first half of each rotation has been very stable throughout the 22 rotations with the change in position (phase) occurring at the same time (rotation 1945). Where there is a difference to note is in the appearance of the positive sector in the last days of each rotation. This sector is always seen in the mean field (refer also to Figure 4) but is only seen in the interplanetary field in late summer and early fall when the earth is at northern heliographic latitudes.

These correspondences are consistent with the model of the large-scale solar and interplanetary field which has been developing in recent years (e.g. Svalgaard *et al.*, 1975; Svalgaard and Wilcox, 1976). In this model, large-scale unipolar regions (that is, the net field averaged over large areas) have roughly north-south boundaries in low latitudes in the photosphere. The topology of the boundary between these regions and the polar fields then is similar to the seam on a baseball. The north-south extent of the boundary (which is a current sheet in interplanetary space) gets progressively compressed as one moves out from the Sun due to the imbalance of polar and equatorial photospheric net field strengths. At large distances (≥ 1 AU) the

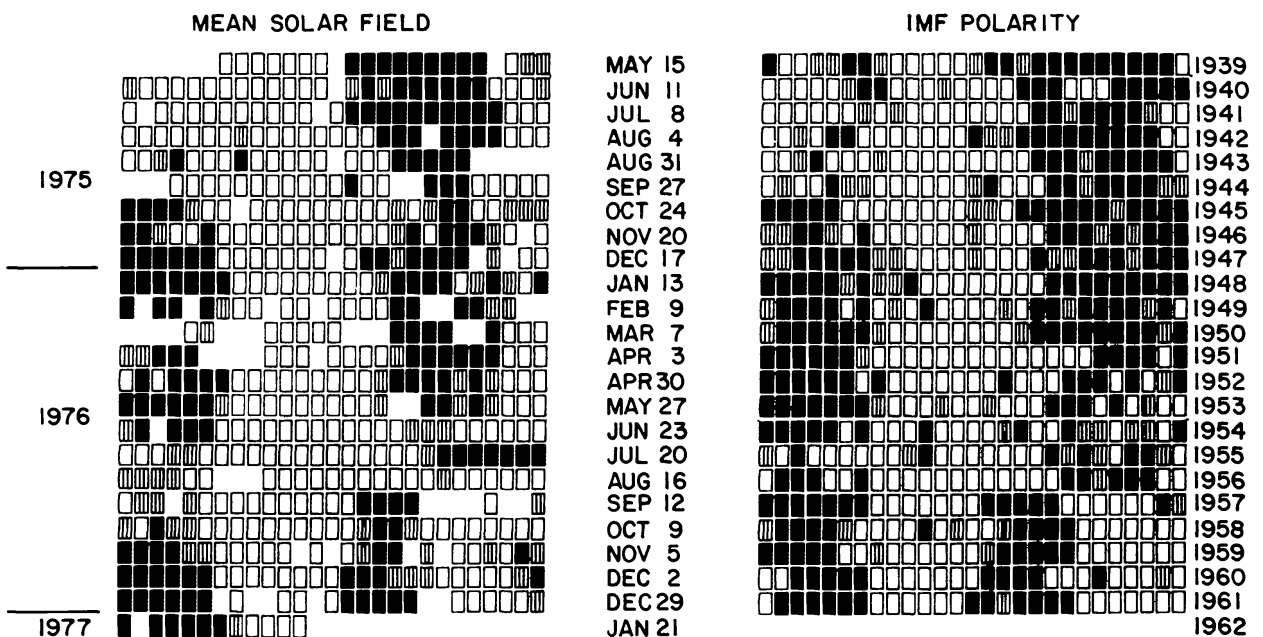


Fig. 5. Mean solar magnetic field polarity and inferred interplanetary magnetic field polarity in 27^d Bartels rotation diagrams. The solar data is shown displaced 4.5^d to allow for Sun-Earth solar wind transit time. The inferred IMF polarities after rotation 1956 are preliminary values.

boundary begins to look more like a wavy hat brim or ballerina skirt with IMF polarity the same as the solar north pole above the boundary and the same as the south pole when below the current sheet. In this model, a four-sector structure can be seen in the mean field, but except when at high northern heliographic latitudes, the earth is south of the smaller positive sector. This simplified picture is sufficient to explain the overall structure at solar minimum, but we expect some refinements will be necessary to understand the situation near solar maximum when the polar fields are smaller than the mean field magnitude and changing polarity, but the correlation between the solar mean field and IMF polarity is still good.

5. Conclusions

The new solar magnetograph at Stanford now provides us with a tool to probe the large-scale organization and evolution of the photospheric magnetic field. By using the mean field observations in conjunction with the low-resolution, low-noise daily magnetograms (begun in May 1976) and IMF observations we hope to better understand both the solar magnetic field and the origin of the IMF. More detailed studies of the relationship of the mean field and interplanetary and geomagnetic parameters, the low resolution magnetograms, and large-scale velocity oscillation studies will be reported in future papers.

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References

- Beckers, J. M.: 1968, *Solar Phys.* **5**, 15.
 Howard, R.: 1974, *Solar Phys.* **38**, 283.
 Howard, R., Tanenbaum, A. S., and Wilcox, J. M.: 1968, *Solar Phys.* **4**, 286.
 Scherrer, P. H., Wilcox, J. M., Kotov, V. A., Severny, A. B., and Howard, R.: 1977, *Solar Phys.* **52**, 3.
 Severny, A. B.: 1971, in R. Howard (ed.), 'Solar Magnetic Fields', *IAU Symp.* **43**, 675.
 Severny, A. B., Wilcox, J. M., Scherrer, P. H., and Colburn, D. S.: 1970, *Solar Phys.* **15**, 3.
 Svalgaard, L., Wilcox, J. M., Scherrer, P. H., and Howard, R.: 1975, *Solar Phys.* **45**, 83.
 Svalgaard, L. and Wilcox, J. M.: 1976, *Nature* **262**, 766.
 Stix, M.: 1974, *Solar Phys.* **37**, 493.