THE MEAN MAGNETIC FIELD OF THE SUN:
METHOD OF OBSERVATION AND RELATION TO THE
INTERPLANETARY MAGNETIC FIELD

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Abstract. The mean solar magnetic field as measured in integrated light has been observed since 1968. Since
1970 it has been observed both at Hale Observatories and at the Crimean Astrophysical Observatory. The
observing procedures at both observatories and their implications for mean field measurements are
discussed. A comparison of the two sets of daily observations shows that similar results are obtained at both
observatories. A comparison of the mean field with the interplanetary magnetic polarity shows that the IMF
sector structure has the same pattern as the mean field polarity.

1. Introduction

In the spring of 1968 a series of observations of the integrated light solar magnetic field
was begun at the Crimean Astrophysical Observatory (Severny et al., 1970). This paper
is the first of several to discuss the integrated light observations made since 1968. The
data includes observations made in the Crimea from 1969 through 1974 and
observations made at Hale Observatories (Mt. Wilson 46-meter tower telescope) from

The term ‘mean magnetic field of the Sun’ as used in this paper refers specifically to
the average field as observed in integrated sunlight (i.e., the Sun seen as a star). The
mean field thus defined is measured by letting unfocused sunlight enter a spectrograph
and measuring the Zeeman line splitting using a Babcock-type magnetograph. The
‘mean field’ represents a weighted average of the net field of the entire visible disc. The
weighting which results from several effects (primarily limb darkening) leads to a slight
emphasis of the center of the disc. (About half the contribution to the mean field comes
from the center 35% of the disc area.)

The main characteristics of the data as observed in 1968 (Figure 1) have been
confirmed by the continuing observations: The photospheric field, when averaged over
most of the solar disc, has a typical magnitude of 0.5 G with 2 or 4 polarity changes per
Fig. 1. Comparison of the magnitude of the mean solar field and of the interplanetary field in 1968. Open circles are the daily observations of the mean solar field, and the dots are 3-hour average values of interplanetary field magnitude observed near the Earth. The solar observations are displaced by $4\frac{1}{2}$ day allow for the average Sun–Earth transit time. The abscissa is the time of the interplanetary observati
solar rotation with the pattern of polarity reversals essentially the same as the interplanetary magnetic sector structure observed by spacecraft near the earth.

Before describing the results of the recent observations in more detail, it is necessary to discuss the expected weighting and the method of observing at the two observatories.

2. Expected Weighting of the Mean Field

Since the term 'mean field' is defined by the method of observation, it is necessary to understand the implications of the observing procedures. This is necessary both for interpreting the results and comparing observations from different observatories. In addition to the usual cautions and corrections which are important for understanding solar magnetic field observations (see, e.g., Harvey and Livingston, 1969 and Howard and Stenflo, 1971), there are some effects unique to the mean field observations.

These effects come from looking at the entire disc at one time. Since integrated light is used for the observations, light from all parts of the Sun is treated equally. However, due to limb darkening the center portion of the disc will be emphasized in the observation. Some additional systematic weighting toward the center of the disc comes from solar rotation. Since the disc-average absorption line will be centered on the magnetograph exit slits, the contribution to the profile from the east and west limbs will be displaced. The result is similar to a saturation of the magnetic signal. Thus the sensitivity of the magnetograph to fields on the limbs will be reduced. This effect produces about half as large a weighting as limb darkening (for the slit dimensions used at Mt. Wilson for the line used, Fe I 5250) but weighs somewhat stronger toward the center than does limb darkening (Scherrer, 1973). A computer-simulation of the observation shows that the average combined weighting can be described by the weight function:

\[ W(\alpha) = 0.08 + 1.19 \cos (\alpha) + 0.12 \cos^2 (\alpha), \]

where \( \alpha \) is the angle from the center of the disc.

There are some additional sources of weighting which are unique to observing in integrated light. Since there is unfocused sunlight at the entrance slit, there will be a pinhole image of the Sun at the diffraction grating and at the photomultiplier tubes. Entrance slit diffraction will fortunately make these exceedingly poor images. Three sources of weighting of the mean field have been associated with this imaging. These are the non-uniformity in grating efficiency with position, some loss from the limbs since the slit diffraction pattern partially misses the grating, and non-uniform response on the photocathodes. Due to difference in optical arrangements, the last two sources of weighting are not noticeable in the Crimean telescope. These weightings have been found to be small compared to limb darkening.

3. Mt. Wilson Observations

Mean field observations were begun at Mt. Wilson in October 1970 and have been
made in a continuing program on every available day since then. Because of the relationship between the angular size of the Sun and the aperture of the spectrograph at the 46 m tower (23 m focal length, 15 cm Littrow lens), the mean field observations cannot be made by simply letting unfocused sunlight enter the spectrograph. To circumvent this problem, an auxiliary lens is placed between the telescope objective and the spectrograph. The combination of the two lenses effectively matches the angular size of the Sun to the spectrograph. The diameter of the auxiliary lens is large enough to produce a region of integrated light about 8 cm in diameter at the entrance slit, but is small enough to allow enough light to pass by it to operate the guiding system. The rest of the instrument is the same as used for other magnetic measurements as described by Howard (1974).

The magnitude of the mean field is usually less than 1 G, so it is very important to establish the correct zero level. In the Babcock-type magnetograph the largest potential sources of zero level error are from the electronics and data recording systems and from instrumental polarization. When all the optics are properly adjusted and the magnetograph is properly balanced, the instrumental polarization will be cancelled. Possible electronic offsets are removed by subtracting the signal found by observing with the modulated circular analyzer turned off. To reduce noise in the signal each of the quantities is observed for 6 min. A complete mean field observation consisting of one integration with the modulation turned on and two with it turned off takes about 20 min. The resulting statistical noise in the measurement is less than 0.07 G. The most conservative way to estimate all sources of observing noise is to compute the standard deviation for days when more than one mean field measurement is made. The average standard deviation for such days at Mt. Wilson is 0.17 G. There may, however, be some additional sources of systematic error as discussed below.

4. Crimean Observations

The basic method of mean field observations used at the Crimean Astrophysical Observatory has been described by Severny et al. (1970). Observations were first made using the large solar tower but were moved to the small tower in the spring of 1970 when the reconstruction of the large tower was begun. Daily mean field observations have been continued at the small tower since that time. The acceptance aperture of the horizontal Czerny-Turner spectrograph is larger than the angular size of the Sun so no auxiliary optics are needed to observe in integrated sunlight. Light from the coelostat and second flat is directed into the spectrograph by a third flat with no image forming optics used. In addition to observing the magnetic signal from 5250, the magnetically insensitive line Fe I 5124 is also used. The value measured in 5124 is subtracted from that from 5250 to correct for both instrumental polarization and electronic and recording errors. The error as determined from the standard deviation of observations made on the same day is about 0.15 G. The complete observation takes about 20 min.
5. Comparison of Mt. Wilson and Crimean Observations

A detailed comparison of the observations for 1971–1974 shows that there is substantial agreement in overall characteristics of the data. The same large scale sector structure can be seen in each of the data sets and the average field values are about the same. The average magnitude of the Mt. Wilson observations is 0.45 G as compared with 0.49 G for the Crimean data. Considering the difference in equipment and procedures this agreement is quite encouraging.

The agreement between the two sets of observations is, however, far from perfect. While there are some extended intervals (such as most of 1974 – Figure 2) when the agreement is excellent, there are others (such as part of 1972) when one or both observatories may have had systematic zero level displacements and increased noise. When all 4 yr are taken together the cross-correlation function has a maximum of 0.4 at a lag of 12 hr. The lag of one half day is consistent with the lag in observation times and confirms that there are meaningful variations in the data with a time scale less than a day.

Of the 814 observations from Mt. Wilson and 751 from the Crimea there are only 464 days with observations at both locations. A straight line fitted to these 464 pairs of observations (by the method of least squares assuming both datasets have the same errors) yields the relationship:

Mt. Wilson mean field = 0.8 Crimean mean field + 0.1.

The small calibration difference revealed this way is consistent with the average magnitudes of the entire datasets. It is not possible to determine whether this factor is instrumental or simply due to the relative proportions of noise in the observations.

Figure 3 shows a scatterplot of the 464 joint observations and the best fit line. While real variations in the solar mean field contribute some of the scatter due to the time difference in the observations (particularly near sector boundaries), the most conservative way to estimate the true errors in the observations is to assume that all the scatter is observational. By examining the distribution of distances of points from the line we conclude that the average error for each separate mean field observation is about 0.5 G. The error for a combined dataset is about 0.35 G.

The error as determined by this comparison is several times larger than would be expected from the error determined separately for each observatory. This suggests some unaccounted for sources of systematic error. The most likely source is zero level errors caused by incomplete cancellation of instrumental polarization. It should be noted that there are differences in the degree of correlation from year to year with apparently sometimes more error at one observatory and sometimes more at the other. As would be expected from the good correlation shown in Figure 2, a scatterplot for 1974 observations alone shows much less scatter than in Figure 3. The scatter in Figure 3 is also reduced if the data from each observatory is first smoothed by a 3-day running mean to help remove zero level errors and to reduce the effect of actual variations in the
Fig. 2. Comparison of the mean solar magnetic field for Mt. Wilson and Crimea observatories for 1974.
Fig. 3. Scatterplot of all same-day pairs of mean field observations for the Mt. Wilson and Crimea observatories for 1971 through 1974. The line is a best fit assuming equal error in both data sets.

mean field. The sources of magnetograph zero level are currently being further investigated and it is expected that the good correlation of the mean field observations made at different observatories will continue to improve.

6. Comparison of the Mean Field with the Interplanetary Magnetic Field

Comparison of the mean field observations are interesting and may lead to a better understanding of errors in magnetic field observations, but understanding the relationship of the mean field to the interplanetary magnetic field may help in understanding the Sun. The correlation in polarity reported by Severny et al. (1970) for 1968 has remained strong. That is, the sector structure seen in the interplanetary magnetic field (IMF) is almost the same as that seen 4.5 days earlier in the mean field.
For the present comparisons, spacecraft observations of the IMF (compiled by King, 1975) have been supplemented with inferred IMF polarities from Svalgaard (1975). The cross-correlation between the mean field and the IMF polarity was computed for each year separately for both the Mt. Wilson and Crimean observatories. It was found that the correlation with the IMF was better for years when the separate mean field observations best agreed with each other. This suggests that the variation of correlation of the mean field with the IMF polarity may be more from variations in the noise in the observations than from a fundamental variation in the source of the IMF as compared to the mean field, although the latter argument cannot yet be completely ruled out.

Fig. 4. The cross-correlation of the combined and smoothed solar mean field with the IMF polarity for the years 1971 through 1974.

To better investigate the relationship between the mean field and the IMF, the mean field data has been combined into a single dataset. To help reduce some of the observational noise the combined data has been smoothed with a 3-day running mean. The correlation function between the combined mean field and the IMF polarity for 1971–1974 is shown in Figure 4. It is interesting to note that even during this interval which contained larger than average high speed solar wind streams, the transit time for the magnetic structure remained about four days.

Figure 5 is a plot of the polarity of the combined mean field and the IMF polarity shown in the familiar Bartels 27-day calendar system. The mean field is plotted four days after it was observed to correspond to the Bartels calendar at earth. It can be seen that the sector structure is the same in both datasets. In particular, note the 27-day (i.e., vertical) pattern before 1972 and after 1973, and the 28.5 day pattern in 1972 and 1973. These main features of the sector structure for these years can be seen in both datasets.

We have seen that the polarity of the IMF follows that of the mean field but a comparison of absolute values shows that the magnitudes are not correlated. The cross-correlation between the mean field magnitude and the IMF magnitude shows no significant correlation at any lag. This result can be understood when we remember that most of the structure of IMF magnitude within a sector is probably governed by solar
Fig. 5. Polarity of the solar mean field and of the IMF. Each row is one Bartels rotation with the solar data displaced 4 days to allow for the Sun–Earth transit time.
wind processes (such as high speed streams). We would expect though to be able to compare a long term average IMF with the photospheric fields.

Discussion

The first conclusion we have come to is that much care must be used when observing the solar mean field. Since the expected mean field value is so small, precautions must be made to reduce instrumental noise and to properly determine the magnetograph zero level. Even with these observational difficulties, it is seen that there is a basic agreement in both the magnitude and polarity structure between the mean field observed in the Crimea and Mt. Wilson. It is also seen that the mean field shows basically the same polarity structure as the IMF.

Our interpretation of the correspondence of the structures can be divided into two parts. First we believe that the mean field observations (by averaging over most of the disc) reveal the large scale structure of the Sun’s magnetic field. This organization as seen in averages of the Mt. Wilson synoptic maps has recently been discussed by Svalgaard et al. (1975). Then, since the IMF shows the same pattern we conclude that the IMF must represent a sampling (or averaging) over a portion of the photosphere similar in size to the mean field source area.

In addition to long term studies of the solar sector structure, with the aid of continuing mean field observations at Mt. Wilson and in the Crimea as well as with the new mean field telescope at Stanford, mean field observations can be useful in identifying the sector structure in real time. This is enabling us to better study the relationship between the sector structure and other solar features.

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