MEASUREMENTS OF SOLAR MAGNETIC FIELDS

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ABSTRACT

Using the photographic technique of Leighton, high spatial resolution measurements of photospheric magnetic fields have been obtained with the following chief results:

1. Regarding sunspot groups as sources of magnetic flux and defining a “source flux” that may be determined uniquely for a sunspot group from flux measurements, we found a variation in source fluxes from group to group ranging from less than 0.2 SFU (1 SFU [solar flux unit] = 10^{21} maxwells) for very “small” spot groups to more than 20 SFU for very “large” groups. This variation of source flux with sunspot group “size” is described by the rule-of-thumb \( \Phi = 1.2 A_m \), where \( \Phi \) is the source flux in SFU and \( A_m \) is the group size in 10^{18} cm^2 defined as the maximum area attained by the sunspot group during its development.

2. Zeeman photographs emphasize that as a bipolar magnetic region (BMR) develops in time and as its magnetic flux spreads over a progressively larger area, the flux density does not decrease smoothly from the vicinity of the source to the outer limit of detectable flux but is distributed in successively smaller bits and fragments. Moreover, measurements obtained from these Zeeman photographs reveal magnetic field strengths of 200-700 gauss in these bits and fragments, showing that fields of a few hundred gauss are not uncommon for small magnetic features even in quiet regions of the Sun.

3. Numbers of polar faculae have been calibrated to give magnetic flux on the polar caps of the Sun as a function of time during the period 1905-1964. The fluxes vary cyclicly with time approximately 90° out of phase with the variation of the sunspot number for the whole solar disk with time during the same period (provided the sunspot number is given a polarity corresponding to the magnetic polarity of the following sunspots of the relevant hemisphere). The maxima of the polar fluxes vary considerably from cycle to cycle (just as the maxima of the sunspot number vary considerably from cycle to cycle), maximum fluxes ranging from 6 to 21 SFU, with 12 SFU being a typical maximum polar flux during 1905-1964.

These results are consistent with the hypothesis that emerging BMR’s are the sources of all the flux on the solar surface, and that the random walk plus differential rotation is the dominant mechanism for the distribution of the flux provided by these sources. More important, these measurements provide a means of testing this hypothesis in more detail than has been possible heretofore.

I. INTRODUCTION

A significant advance in our understanding of the solar cycle was made by H. W. Babcock (1961) in his presentation of a theory of the topology of the Sun’s magnetic field and the 22-year cycle. Leighton (1963, 1964) has clarified one aspect of the solar cycle (the expansion and apparent “migration” of unipolar and bipolar magnetic regions) by suggesting a definite physical mechanism by which magnetic fields may be transported on the solar surface. Leighton’s mechanism is a random walk associated with the non-stationary large-scale cellular convection called supergranulation (Leighton 1960; Leighton, Noyes, and Simon 1962). Although most of the calculations reported by Leighton were necessarily based upon incomplete information, particularly concerning fluxes in sunspot groups, the agreement of his model with several observed features of the solar cycle suggests that the random walk is a dominant mechanism in the dispersal and migration of magnetic fields on the Sun. The measurements described in this paper were obtained in order to permit a more quantitative test of Leighton’s random-walk mechanism.

II. METHOD AND ACCURACY OF MEASUREMENT

The measurements described here were derived from Zeeman photographs (“Z-photos”) obtained by the author at the 60-foot tower telescope on Mount Wilson during

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† Now at Kitt Peak National Observatory, Tucson, Arizona.
the summers and autumns of 1963 and 1964. The method of obtaining these photographs, in which lighter-than-average features indicate line-of-sight components of photospheric magnetic field of one magnetic polarity and darker-than-average features indicate components of opposite polarity, has already been described (Leighton 1959; Sheeley 1965).

By comparing the transmission of a magnetic feature with the transmission of the neutral gray background on a Z-photo, one obtains a quantity proportional to the line-of-sight component of magnetic field of the magnetic feature. Similarly, by comparing on a Z-photo the average transmission of an entire magnetic region with the average transmission of a zero-field region of the same area, one obtains a quantity roughly proportional to the magnetic flux through the region of interest. The flux measurements described here were carried out in this way. The accuracy was increased by making two sets of such measurements—one for the Z-photo and one for a “reciprocal” Z-photo in which the lighter-than-average and darker-than-average magnetic polarity scheme had been reversed. The geometric mean of the two sets of measurements was then used to obtain the flux.

The proportionality constant, or sensitivity, relating the transmission measurement to the flux and field strength depends on both the photographic contrast of the original plate and the intensity versus wavelength spectrum of the magnetic feature of interest. Near the disk center, most features have roughly the same intensity so that the sensitivity can be obtained from a measurement of \( \frac{d \log_{10} T(\lambda)}{d \lambda} \)—the average sensitivity of transmission on the original plate to variations in wavelength. Sunspots are notable exceptions. The umbras of sunspots are sometimes so underexposed that their exposures lie off the linear portion of the characteristic curve and thus correspond to photographic contrasts lower than that obtained for the average solar disk. Often no flux at all is detectable in relatively large and dark umbras. For relatively small sunspots the contrast is generally large enough that some flux is detectable. However, one cannot exclude the possibility that this flux may be due to polarized light from neighboring field regions that has been scattered into the umbral field of view. Flux is generally detectable in the penumbra of even the largest sunspots, but lack of knowledge of the penumbral spectral line profiles makes an accurate calibration of this flux difficult.

The principal sources of error limiting the accuracy of these flux and field strength measurements were: (1) variations of the zero-field transmission on individual Z-photos; (2) registration problems caused by poor seeing and guiding; (3) photographic reduction errors.

By limiting the areas of field integration to regions just larger than the magnetic features of interest, the errors produced by variations in the zero-field transmission were kept less than 25 per cent for \( \Phi > 0.5 \) SFU (recall that 1 SFU = \( 10^{21} \) maxwells) and \( \pm 0.1-0.2 \) SFU for \( \Phi < 0.5 \) SFU. Problems caused by poor seeing and guiding were partially avoided by not measuring Z-photos containing many random seeing and guiding fluctuations comparable to the smallest resolvable features of interest. Since it was not possible to eliminate completely occasional seeing and guiding fluctuations, measurements of field strengths in features smaller than 3000 km in diameter should be regarded as lower limits to the fields measurable in the absence of such fluctuations. Errors result from deviations of photographic contrast from unity in the reduction stages of a Z-photo. Although unit contrast could be checked and regulated within about 10 per cent in the contact print stages, no suitable method of maintaining unit contrast in the two projection print stages was employed. Deviations of \( \gamma_S \) and \( \gamma_D \) (the contrasts of the projection print stages of the singly and doubly canceled images) from unity result in the overestimation of fluxes and field strengths by a factor \( \gamma_S \gamma_D \). Ex post facto measurements suggest that \( \gamma_S \) and \( \gamma_D \) were generally not outside the range 1.0–1.3 so that errors introduced in the photographic reduction process probably do not result in overestimation of the fluxes and field strengths by more than a factor of 1.7. Magnetic fluxes of different magnetic features or regions on a given Z-photo may be compared relatively precisely.
since variations in the zero-field transmission are the only appreciable source of relative error. Thus, for example, one could compare the fluxes in the leading and following parts of a bipolar magnetic region (BMR) sufficiently accurately that if there had been flux differences of as much as a factor of 2 they would have been detected.

III. RESULTS

a) Magnetic Fluxes Associated with Sunspot Groups

Magnetic fluxes associated with sunspot groups were measured using the photographic technique. Fluxes in the umbras of sunspots were supplemented by fluxes calculated from Mount Wilson magnetic observations of sunspots whenever these observations were available. (The umbral fluxes were calculated by multiplying the measured field strength by the area of the umbra.) Whenever an appreciable imbalance between fluxes of positive and negative polarity was obtained photographically, a corresponding imbalance of calculated sunspot umbral flux was obtained. The umbral flux imbalance was always in the direction to account for the photographic imbalance, but, especially for small sunspots, the amount of umbral flux imbalance was not always large enough to account for the photographic imbalance. This discrepancy might be resolved either if the photographically measured fluxes were too large or if the Mount Wilson field strengths of small sunspots were too small, or both.

The fluxes associated with sunspot groups varied considerably from group to group. A flux of 0.2 SFU (1 SFU = 10^{21} maxwells) was measured for a small BMR in which sunspots were never observed at Mount Wilson. Typical spot groups during the summer of 1964 had fluxes ranging from 1 to 5 SFU. The sunspots in these groups generally were very small, without penumbras, and did not last more than a week. A moderate-sized sunspot group having a characteristic leading spot with penumbra was measured in the autumn of 1963 and a flux of approximately 12 SFU obtained. A very large and active \gamma-type sunspot group with considerable penumbra was measured and found to have 20–40 SFU. These measurements were compared with three flux measurements of Bumba (1961), who obtained values ranging from 14 SFU to more than 50 SFU for very large sunspot groups.

The flux of a given BMR generally increased to a maximum value in a few days or less and then slowly declined. A source flux, $\Phi$, was defined as the average of the absolute values of the total fluxes of leading and following polarity in a given BMR at the time when this average was greatest. If the leading and following fluxes balance, then $\Phi$ may be interpreted as the maximum flux emanating from one part of a BMR and returning to the other part. To describe the variation of source flux with the “intrinsic size” of the BMR, a parameter of size $A_m$ was defined. $A_m$ is the area of the solar surface covered by all of the sunspots (umbras plus penumbra of both leading and following parts) of the associated group at the time when this area is largest.

Table 1 contains the source fluxes and intrinsic sizes of the nine groups measured. Also included are the umbral and photographically measured flux imbalances for each of these groups. The source fluxes, $\Phi$, have been plotted versus the intrinsic sizes, $A_m$, in Figure 1. From Figure 1 it is apparent that the source fluxes can be represented by the relation $\Phi = 1.2 A_m$, where $\Phi$ is in SFU and $A_m$ in 10^{18} cm^2.

In the last two columns of Table 1 $\Delta \Phi_l = |\Phi_{l'}| - |\Phi_{f'}|$, $\Phi_{l'}$ and $\Phi_{f'}$ refer to the umbral fluxes calculated from the Mount Wilson magnetic observations of sunspots for the leading and following sunspots, respectively; $\Delta \Phi_m = |\Phi_{m'}| - |\Phi_{m'}|$, $\Phi_{m'}$ and $\Phi_{m'}$ refer to the photographically measured magnetic fluxes for the leading and following parts of each BMR, respectively.

In Table 1 for MWO group 15852 (see data marked with ||) the flux of leading magnetic polarity was spread out considerably more than the flux of following polarity. Therefore, one might expect relatively more flux of leading polarity to be undetectable
TABLE 1

SOURCE FLUXES ASSOCIATED WITH SUNSPOT GROUPS

<table>
<thead>
<tr>
<th>Group No.</th>
<th>Date of Observation</th>
<th>Position of Group</th>
<th>Source Flux (SFU)</th>
<th>$A_m(10^{14} \text{ cm}^2)$</th>
<th>$\Delta A_m$(SFU)</th>
<th>$\Delta \Phi$(SFU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15767</td>
<td>9/16/63</td>
<td>S10, W10</td>
<td>11 4</td>
<td>10 2</td>
<td>+1 6</td>
<td>- 4 2*</td>
</tr>
<tr>
<td>15768</td>
<td>9/20/63</td>
<td>N13, W3</td>
<td>20 8</td>
<td>39 3</td>
<td>-7 1</td>
<td>+10 6</td>
</tr>
<tr>
<td>15836</td>
<td>6/15/64</td>
<td>N6, E18</td>
<td>1 9</td>
<td>1 3</td>
<td>0 0</td>
<td>+ 0 2</td>
</tr>
<tr>
<td>15845</td>
<td>7/16/64</td>
<td>N28, E13</td>
<td>1 6</td>
<td>1 1</td>
<td>+0 1†</td>
<td>- 1 0†</td>
</tr>
<tr>
<td>15851</td>
<td>8/13/64</td>
<td>N22, W42‡</td>
<td>9 9‡</td>
<td>8 8‡</td>
<td>+1 6‡</td>
<td>- 1 2‡</td>
</tr>
<tr>
<td>BMR§</td>
<td>8/15/64</td>
<td>N9, E36</td>
<td>0 2</td>
<td>0 0</td>
<td>+0 1</td>
<td>0 0</td>
</tr>
<tr>
<td>15852</td>
<td>8/17/64</td>
<td>N8, W19</td>
<td>4 7</td>
<td>1 8</td>
<td>+0 1†</td>
<td>- 0 9†</td>
</tr>
<tr>
<td>15854</td>
<td>9/7/64</td>
<td>N39, W17</td>
<td>1 9</td>
<td>1 0</td>
<td>+0 2</td>
<td>- 0 4</td>
</tr>
<tr>
<td>15855</td>
<td>9/13/64</td>
<td>N7, W50‡</td>
<td>2 2‡</td>
<td>1 1‡</td>
<td>-0 2§</td>
<td>+ 1 3‡</td>
</tr>
</tbody>
</table>

* The flux of MWO group 15767 could not be isolated with certainty from the flux of a nearby BMR
† It is possible to explain this imbalance in terms of a similar imbalance in a nearby BMR
‡ A foreshortening correction of the form $(1/\cos \theta)^2$ has been applied to the measured flux, where $\theta$ is the heliocentric position of the group
§ One in which sunspots were never seen at Mount Wilson
‖ See text.
¶ See text.

Fig. 1.—Source fluxes, $\Phi$, plotted versus sunspot group size, $A_m$, for the BMR's of Table 1. "NRS" refers to our measurements and "VB" refers to the measurements of Bumba (1961) (1 SFU = $10^{21}$ maxwells). There are four points in the unresolved cluster at $\Phi \sim 2$ SFU.
Fig. 2.—Photographs of the BMR associated with Mount Wilson sunspot group 15851. The upper photos were taken within a few days of the formation of the BMR, and the lower photos were taken during the next disk appearance. In the Z-photos, lighter-than-average features indicate positive magnetic polarity (magnetic vector directed toward the observer) and darker-than-average features indicate negative polarity (magnetic vector directed away from the observer). $\Phi_s$ refers to the source flux and $\Phi_l$ and $\Phi_f$ refer to the absolute values of the total leading and following fluxes, respectively. In each of the photographs north is roughly toward the top of the page, and east is to the right. On August 13, 1964, the BMR was located at roughly 22° N., 42° W. On September 9, 1964, the contiguous features of strong but opposite magnetic field were located at approximately 21° N., 6° E.
Fig. 3.—The top photograph is a spectroheliogram taken near the solar disk center in the core of Hα. The other two photographs are Z-photos of the same region. In the Z-photos, lighter-than-average features indicate positive magnetic polarity (magnetic vector directed toward the observer) and darker-than-average features indicate negative polarity (magnetic vector directed away from the observer). North is approximately toward the top of the page, and east is to the right. These fields and fluxes may be as much as twice their true values due to possible departures from unit contrast during the projection print stages of photographic reduction of the Z-photos. “Range of field” refers to the upper and lower limits of field that one might obtain from different interpretations of the microphotometer tracings.
Fig. 4.—(a) Spectroheliogram taken in the core of Ha about 1 1/2 hours after the Z-photos in (b) and (c). The arrow indicates a brighter-than-average feature corresponding to the magnetic feature indicated in (b). (b) Z-photo in which lighter-than-average features indicate a magnetic field directed toward the observer (positive polarity) and darker-than-average features indicate a magnetic field directed away from the observer (negative polarity). (c) Z-photo having the opposite polarity to that of (b): darker-than-average features indicate positive fields and lighter-than-average features indicate negative fields. This Z-photo corresponds to a time about 2 min later than that of (b). Two Z-photos were included rather than one to aid in the identification of the very tiny magnetic features. The features in (c) are not as sharp as those in (b) because of a slight misalignment of plates in the doubly canceled stage. Note that most of the very tiny magnetic features correspond to brighter-than-average features in the Ha spectroheliogram even though it was taken about 1 1/2 hours after the Z-photos. In all three pictures, north is approximately toward the top of the page and east is to the right.
below the measurement threshold than flux of following polarity. This might account for part of the difference in magnitudes of $\Delta \Phi_l$ and $\Delta \Phi_f$ for MWO group 15852.

Also for MWO group 15855 (see data marked with #), the fluxes corrected for foreshortening were $\Phi^l = \Phi^m_1 + \Phi^s_1 = 0.9 + 0.1 = 1.0$ and $\Phi^f = \Phi^m_2 + \Phi^s_2 = 0.4 + 0.2 = 0.6$ SFU, where $l$ refers to leading, $f$ refers to following, $m$ refers to photographically measured, and $s$ refers to umbral spot fluxes. If the lines of force from the leading and following parts of the BMR were inclined toward each other approximately $14^\circ$ from the normal, this would account for the observed flux imbalance. The common values of flux normal to the surface would then be approximately 2.0 SFU.

b) Small-Scale Magnetic Fields

It was observed that, as BMR's develop, their fluxes are distributed in bits and fragments of progressively smaller size until finally they escape detection below the threshold of the photographic measurement. This is illustrated in Figure 2 which shows the BMR corresponding to Mount Wilson group no. 15851 a few days after the birth of the spot group and again on its next disk appearance. Flux measurements of these relatively small magnetic features yielded values ranging from 0.05 SFU for very small points less than 3000 km in diameter to 0.4 SFU for network fragments. The corresponding magnetic fields ranged from 200 to 700 gauss—field strengths considerably larger than had been anticipated away from regions of sunspot activity. In an attempt to see if these large fields were the result of errors in photography, a Z-photo was prepared for which the photographic contrast at each stage of reduction (including the two stages of projection printing) had been carefully measured. All the stages of contact printing possessed contrasts that were as close to 1.0 as one could measure. The contrasts, $\gamma_S$ and $\gamma_D$, of the projection print stages of the singly and doubly canceled images were $\gamma_S = 1.05$ and $\gamma_D = 0.87$, respectively. Thus, the net correction to the measured fields was no more than 10 per cent. Measurements revealed magnetic-field strengths ranging from 150 to 400 gauss for small magnetic features in a large unipolar magnetic region (UMR). A field strength of 400 gauss was measured in a feature less than 3000 km in diameter. In conclusion, the measurements of field strengths of several hundred gauss in small features outside active regions are accurate within about $\sim 50$ per cent and are not the result of errors in photography. These results are illustrated in Figures 3 and 4. In particular, note the following in Figure 3:

1. In detail, wherever there are adjacent regions of opposite magnetic polarity, there are disk filaments in Hα. Note especially that the three white dots of positive magnetic field nearly surrounded by field of negative polarity are encircled by a small absorbing feature in the Hα spectroheliogram.

2. The region in the photographs seems to contain four bipolar regions. Three of these are in the southern hemisphere, including the one with the large leading sunspot, and the other BMR is in the northern hemisphere. The region containing the large sunspot has apparently formed in another BMR just to the north of it, thus giving the impression of a single bipolar region.

3. No magnetic flux is indicated in the umbra of the large sunspot, although, some flux is indicated in its penumbra.

4. Although it is not apparent from this figure, the following part of the BMR in the northern hemisphere is the westernmost limit of the UMR that was observed for many solar rotations in 1963. The BMR seems to have formed near the western end of the UMR and contributed additional flux of following (negative) polarity to it. The very bright and somewhat rounded magnetic feature in the leading part of this BMR corresponds to a sunspot.

5. Although it is not evident from the figure, sunspots are located in those features having 720 gauss or more.
c) Magnetic Fluxes at the Poles of the Sun

Figure 5 shows the number of north and south polar faculae, respectively, during the period 1905–1964 (see also Sheeley 1964). These polar faculae relations have been calibrated to give magnetic flux in the polar regions of the Sun as a function of time during the same period. The calibration was achieved statistically by measuring magnetic fluxes associated with equatorial faculae of size and brightness similar to that of polar faculae. Table 2 summarizes these flux measurements for faculae in two equatorial regions (one of which is shown in Fig. 2). From Table 2, 0.2 SFU has been adopted as the magnetic flux corresponding to the average polar facula, with 0.1 SFU corresponding to the smaller, fainter polar faculae and 0.3–0.4 SFU corresponding to the larger, brighter polar faculae. To account for the polar faculae on the far side of the Sun that are not seen and therefore not included in the polar faculae relations, a correction factor of 1.5

Fig. 5.—The numbers of north and south polar faculae versus time, plotted with “polarities” to represent polarities of the corresponding polar magnetic fields. A “positive” number of polar faculae represents a positive magnetic field (magnetic vector directed toward the observer), and a “negative” number represents a negative magnetic field (magnetic vector directed away from the observer). Solid curves: numbers of faculae; dashed curves: sunspot numbers. The solid curves have been drawn by eye. For some years, measurements of numbers of polar faculae have been repeated as indicated by more than one point for a given year. Not many data were available during February 15–March 15 for 1911, 1912, and 1913 as shown in the curve for the south polar faculae. The sunspot number for the whole solar disk is plotted twice with “polarities” for comparison with the numbers of north and south polar faculae. In each case, the “polarity” is the polarity of the magnetic fields of the following sunspots in the respective hemisphere. Although the decrease in the number of north polar faculae during 1941 and 1942 was ignored in drawing the curve, this decrease was probably real.
was applied yielding $1.5 \times 0.2$ SFU = 0.3 SFU per visible polar facula as the factor by which the polar faculae relations shown in Figure 5 may be calibrated in terms of magnetic flux normal to the solar surface. Thus, for example, in 1954 we find approximately $40 \times 0.3$ SFU = 12 SFU as the north and south polar fluxes. This is not significantly different from the value of 8 SFU estimated by Babcock and Babcock (1955) from their polar magnetograms.

The polar fluxes vary cyclicly with time, approximately 90° out of phase with the variation of the sunspot number for the whole solar disk with time during the same 1905–1964 period (provided the sunspot number is given a polarity corresponding to the magnetic polarity of the following sunspots of the relevant hemisphere). The maxima of the polar fluxes vary considerably from cycle to cycle (just as the maxima of the sunspot number vary considerably from cycle to cycle), maximum fluxes ranging from 6 to 21 SFU with 12 SFU being a typical maximum polar flux during 1905–1964.

### TABLE 2

**MAGNETIC FLUXES ASSOCIATED WITH EQUATORIAL FACULAE**

**OF SIZE AND BRIGHTNESS SIMILAR TO THAT OF POLAR FACULAE**

<table>
<thead>
<tr>
<th>Region</th>
<th>Date</th>
<th>Fluxes (SFU) per Equatorial Facula</th>
<th>Average Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>Following part of 15851</td>
<td>9/6/64</td>
<td>East end 0 2 Middle .2 Middle .1 Middle .1 West end .6 .2 .13</td>
<td>0 2</td>
</tr>
<tr>
<td>Following part of 15851</td>
<td>9/7/64</td>
<td>East end .1 Middle .6 .0 .1 .1 .0 West end .1 .2 .8 .4</td>
<td>.15</td>
</tr>
<tr>
<td>15852</td>
<td>9/12/64</td>
<td>Leader .3 .1 .2 .2 .9 .1 .2 .3 .3 .1</td>
<td>.32</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Follower .1 .3 .2 0 2 0 2 0 2 0 2</td>
<td>0.20</td>
</tr>
</tbody>
</table>
Before leaving the topic of the polar fields, we shall consider some observations that may help to clarify our ideas about the polar fields and their relation to magnetic fields in the sunspot belts. First, in the process of counting polar faculae several plates were encountered on which the polar faculae were not centered about the pole marker. In every such case, the pole marker was found to be improperly placed, the correct position always being amid the polar faculae. This shows that the polar faculae are indeed polar phenomena and not just the trailing end of UMR's that are expanding toward the poles. This is consistent with the results of Babcock and Babcock (1955), who found no evidence of any persistent obliquity between magnetic and rotational axes on polar magnetograms obtained since 1952, and extends their results back to 1905.

Second, also in the process of counting polar faculae, large trailing regions of equatorial faculae were observed streaming poleward and eastward just prior to or during sunspot maximum in every sunspot cycle during the period 1905–1964. These “streams” undoubtedly correspond to the large unipolar magnetic regions described by Bumba and Howard (1965). The streams were especially noticeable in the hemisphere whose pole tipped away from Earth. (This was because the tail ends of the streams in this hemisphere were 7° closer to the polar limb, whereas the tail ends of the streams in the other hemisphere were 7° farther from the polar limb than they would have been at the times of year when the poles are equidistant from Earth.) They extended to the polar regions, often coming within 30° of the poles themselves. (This includes the correction of 7° for the inclination of the Sun’s axis to the ecliptic.) Yet, during these times the immediate vicinity of the poles had very few, if any, polar faculae. Comparison of these white-light photographs with the original polar magnetograms taken by H. D. Babcock (1959) during 1958 (and kindly made available to the author by R. F. Howard) showed that these facula streams generally correspond to magnetic field having the polarity of the following sunspots of the corresponding hemisphere. These observations show, as first pointed out by Babcock and Babcock (1955), that considerable care is necessary in the interpretation of polar magnetograms near the time of sunspot maximum because the facula streams could easily be mistaken for part of the polar fields, especially in the hemisphere whose pole is tilted away from Earth, since the facula streams appear to extend nearly to the pole in that hemisphere. In summary, by extending measurements of the polar fields back to 1905, these observations further strengthen the suggestion (H. W. Babcock 1961) that just prior to or during the time of sunspot maximum in every cycle considerable amounts of magnetic flux from the sunspot belts begin to arrive in the polar regions in great trailing streams.

IV. DISCUSSION

Howard and Harvey (1964), with an angular resolution of 10″ and with good seeing so that a resolution of 1″ was realized, found that calcium plages were outlined by a 15-gauss contour. However, they suggested that, if one considers that the magnetic gradient from a plage to non-plage region is probably not smooth and that the spatial resolution is only 10″, the actual field at the outer boundary of the plage is somewhat greater than 15 gauss, probably being 40–50 gauss. They stated further that the plages seen in the core of Hα fall within 60-gauss contour lines, although they do not entirely fill these lines. Since our measurements refer to the maximum field in small magnetic features, we might expect our measured field strengths to be somewhat greater than those of Howard and Harvey. Earlier, Howard (1962), using an aperture of about 2″ measured rms magnetic-field fluctuations of 8 gauss with peaks of 10–20 gauss spaced 20000–30000 km apart on the solar surface. He made these observations on six days between June 18 and July 17, 1959, in quiet regions away from plages. Our observations during the summer of 1964 showed that fields of a few hundred gauss occur in small features less than 3000 km in diameter, and that these features correspond to brighter-than-average features in the core of Hα (see Fig. 4). Since these bright features in Hα are distributed all over the solar
surface, we might expect that Howard would have encountered some. However, even if he had encountered such a feature, seeing or guiding fluctuations might have resulted in an underestimate of its field strength. Kiepenheuer (1953) has demonstrated the importance of good seeing for magnetic-field measurements at the 150-foot tower on Mount Wilson. He concluded that the magnetic fields outside sunspot groups have a fine structure whose dimension must be less than about 10''-20'', and that his measurements of a few gauss represent averages of fields that might easily exceed 20 gauss even in quiet regions outside the sunspot belts.

There have been other reports of strong fields outside sunspots. Howard (1959) with 10'' resolution at Mount Wilson found magnetic features with fields exceeding 75 gauss near sunspots. Beggs and von Klüber (1956), using a magnetograph similar to that at Mount Wilson with a slit length of 4'', found many fields of strength up to 100 gauss outside spots in the sunspot belts. Leighton (1959), using the photographic technique, found fields of 100-200 gauss in extensive areas throughout plage regions. Hale (1922) and Hale and Nicholson (1938), in their systematic search for "invisible" sunspots late in 1921 and early in 1922, recorded fields up to 700 gauss in active regions outside sunspots, and concluded that field strengths of 200-500 gauss outside sunspots were not uncommon in active regions.

Finally, using the magnetograph at the 150-foot tower on Mount Wilson with an angular resolution less than 5'' and with good seeing conditions, Harvey (1965) has found line-of-sight field components as large as 70 gauss associated with polar faculae. With the same equipment, Harvey and Sheeley (1965) have found fields easily exceeding 200 gauss in active regions outside sunspots near the disk center.

V. SUMMARY AND CONCLUSIONS

New measurements of solar magnetic fields have been obtained which reveal how much flux is associated with sunspot groups of various sizes, how this flux is distributed on the solar surface subsequent to its initial appearance, and how strong the resulting magnetic fields are. The behavior of the polar fields over several solar cycles has also been determined.

These measurements are generally consistent with the hypothesis that BMR’s are the sources of all of the flux on the solar surface, and that the random walk plus differential rotation is the dominant mechanism for the distribution of the flux provided by these sources. More important than this, however, these measurements provide a means of testing this hypothesis in more detail than has heretofore been possible. A logical consequence is to use these measurements to calculate the cumulative effect of the many individual sunspot groups that occur during a solar cycle. One might begin by considering past sunspot cycles in order to test the hypothesis. One would hope to account for the formation of the large UMR’s (facula streams) that expand poleward just prior to or during sunspot maximum as well as the detailed variation of the polar fields themselves. If this were successful, one might use sunspot groups of the present cycle to predict the future polar fields. The chief difficulty would appear to be the measurement of the positions, the axial tilts, the doublet separations, and the dates of birth of the many individual sunspot groups during a solar cycle. This would be complicated further by the fact that many of the groups are born and die on the back side of the Sun where they are not detected from Earth. It is hoped that further study will yield a practical solution to this problem.

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REFERENCES

Harvey, J. W. 1965, unpublished.
——. 1962, *ibid.*, 136, 211.