SIMULTANEOUS MEASUREMENTS OF MAGNETIC FIELDS AND BRIGHTNESS FIELDS USING A 4-IMAGE SPECTROHELIOGRAPH*

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Abstract. The use of an auxiliary beamsplitter with the Kitt Peak 15-foot spectroheliograph permits spectroheliograms to be taken simultaneously in 4 identical images of the sun. By using two of these images for a Zeeman spectroheliogram, a third image for a Fei λ4071 spectroheliogram, and the fourth image for a 6107Å continuum spectroheliogram, simultaneous measurements of magnetic fields and brightness fields have been obtained. Within the limits of intensity variations imposed by doppler shifts and brightness fluctuations of the continuum, a quantitative relation does exist between the measured values of brightness and magnetic field strength of the photospheric network. For intensities measured + 0.12 Å from the core of Fei λ4071, this relation is

$$\ln(1 + \Delta I/I) = \alpha |B_i|,$$

where $B_i$ refers to the component of magnetic field normal to the solar surface, $\Delta I/I$ is the fractional excess of brightness of the magnetic regions relative to the brightness of non-magnetic regions, and $\alpha = (6 \pm 2)\%/100$ gauss.

1. Introduction

Ever since the close spatial correspondence between the pattern of photospheric magnetic fields and the pattern of CaII emission became well established (Leighton, 1959; Howard, 1959), numerous investigators have attempted to determine whether a quantitative relation exists between the strength of the field and the brightness of the emission (Simon and Leighton, 1964; Tsap, 1966; Kuznetzov and Stepanov, 1967; Livingston and Zirker, 1968). Some observers have made similar studies using low-excitation lines of neutral metals rather than K2 as the brightness indicator (Harvey and Livingston, 1969a). One feature that all of these investigations show in common is an average tendency for brightness to increase with field strength, together with a large amount of scatter of the individual measurements from this average. This leads us to wonder how to interpret the scatter. Does it reflect the fact that there is no single-valued relation between brightness and field strength, or does it reflect measurement limitations?

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There are several factors that one would expect to produce scatter. First, although the pattern of $K_2$ emission resembles the pattern of photospheric magnetic fields, detailed spatial differences do exist (Chapman and Sheeley, 1968). These differences seem to be associated with the different heights in the solar atmosphere at which the $K_2$ emission and the photospheric fields occur. (The bright network visible on spectroheliograms in the $K_1$ wings, in low-excitation lines of neutral metals, and in molecular lines appears to coincide exactly with the pattern of photospheric magnetic fields and therefore seems to be a much better indicator of the presence of the photospheric fields than does the $K_2$ chromospheric network.) Second, because fluctuations in atmospheric seeing produce enormous effects on the measurements of the field strength and the brightness of the photospheric network (see for example, Deubner, 1968), one would expect non-simultaneous measurements to result in considerable scatter. Third, if the spectral lines used to measure field strength and brightness differ appreciably in wavelength, the differential refraction of the Earth's atmosphere can shift the images sufficiently that these measurements may be obtained at different times and under different seeing conditions (Simon, 1966). Thus, unless this effect were somehow taken into account, it would contribute scatter. This would be the case for example if brightness were measured in the wing of the Ca II K line at $\lambda 3934$ and magnetic field were measured using Fe I $\lambda 5250.2$ or Ca I $\lambda 6103$.

In the past, the limitation of simultaneity has prevented a good quantitative study of the relation between line brightness and photospheric magnetic field strength using the spectroheliograph. However, in the same way that Leighton (1959) obtained duplicate images at the single exit slit of the Mount Wilson spectroheliograph, by placing a beamsplitter in front of the entrance slit of the 15-foot spectroheliograph at Kitt Peak we have obtained duplicate solar images at each of its two exit slits – thus obtaining four spatially identical images. By using two of these images for a Zeeman spectroheliogram, a third for a line intensity spectroheliogram, and the fourth for a continuum spectroheliogram, simultaneous measurements of the brightness and the magnetic field strength of the photospheric network have been made. The problem of differential refraction was removed by orienting the spectroheliograph so that its slits are parallel to the atmospheric dispersion. This paper presents the preliminary results of a study to see whether a quantitative relation between brightness and field strength exists when the factors mentioned above have been removed. A new technique is described whereby the strength of the magnetic field and the brightness of the network can be compared accurately over an entire two-dimensional field of view by means of a suitable photographic cancellation between a Zeeman spectroheliogram and a brightness spectroheliogram.

2. Experimental Techniques

A. OBSERVATIONS

As we have already mentioned, by placing a beamsplitter in front of the entrance slit of the 15-foot spectroheliograph at Kitt Peak, one obtains duplicate images in each
of the two exit slits. The two images in slit No. 1 were used for Zeeman spectroheliograms in CaI $\lambda$ 6103. One of the images in slit No. 2 was used for a spectroheliogram in the 6107 Å continuum. The other image in slit No. 2 was used for a spectroheliogram at $+0.12$ Å from the core of FeI $\lambda$ 4071. This line was chosen for several reasons: First, it shows the photospheric network well, especially at $\Delta \lambda = +0.12$ Å. Second, the slope of its line profile is sufficiently small that intensity fluctuations produced by doppler shifts are relatively small. Third, it lies in the blue region of the spectrum where Zeeman sensitivities are small and will not contribute to brightness fluctuations. (The Zeeman sensitivity of $\lambda$ 4071 is $\Delta \lambda/\beta = 0.51 \times 10^{-5}$ Å/gauss.) Fourth, its position in the 6th order is sufficiently close to the position of $\lambda$ 6103 in the 4th order that these lines can be observed simultaneously. The relevant spectroheliograph data is summarized in Table I. Differential refraction was taken into account by orienting the spectroheliograph so that its slits were parallel to the atmospheric dispersion.

### Table I

<table>
<thead>
<tr>
<th>Spectroheliograph data</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Slit No. 1</strong></td>
</tr>
<tr>
<td><strong>side a</strong></td>
</tr>
<tr>
<td>Wavelength</td>
</tr>
<tr>
<td>Grating order</td>
</tr>
<tr>
<td>Order-separating filters</td>
</tr>
<tr>
<td>Emulsion</td>
</tr>
<tr>
<td>Dispersion</td>
</tr>
<tr>
<td>Slit width</td>
</tr>
</tbody>
</table>

Entrance slit width: 100 µ
Spectroheliograph scan rate: 45 sec/cm
Development: 7 minutes in Eastman Kodak HC 110 ($\gamma \approx 2-4$)

### B. Reductions

The photographic reduction of Zeeman spectroheliograms was not carried beyond the singly-canceled stage (see Leighton, 1959). The reason for this was to eliminate time and seeing differences that would result from a double-cancelling of spectroheliograms taken at different times. Streaks caused by polaroids, filters, and slit dust were removed in the following way. A 2 cm × 25 cm strip of the original plate containing a minimum of solar structure was masked off and used to expose a 20 cm × 25 cm film sheet. During the exposure this strip was moved at a uniform rate in a direction parallel to its streaks. Solar features averaged to give a uniform exposure and the unwanted streaks reinforced to produce a "streak film". This film was then developed to unit contrast and used to cancel the streaks on the original plate. Although the Zeeman spectroheliograms were not reduced to the doubly-canceled stages, a second Zeeman pair was always made with the quarter-wave plate rotated 90° so that if there were any residual background effect tending to enhance one polarity relative to the other, it would be noticed and could be allowed for.
Next a set of copies of the FeI $\lambda$4071 spectroheliogram was made with contrasts ranging from 0.20 to 1.3. These were successively placed in register with the singly-cancelled Zeeman spectroheliogram and a contrast $\gamma_L$ found for which the photospheric network on the FeI $\lambda$4071 spectroheliogram best cancelled the non-sunspot magnetic field of appropriate polarity. This test was quite sensitive – independent observers being able to estimate $\gamma_L$ within approximately 0.05. This value of $\gamma_L$ then determined the relation between brightness and magnetic field strength. Finally, since features on the difference spectroheliogram corresponded to visible features on the 6107 Å continuum spectroheliogram, a set of copies of the 6107 Å spectroheliograms was made to see what would remain if these features were similarly cancelled. We shall consider this further in Section 3.

C. CALIBRATIONS

At the end of each plate a spectroheliogram of a short strip of the sun was taken with a calibrated stepwedge on the entrance slit and with the image out of focus. In this way each FeI $\lambda$4071 plate contained a stepwedge from which relative intensities were determined.

Zeeman spectroheliograms were calibrated from the “expanded line profile” of the average solar disk (see Leighton, 1959). With the slits set correctly $-0.07$ Å from the core of CaI $\lambda 6103$, the calibration curves were linear for field strengths up to about 1000 gauss. At this slit position, the slope (photographic density per angstrom) of the line profile on an uncancelled spectroheliogram was typically $6$ Å$^{-1}$, corresponding to a density calibration on the singly-cancelled plate of 12 Å$^{-1}$ or 4.2%/100 gauss for $\lambda 6103$.

There were two factors which one might expect to influence the calibration of the Zeeman photographs. First, doppler shifts might shift the effective slit position and consequently change the calibration. Second, the line profile of $\lambda 6103$ is intrinsically weaker in non-sunspot magnetic field regions than in “quiet” regions of the disk so that we might expect calibration in terms of the average profile to give inaccurate measurements of field strength.

First we shall consider the effect of doppler shifts. In the process of making the singly-cancelled stage of a Zeeman photograph it is possible to see at a glance how well doppler shifts in non-field regions are cancelled. In general, if the exit slit is positioned sufficiently close to $\Delta \lambda = -0.07$ Å for both spectroheliograms of an uncancelled Zeeman pair, and if both of these plates have the same contrast, then the doppler shifts contribute no signal to the singly-cancelled stage. Since the doppler shifts of such photospheric lines are less in non-sunspot magnetic field regions of the sun than in quiet regions (Sheeley, 1967), we conclude that if the doppler shifts in quiet regions are cancelled on the Zeeman spectroheliogram, then the smaller doppler shifts in field regions are also cancelled.

Second, we shall consider the effect of line profile changes on the calibration of CaI $\lambda 6103$ Zeeman spectroheliograms. Low excitation lines of neutral metals weaken appreciably in regions of non-sunspot magnetic field. That these profile changes can
significantly affect the calibration of magnetic field measurements has been well-established (Chapman and Sheeley, 1968; Harvey and Livingston, 1969b). To obtain an idea of how the calibration of Ca I λ6103 Zeeman spectroheliograms in terms of the average line profile would compare to the calibration in terms of the profiles in the magnetic field regions, doublepass photoelectric profiles of λ6103 were taken using the 45-foot spectrograph. The aperture of the entrance slit was set to give 1–2 seconds of arc resolution under favorable seeing conditions. Although in some regions of the disk the core of λ6103 was 50% brighter than average, the wings beyond about 0.05 Å did not differ very much from the average profile. To obtain an upper limit on the corrections that would have to be applied to calibrations based on the average profile, the photoelectric profiles of a bright region and an average region were transformed from intensity profiles to photographic density profiles using a typical characteristic curve for our Zeeman plates. We found that for the most-weakened profiles, calibration in terms of the average profile would result in an underestimation of the magnetic field strength by approximately 15% if the slit position was set at Δλ = −0.07 Å. Finally, we should mention in connection with this profile effect that if the two uncancelled Zeeman spectroheliograms are not taken at exactly the same displacement from the core of λ6103 a residual background tending to enhance one magnetic polarity over the other will occur. The magnitude of this effect depends on the product of the wavelength separation of the two images and the difference between the slopes of the line profile in a magnetic region and in a non-magnetic region. Since we could never be sure that this wavelength separation was precisely zero, it was important to position the slit sufficiently far into the wing that the difference in slopes was small. Although for some Zeeman spectroheliograms this effect was negligible, in general it was probably the largest source of error in the calibration of magnetic field strengths.

3. Results

Figure 1 shows at the top four spectroheliograms taken simultaneously with the axis of the quarter-wave plate oriented at −45° to the entrance slit and at the bottom four spectroheliograms taken approximately 5 minutes later with the quarter-wave axis at +45° to the slit. When a γ = 1 copy of column "a" is placed in register with column "b", a Zeeman spectroheliogram is obtained as shown in column "a" of Figure 2. Reproduced for comparison is the pair of Fe I λ4071 spectroheliograms from column "c" of Figure 1. A small, fine-scale background noise appears on parts of the Zeeman photograph due to slight differences in the magnification of the uncancelled pairs of spectroheliograms. This effect is not important for the purpose of this paper. It is evident in Figure 2 that the pattern of magnetic field and the photospheric network are very closely related. The density fluctuations on the Zeeman spectroheliogram are proportional to the line-of-sight component of magnetic field, and since this region was near the center of the solar disk these measurements represent field components normal to the solar surface.

By making a γ_L = 0.98 negative copy of the Fe I spectroheliograms in column "b"
Fig. 1. Spectroheliograms taken simultaneously with the 82 cm solar image and the 4-image spectroheliograph. The four pictures in the first row were taken simultaneously with the axis of the quartz plate oriented at $-45^\circ$ relative to the entrance slit. The four pictures in the second row were taken 5 minutes later with the axis oriented at $+45^\circ$. The four pictures in the top row were taken on September 1, 1969. The four pictures in the bottom row were taken with the 82 cm image of the sun.

Uncancelled Zeeman Photographs

$\lambda = 6003$

$\lambda_{FeI} = 4071$

$\Delta \lambda = 0.12 \AA$

CaII $\lambda 6073$

6073$\AA$ Continuum

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Fig. 2. A comparison of the line-of-sight magnetic field and the brightness of the photospheric network. Column "a" shows the singly-cancelled Zeeman photograph obtained by photographically subtracting the un-cancelled Zeeman photographs in Figure 1. The Fe I spectroheliograms of Figure 1 are reproduced here in column "b" for comparison.
Fig. 3. A comparison between spectroheliograms in the 6107 Å continuum and differences between the magnetic field strength and the brightness of the photospheric network. Column “a” was obtained by developing the FeI photographs in column “b” of Figure 2 to an appropriate contrast and photographically subtracting them from the Zeeman photographs in column “a” of Figure 2. For the cancelled polarity, one can see that difference signals on the $B_{ll}$ - FeI spectroheliograms correspond to recognizable features in the 6107 Å continuum.
of Figure 2 and placing it in register with the Zeeman photographs in column "a", one obtains the spectroheliograms shown in column "a" of Figure 3. (The fact that this $\gamma_L$ was approximately unity is fortuitous. The matching values of $\gamma_L$ for other plates differed in general from unity, one being as low as 0.28.) Three features of this difference or $B_\parallel - \text{Fe I}$ spectroheliogram are clear. First, magnetic fields of one polarity are cancelled within a noise level that appears comparable to that in non-field regions. Second, magnetic fields of opposite polarity appear with increased contrast. Third, all the features of the first polarity that are not significantly cancelled appear to be sunspots. This is shown clearly by comparison with the 6107 Å continuum spectroheliograms in column "b" of Figure 3. There are structures on the $B_\parallel - \text{Fe I}$ spectroheliogram that one might regard as part of the noise level of the background rather than as sunspots. These signals come directly from the background noise level of the

![Spectroheliogram](image)

Fig. 4. Spectroheliograms obtained by developing the 6107 Å continuum spectroheliograms of Figure 3 to a suitable contrast and photographically adding them to the $B_\parallel - \text{Fe I}$ spectroheliograms. The low noise level of the background on this figure indicates that the brightness and the field strength of the photospheric network are quantitatively related.
Fe I spectroheliogram. A comparison with the 6107 Å continuum spectroheliogram shows that these features also occur in the continuum.

By developing a positive copy of the continuum spectroheliograms to a suitable contrast and placing it in register with the \( B_{\|} - \text{Fe I} \) spectroheliogram, the effects of the background noise are reduced and the sunspots themselves tend to be cancelled. The \( B_{\|} - \text{Fe I} + 6107 \) Å spectroheliograms obtained in this process are shown in Figure 4. Three features of Figure 4 are clear. First, most of the medium-scale noise contributed by the Fe I background has been cancelled by corresponding noise on the continuum background. Second, a fine-scale noise appears. This is presumably in part due to the different sizes of features on the Fe I and 6107 Å continuum spectroheliograms and in part due to the fact that small-scale features occur at the level where the continuum is formed that do not occur at the higher level of the atmosphere where Fe I \( \lambda 4071 \) is formed. Third, the small-scale noise level on the \( B_{\|} - \text{Fe I} + 6107 \) Å spectroheliogram seems to have a considerably smaller amplitude in the regions of the disk where there are magnetic fields than in the non-field regions of the disk. We interpret this noise reduction as the result of an inhibition of the 6107 Å continuum granulation by the magnetic field.

Finally, since the order in which the spectroheliograms are combined to form \( B_{\|} - \text{Fe I} + 6107 \) Å is not important, we might have first photographically subtracted 6107 Å from Fe I to form \( \text{Fe I} - 6107 \) Å and then subtracted this \( \text{Fe I} - 6107 \) Å picture from \( B_{\|} \) to obtain \( B_{\|} - \text{Fe I} + 6107 \) Å. For completeness the \( \text{Fe I} - 6107 \) Å spectroheliogram so obtained is shown in Figure 5. This figure illustrates in two dimensions the effect of normalizing the Fe I \( \lambda 4071 \) spectra directly to their respective continua. A noticeable feature of this spectroheliogram is the contribution of small-scale noise from the continuum.

We have seen that the magnetic field strength and the brightness of the photospheric network tend to cancel on the \( B_{\|} - \text{Fe I} \) spectroheliogram, and we have noticed that if the Fe I \( \lambda 4071 \) intensity is normalized to the 6107 Å continuum, then even sunspots and the non-field Fe I background tend to cancel. Next we consider measurements of how well these features do cancel, and thereby estimate how accurately the brightness and field strength of these magnetic regions are related.

Table II summarizes the microphotometer measurements of photographic density variations on the Fe I, \( B_{\|} - \text{Fe I} \), and \( B_{\|} - \text{Fe I} + 6107 \) Å spectroheliograms. These density changes can be related to intensities and magnetic field strengths using the following relations:

\[
\Delta D_{\text{Fe I}} = \gamma_{L,\gamma_{\text{Fe}}} \Delta \log_{10} I \\
\Delta D_{B_{\|}-\text{Fe I}} = \kappa B_{\|} - \gamma_{L,\gamma_{\text{Fe}}} \Delta \log_{10} I \\
\Delta D_{B_{\|}-\text{Fe I} + 6107} = \kappa B_{\|} - \gamma_{L,\gamma_{\text{Fe}}} \Delta \log_{10} (I_{\text{Fe}}/I_{6107})
\]

where the \( \Delta D \)'s are the density changes, \( \kappa \) is a calibration factor obtained from the profile and Zeeman sensitivity of Ca I \( \lambda 6103 \), and \( \Delta \log_{10} I \) and \( \Delta \log_{10} (I_{\text{Fe}}/I_{6107}) \) represent the logarithmic changes of Fe I intensity and of Fe I intensity normalized to
Fig. 5. Spectroheliograms obtained by suitably subtracting the 6107 Å continuum spectroheliograms from the Fe I λ4071 spectroheliograms. This Fe I − 6107 Å spectroheliogram represents a normalization of the λ4071 spectrum to the 6107 Å continuum.

### TABLE II

Summary of photographic density variations

<table>
<thead>
<tr>
<th>Spectroheliogram</th>
<th>Non-field region</th>
<th>Field region</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum noise</td>
<td>Average noise</td>
</tr>
<tr>
<td>Fe I</td>
<td>± 0.12</td>
<td>± 0.05</td>
</tr>
<tr>
<td>$B_\parallel$ − Fe I</td>
<td>± 0.12</td>
<td>± 0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B_\parallel$ − Fe I + 6107 Å</td>
<td>± 0.13</td>
<td>± 0.04</td>
</tr>
</tbody>
</table>

* Density changes produced by sunspots and by magnetic fields of the “non-cancelling” polarity were excluded from these data.
the 6107 Å continuum, respectively. From equations (2) and (3) we may write:

\[
\begin{align*}
\left| \ln (1 + \Delta I/I) - \alpha |B_\parallel| \right| & < \varepsilon_N, \\
\left| \ln (1 + \Delta J/J) - \alpha |B_\parallel| \right| & < \varepsilon'_N,
\end{align*}
\]

where:

- \( |B_\parallel| \) refers to the absolute value of the line-of-sight component of magnetic field of the "cancelling polarity".
- \( \Delta I/I \) refers to the fractional change of FeI λ4071 intensity between a region with and a region without a detectable magnetic field.
- \( \Delta J/J \) is the same as \( \Delta I/I \) except the intensities are normalized to the 6107 Å continuum.
- \( \varepsilon_N \) and \( \varepsilon'_N \) refer to noise fluctuations on the \( B_\parallel - \text{FeI} \) and \( B_\parallel - \text{FeI} + 6107 \text{ Å} \) spectroheliograms, respectively, and can be obtained from photographic density changes by dividing by the factor \((\gamma_L^\gamma_L Fe/2.30)\).
- \( \alpha \) equals \((2.30\kappa/\gamma_L^\gamma_L Fe)\).

For the measured values of \( \gamma_L = 0.98 \) and \( \gamma_{Fe} = 2.90 \), Table II indicates that in non-field regions of the disk the noise fluctuates by less than \( \pm 0.10 \) at most and less than \( \pm 0.04 \) on the average on both the \( B_\parallel - \text{FeI} \) and the \( B_\parallel - \text{FeI} + 6107 \text{ Å} \) spectroheliograms. In magnetic field regions the average noise fluctuations are less than \( \pm 0.03 \) on the \( B_\parallel - \text{FeI} \) spectroheliogram and less than \( \pm 0.015 \) on the \( B_\parallel - \text{FeI} + 6107 \text{ Å} \) spectroheliogram. Therefore, we estimate that the brightness and magnetic field strength satisfy the relation \( \ln (1 + \Delta I/I) = \alpha |B_\parallel| \) within approximately \( \pm 0.03 \) and perhaps even more accurately if intensities are normalized to the continuum. Having described the extent to which a relation may exist, we next present measurements of the proportionality constant \( \alpha \).

As we have mentioned above, \( \alpha = 2.30 \kappa/\gamma_L^\gamma_L Fe \), where \( \kappa \) is a calibration factor of the Zeeman spectroheliograms. Measurements of \( \kappa, \gamma_L, \) and \( \gamma_{Fe} \) for plates obtained on three days in August and two days in September 1969 give values of \( \alpha \) ranging from 3.6 to 8.9\%/100 gauss, each with its own accuracy of roughly \( \pm 30\% \). These are summarized in Table III. From the measurements of this table we have adopted \((6 \pm 2)\%/100 \text{ gauss} \) as an estimate of the value of \( \alpha \). Finally, we should add that isodensitometer tracings were made of the \( B_\parallel \) and FeI spectroheliograms taken on these five days and independent measurements of \( B_\parallel \) and \( \Delta I/I \) were obtained. These measurements resulted in values of \( \alpha \) that were consistent with those in Table III. In addition, the isodensitometer tracings gave somewhat more scatter from the relation \( \ln (1 + \Delta I/I) = \alpha |B_\parallel| \) than the cancellation technique gave. This is due partly to the fact that the cancellation method is a much more sensitive technique than the independent measurement of \( B_\parallel \) and \( \Delta I/I \) from isodensitometer tracings and partly to the fact that a unique background intensity could not be precisely defined from the isodensitometer tracings. The cancellation procedure does not require an advance definition of background but simply measures the background variation remaining after the "best" \( B_\parallel \) vs. \( \Delta I/I \) relation has been "subtracted out".
TABLE III
Measurements of \( \alpha \)

| Date   | \( \gamma_L \)   | \( \gamma_Fe \) | \( \kappa(\% /100 \text{ gauss}) \) | \( \frac{2.30 \kappa}{\gamma_L \gamma_Fe} \) (\% /100 gauss) | Reasonably well-balanced
<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>8/4/69</td>
<td>0.28 ± 0.05</td>
<td>3.5 ± 0.3</td>
<td>3.8 ± 0.4</td>
<td>8.9 ± 3.2</td>
<td>yes</td>
</tr>
<tr>
<td>8/5/69</td>
<td>0.52 ± 0.10</td>
<td>3.8 ± 0.3</td>
<td>5.2 ± 0.4</td>
<td>6.1 ± 2.1</td>
<td>yes</td>
</tr>
<tr>
<td>8/28/69</td>
<td>0.62 ± 0.09</td>
<td>2.6 ± 0.1</td>
<td>4.2 ± 0.4</td>
<td>6.0 ± 1.6</td>
<td>no (opposite polarity would give a larger ( \alpha ))</td>
</tr>
<tr>
<td>9/1/69</td>
<td>0.98 ± 0.04</td>
<td>2.9 ± 0.3</td>
<td>4.5 ± 0.4</td>
<td>3.6 ± 0.8</td>
<td>no (opposite polarity would give a larger ( \alpha ))</td>
</tr>
<tr>
<td>9/2/69</td>
<td>0.50 ± 0.08</td>
<td>3.4 ± 0.4</td>
<td>4.2 ± 0.4</td>
<td>5.7 ± 2.0</td>
<td>yes</td>
</tr>
</tbody>
</table>

\( a \) In some cases a zero-point problem occurred which tended to favor one field polarity over another. When this happened, different values of \( \gamma_L \) were required to cancel fields of opposite polarity. We indicate in this column whether the polarities are approximately balanced by the same value of \( \gamma_L \) and if not, which direction \( \alpha \) would change if the other value of \( \gamma_L \) had been used. (In general if two different \( \gamma_L \)'s are so required, the "correct" \( \alpha \) would be obtained by using their average in the formula above.)

\( b \) On these days, the spectroheliograph was not oriented to allow for differential refraction of the earth's atmosphere.

4. Discussion

In the previous section we have presented measurements that show: (1) to what extent a quantitative relation exists between the magnetic field strength and the brightness of the photospheric network; (2) approximately what this relation is when the brightness of the photospheric network is measured at +0.12 Å from the core of Fe I \( \lambda4071 \). Now we shall consider these observations in more detail.

Since the variations in photographic density on the \( B_{||} - \text{Fe I spectroheliogram} \) are essentially the same in both magnetic and non-magnetic regions, it is tempting to suppose that they have a single, non-magnetic origin – namely, the small-amplitude brightness variations on the Fe I spectroheliogram. These spatial changes of Fe I brightness are partly due to changes in continuum intensity and, as we have seen on the \( B_{||} - \text{Fe I +6107 Å spectroheliogram} \), they can be removed to some extent by normalizing to the continuum. Since the Fe I spectroheliogram was taken at +0.12 Å from the core of \( \lambda4071 \), small-amplitude brightness fluctuations may also be due to doppler shifts. For the \( \lambda4071 \) profile given in the Utrecht Atlas (Minnaert et al., 1940), a 5% change in relative intensity at \( \Delta \lambda = +0.12 \) Å corresponds to a line-of-sight velocity change of 1 km/sec. Although such velocity changes are not uncommon in the solar photosphere (for example, see Kirk and Livingston 1968), one might expect their effect to be reduced somewhat by normal atmospheric seeing conditions. Just as we removed the effect of continuum brightness fluctuations by means of a photographic cancellation, we might hope to remove any such velocity-produced brightness variations by adding spectroheliograms taken simultaneously at +0.12 Å and -0.12 Å form the core of \( \lambda4071 \). Regardless of the cause of these small-amplitude spatial
variations of Fe I brightness, we know that they change with time much faster than does the magnetic field pattern. The spatial details of the background on the two Fe I spectroheliograms taken five minutes apart are completely different, whereas the detailed magnetic field pattern is essentially unchanged. Thus, in principle, one might hope to eliminate these spatial variations of the background by means of a time average, and in this way place even finer limits on the extent to which a quantitative relation exists between the brightness and magnetic field strength of the photospheric network.

Finally, having concluded that, within a certain well-defined noise limit, a quantitative relation does exist between the measured brightness and field strength of the network, we next consider why such a relation should exist at all. Numerous authors have suggested plausible mechanisms for the heating of magnetic regions of the solar atmosphere and it is not difficult to imagine that at least one of these mechanisms would predict a quantitative relation between field strength and temperature. On the other hand, it might seem more than a coincidence that such a relation would take just that form for which density changes on Zeeman photographs are proportional to density changes on simultaneous spectroheliograms in temperature-sensitive lines. Perhaps an equally plausible interpretation can be made on the basis of the suggestion of Livingston and Harvey (1969) that all non-sunspot magnetic regions of the photosphere may have the same field strength and temperature, and that variations in the measured values result from an inability to resolve the individual elemental field regions. If this were the case, and if variations in atmospheric seeing conditions affect the measurement of field strength and intensity of these magnetic regions in precisely the same way, then we would expect to find a quantitative relation between the measured values of field strength and brightness with just that form we observe. While this explanation may well be correct, the best Zeeman spectroheliograms that we have yet obtained do show a range of non-sunspot field strengths from our noise limit near 100 gauss to a maximum of roughly 700 gauss. Zeeman and brightness spectroheliograms with spatial resolution comparable to the best granulation photographs are clearly desirable to resolve this question.

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