ON THE FILAMENTARY NATURE OF SOLAR MAGNETIC FIELDS

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Abstract. A method is presented for obtaining information about the unresolved filamentary structure of solar magnetic fields. A comparison is made of pairs of Mount Wilson magnetograph recordings made in the two spectral lines Fe I 5250 Å and Fe I 5233 Å obtained on 26 different days. Due to line weakenings and saturation in the magnetic filaments, the apparent field strengths measured in the 5250 Å line are too low, while the 5233 Å line is expected to give essentially correct results. From a comparison between the apparent field strengths and fluxes and their center to limb variations, we draw the following tentative conclusions: (a) More than 90 % of the total flux seen with a 17 by 17 arc sec magnetograph aperture is channeled through narrow filaments with very high field strengths in plages and at the boundaries of supergranular cells. (b) An upper limit for the interfilamentary field strength integrated over the same aperture seems to be about 3 G. (c) The field lines in a filament are confined in a very small region in the photosphere but spread out very rapidly higher up in the atmosphere. (d) All earlier Mount Wilson magnetograph data should be multiplied by a factor that is about 1.8 at the center of the disk and decreased toward the limb in order to give the correct value of the longitudinal magnetic field averaged over the scanning aperture.

1. Introduction

Solar magnetic fields are in general not smoothly distributed over the solar surface, but appear on the small scale to protrude through the photosphere in concentrated bundles of lines of force each having a cross-section probably less than one arc sec. It is likely that these fundamental elements of the magnetic field will not be fully resolved until one can make high-resulution observations with large space telescopes. In this investigation, however, we shall analyze the properties of these sub-telescopic structures using a 17 by 17 arc sec aperture. It may appear paradoxical that such a thing can be done. The reason it is possible at all to get information about these magnetic elements with such a large aperture becomes clear when we examine how the polarization in spectral lines arises inside and outside the strong field regions.

The inadequacy of homogeneous models and the importance of accounting for the filamentary nature of solar magnetic fields has been pointed out several times by

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Alfvén (1961, 1963, 1967). Howard (1959) suggested that the magnetic field of the Sun could be concentrated in bundles of field lines that correspond to the bright 'chromospheric granules' seen in the Ca II line and which may be related to spicules. Stenflo (1966) discussed the influence of a filamentary structure on the magnetograph observations and suggested (Stenflo, 1968b) that the field may be concentrated at the boundaries of supergranular cells in regions where the line profile is different due to the higher temperature, where the contribution to the magnetograph signal is saturated due to the strong Zeeman splitting, and where the spectral line is red-shifted due to downward motions.

The first direct observations of what may be called magnetic filaments were made by Sheeley (1967), who found that the high-field regions coincided with gaps in some of the spectral lines used. There was a one-to-one correlation between the strong fields and the photospheric network. Similarly, Beckers and Schröter (1968) found that an active region which they studied with high angular resolution appeared to have a very pronounced filamentary structure. Tanenbaum *et al.* (1969) and Frazier (1970) have clearly demonstrated a coincidence between the strong localized fields and the downdrafts at the supergranular cell boundaries. Comparing magnetograph recordings made simultaneously in different spectral lines, Harvey and Livingston (1969) explained the discrepancies between the results obtained in the various lines in terms of line weakenings in strong-field regions or filaments. There was a linear relation between the apparent field strengths measured in two different lines, with a very small scatter of the points around the straight line. This suggested that most of the magnetic field is concentrated in filaments with more or less the same field strength. The reason that a magnetograph normally records a continuous range of field strengths is then that a smaller or larger number of filaments happen to be inside the scanning aperture, and not because of continuous variation of the 'true' field strength.

Livingston and Harvey (1969) found observational support for this idea and estimated the magnetic flux through a single filament to be 2.8×10^{18} Mx, which would correspond to a field strength of 525 G over a one $(\text{arc sec})^2$ area. The true size of such an element is, however, not known. Note that our analysis in this paper assumes that all filaments have the same field strength, although no value is assumed.

The increase in size of the bright spots in the photospheric and chromospheric network as we look higher up in the solar atmosphere (Hale and Ellerman, 1903; Simon and Noyes, 1971) seems to indicate that the cross-section of a filament increases rapidly with height, i.e. the field strength decreases. Let us call this rapid spreading out of the field lines the 'mushroom effect'. Due to the much lower gas pressure in the chromosphere, the field lines can no longer be confined. Many of them fan out almost horizontally and are probably responsible for the force-free fibril pattern in Hα filtergrams.

Although a major part of the total flux on the Sun may be confined to narrow filaments, it is clear that some fraction of the flux must be present in the interfilamentary medium. We may expect the filaments to be formed out of the interfilamentary field and dissolve again into it. Since the interfilamentary magnetic fields are very weak, it is hard to observe them reliably. The only observations so far which show the interfilamentary field without contributions from filaments within the scanning aperture are those of Livingston and Harvey (1971). The recordings were made with high resolution (2 by 2 arc sec) as well as with long integration times in order to reduce the noise to a minimum. The interfilamentary fields they recorded showed field strengths of the order of 1–2 G with a more or less random distribution of polarities. No further study of the role played by the interfilamentary fields has been made, however.

From this introduction it should be clear what we mean when we refer to magnetic filaments and interfilamentary fields. The filaments are the localized regions in the photosphere corresponding to the gaps in most spectral lines of neutral metal atoms. The interfilamentary fields represent everything we find between the filaments.

Further implications of a filamentary structure have been discussed in a recent review of the subject (Stenflo, 1971).

2. Methods of Analysis

The contribution $\mathbf{i}_{\|}$ from a surface element to the signal of a longitudinal magnetograph can be written

$$\mathbf{i}_{\|} \sim I_c \frac{\partial r_\lambda}{\partial \lambda} f_\lambda(H) \cos\gamma, \tag{1}$$

which is valid for the case of infinitely narrow exit slits positioned in the line wing at wavelength λ. I_c is the intensity of the adjacent continuous spectrum, r_λ is the line depth, and γ is the angle between the magnetic field and the line of sight. The function $f_\lambda(H)$ is proportional to the field strength H for weak fields, but it saturates for strong fields when the Zeeman splitting becomes comparable to the line width and the separation between the exit slits. The finite width of the exit slits can be taken into account by integrating the above expression over the width of the slits.

For weak fields the signal is proportional to the longitudinal component of the field. As most of the magnetic flux that exists on the Sun seems to occur in filaments where the field strength is quite high, the function $f_\lambda(H)$ will generally be saturated in these elements. In their analysis Livingston and Harvey (1969) interpreted the lowering of the magnetograph signal in the filaments entirely in terms of line weakenings, i.e. lowering of $|\partial r_\lambda/\partial_\lambda|$. We feel, however, that the saturation of $f_\lambda(H)$ may play a significant role as well. Both $|\partial r_\lambda/\partial\lambda|$ and $f_\lambda(H)/H$ should, however, decrease with increasing H. The result of Harvey and Livingston (1969) and of Frazier (1970) that the magnetograph signal is reduced by a given factor which seems to be the same for all points in the recorded area thus strongly suggests that we have practically the same field strength in all the filaments in the regions studied.

The most commonly used spectral line for magnetograph observations, Fe I 5250 Å, is very temperature sensitive, i.e. it seems to weaken considerably in the filaments, and saturates quickly because it is narrow and has a large Landé factor ($g=3$). The line Fe I 5233 Å on the other hand has been shown to be quite insensitive to temperature fluctuations, at least in the line wings where the magnetic field is measured. The

5233 Å line is about three times broader than the 5250 Å line, and its Landé factor is somewhat smaller ($g_{\text{eff}} = 1.3$). Accordingly, saturation of the function $f_\lambda(H)$ for the 5233 Å line will probably not be important for the field strengths we are considering. For these reasons it seems likely that the 5233 Å line should give the true field strength (averaged over the scanning aperture). By comparing simultaneous magnetograph recordings in the 5250 Å and 5233 Å lines it is possible to get information about the magnetic filaments, since they are responsible for the deficiency in the 5250 Å line.

To facilitate a quantitative treatment of the problem, we must introduce a model. Following the earlier notation by Stenflo (1968b; 1971) we assume that the fraction A_f of the solar surface inside a given magnetograph aperture is occupied by filaments which have the field strength H_f, while the remaining part of the surface, $A_f = 1 - A_f$, contains the interfilamentary fields of average strength H_f. Assuming that we record the true net field in the 5233 Å line, we have

$$H_{5233} = A_f H_f + A_i H_i . \tag{2}$$

The contribution to the magnetic signal in the 5250 Å line is lowered in the filaments by a factor δ because of the decrease in the factor $|\partial r_\lambda / \partial \lambda| f_\lambda(H)/H$. Accordingly,

$$H_{5250} = \delta A_f H_f + A_i H_i . \tag{3}$$

The relative contribution of the filamentary and interfilamentary magnetic fluxes inside the scanning aperture may vary considerably over the solar surface. As we mentioned above, there are reasons to believe that H_i is not much larger than 2 or 3 G. When a field stronger than, say, 10 G is recorded, it is likely that the main contribution to the observed field comes from the filaments. If we therefore plot the observed H_{5250} as a function of H_{5233}, the slope of the curve should equal δ, except for the weakest field strengths where we may have an appreciable contribution from the interfilamentary fields H_i.

Although the interfilamentary fields probably give an insignificant contribution when apparent fields stronger than 10 G are recorded, it is still quite possible that they may give an important contribution to the total magnetic flux at the solar surface, because most of the solar surface is covered by apparently weak fields outside active regions. Before we continue, let us clarify what we mean by interfilamentary flux. On a small scale the field may be in a kind of turbulent state with polarity changes over very small distances. If the fluxes of each polarity are added up separately, they may be quite large, whereas the net flux averaged over some area may be much smaller. To contribute to the signal of a magnetograph using a 17 by 17 arc sec aperture, the fluctuating interfilamentary field should not average to zero over that area. When discussing the interfilamentary flux $A_i H_i$ in this paper, we mean the average over the 17 by 17 arc sec aperture, and in order to contribute the field must have some statistical coherence properties over that aperture. From the work of Livingston and Harvey (1971) it appears that there are variations in the interfilamentary field on a distance scale that is not small compared to 17 arc sec.

The overall role played by the interfilamentary magnetic fields can be studied by measuring the large-scale magnetic flux in the two lines 5250 Å and 5233 Å. The ratio ϱ between the fluxes observed in these two lines is given by

$$\varrho = \frac{\overline{H}_{5250}}{\overline{H}_{5233}} = \frac{\delta\overline{A_f H_f} + \overline{A_i H_i}}{\overline{A_f H_f} + \overline{A_i H_i}}, \tag{4}$$

where a bar above a symbol indicates an ensemble average. The fraction R_i of the total flux that is carried by the interfilamentary fields is

$$R_i = \frac{A_i H_i}{A_f H_f + A_i H_i}, \tag{5}$$

or, using (4),

$$R_i = \frac{\varrho - \delta}{1 - \delta}. \tag{6}$$

Both ϱ and δ can be determined from the observations with a large aperture, which gives R_i according to (6).

In the determination of ϱ it is much better to measure the fluxes F_+ and F_- of each polarity separately and not just the net flux F, which is often much smaller than F_+ and F_-, and is seriously affected if instrumental zero line displacements are present (which was the case in these observations, as we shall show). The total flux.

$$\mathbf{B}^{\text{tot}} = |F_+| + |F_-| \tag{7}$$

is, however, unaffected by errors in the zero line, since, for instance a positive shift in the zero line will decrease $|F_+|$ by the same amount as $|F_-|$ is increased. In our determination of ϱ we have therefore used

$$\varrho = \frac{F_{5250}^{\text{tot}}}{F_{5233}^{\text{tot}}}. \tag{8}$$

3. The Observations

For many years the 150-ft tower telescope at Mount Wilson has been used to obtain daily full-disk scans of the solar surface in order to plot magnetograms. During this period the spectrum line λ5250 (Fe I) has been used. For a period of about five weeks (June 5 through July 6) in the summer of 1970 we attempted to obtain two magnetograms each day, one in Fe I 5250 Å and the other in Fe I 5233 Å. In the end such pairs of magnetograms for 26 days were found to be usable.

Each observation required close to two hours to obtain, including setup, calibration, etc. Sometimes one or two hours elapsed between the end of the first observation and the start of the second. About half the time the 5250 Å observation was the first of the two for the day, and about half the time it was the second. The usual 17 arc sec square aperture was employed for both lines with an image slicer, and for both lines the integration time was 0.4 s – which is the usual magnetogram value.

The exit slit widths for the 5250 Å line were each 0.075 Å, and the occulted space between them was 0.018 Å. For 5233 Å these values were 0.16 Å and 0.12 Å, respectively. In each case the calibration was obtained in the usual way. A circular polarizer was inserted into the light path ahead of the KDP analyzer, and a known shift of the line was introduced. The difference of the Zeeman signal between the two line positions is the basic information for the calibration.

The data for the magnetograms were digitized, as usual, and recorded on magnetic tape. The north-south dimension of the aperture (17 arc sec) corresponded to the scan line increment step, so that the entire disk of the sun was covered by the observations. Each observation resulted in approximately 11000 data points. The instrument and data acquisition techniques have been discussed in more detail (Howard *et al.*, 1968).

The magnetic field value at each point is obtained in practice by dividing the magnetic signal by the intensity signal and multiplying by a calibration constant. Both the magnetic and intensity signals are obtained from the analog voltage signal of the magnetograph amplifier by feeding this signal to a voltage-to-frequency converter and counting the cycles during the integration period. The scanning motion is continuous, so that in the scan direction the distance covered during one integration interval is less than the dimension of the aperture. The field strength measured is a true integral over the area scanned because there is no RC-type integration in time involved.

Figure 1 shows a comparison between two magnetograms made on the same day in the two lines. The gauss levels are different for the two plots in order to show contour lines that give approximately the same appearance.

4. Results

4.1. THE DETERMINATION OF δ

4.1.1. *Point-by-point Comparison*

As indicated above by (2) and (3), δ can be determined by plotting pairs of observed field strengths in a H_{5233}–H_{5250} diagram and determining the slope of the line fitting the points for fields stronger than about 10 G. The interpretation of these observations is, however, complicated by the circumstance that the magnetograms recorded in the two spectral lines could not be obtained simultaneously but are generally separated in time by a few hours. During that time interval the Sun has rotated differentially. Also the magnetic field values are not read off at exactly the same point on the solar disk for the two separate raster scans. Therefore we developed a computer program to correct for differential rotation and relate points in one magnetogram to points in the other with the same heliographic coordinates. However sophisticated such a program may be, it can never give perfect matching between the points. Time variations of the fields will also degrade the correlation between them. If H_{5233} is plotted as a function of H_{5250}, the slope of the relation will therefore be smaller than the true slope due to mismatching and time changes.

Instead of plotting all the pairs of values as points in the diagram (20000 points per pair of magnetograms, and 26 pairs of magnetograms), we divided the material in

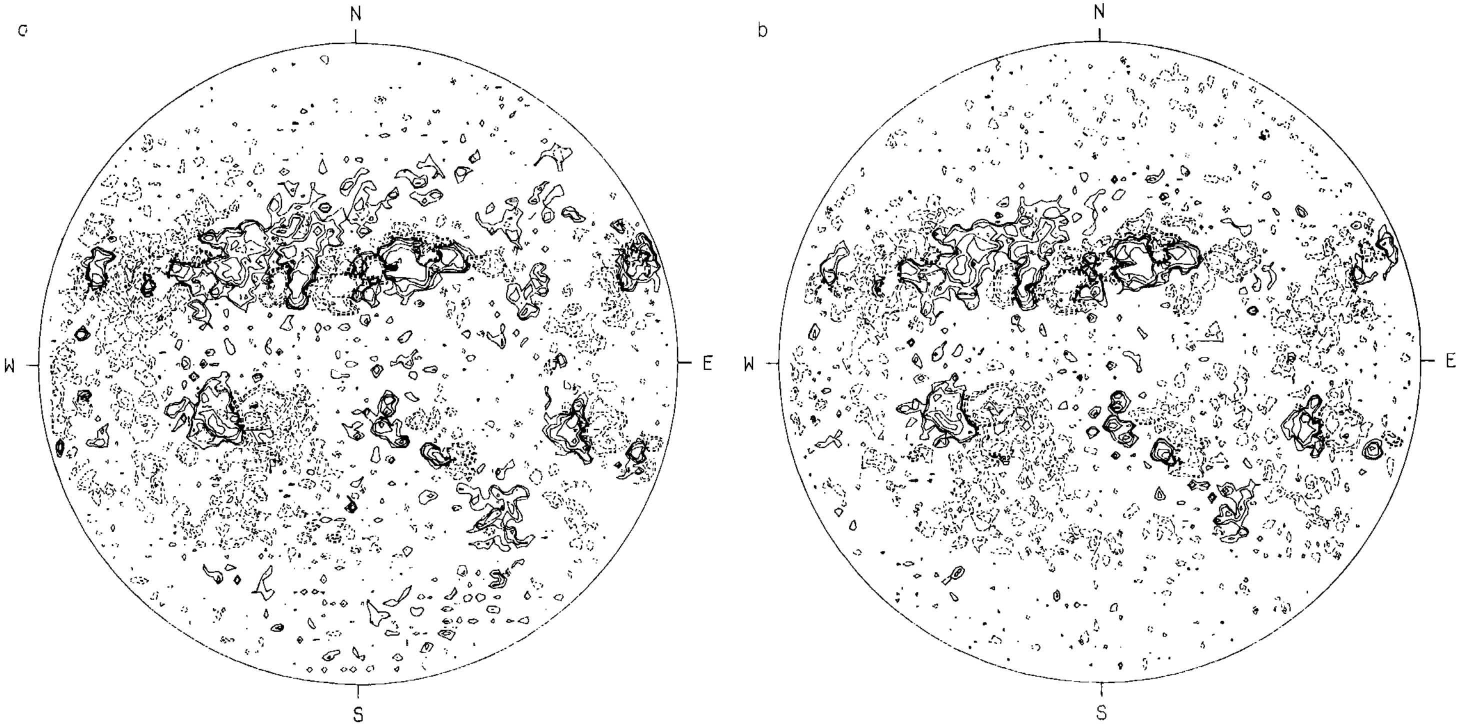

Fig. 1. Two isogauss maps of the Sun from two observations made on June 16, 1970. The aperture, scanning speed, and time constant were the same for both observations. (a) was made using the Fe I 5250 Å line. The observation started at 17.34 UT and ended at 18.74 UT. The gauss levels on the plot are ±5, 10, 20, 40, 80. (b) was made with the Fe I 5233 Å line. The observation started at 21.78 UT and ended at 23.18 UT. The gauss levels are ±9, 18, 36, 72, 144 G. For both plots solid contour lines represent positive fields, and dashed lines represent negative fields.

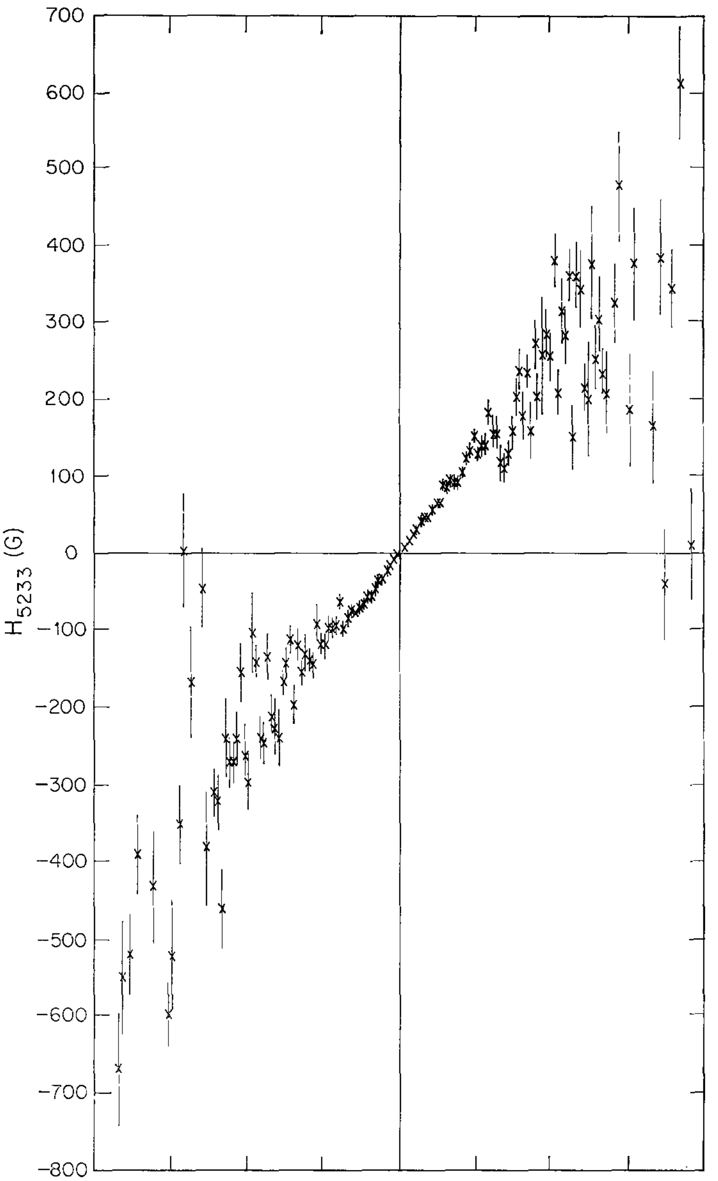

Fig. 2. Average field strengths in the 5233 Å line for the same portions of the solar disk for which the 5250 Å line records values from 0–5, 5–10 G, etc. The error bars are proportional to standard deviations and are included to illustrate that many more points are involved in the lower field values. This plot contains data for the full solar disk from all the 26 pairs of observations.

intervals of 5 G in H_{5250}, and determined the mean value of H_{5233} and its standard deviation for the matching points in each interval. Figure 2 shows the results for the full solar disk with the data from all 26 days taken together. The slope is about 1.45, but this does not represent the true value of $1/\delta$ because of the effects mentioned above.

If there were a significant interfilamentary field, H_f, present, the line would not go through the origin, but would be displaced (Stenflo, 1971). Figure 3 gives a schematic illustration of this effect. The dashed line is obtained if H_f has a constant value and is of the same sign as H_f. The solid line is obtained if H_i and H_f are of opposite sign. From the separation of the lines fitting the points of positive and negative polarity, Δ, one can estimate the value of H_f. This method is independent of instrumental zero-line shifts, since we do not use the actual position of the origin in the diagram. We can find no significant separation between the lines fitting the positive and negative sides of Figure 2 using a least squares solution for each line. From the probable errors of the solution we estimate the upper limit for H_f as seen by the 17 by 17 arc sec aperture to be about 3 G. Certainly if this value were close to 5 G, it would show up clearly outside active regions on isogauss plots, which normally have a lowest level of 5 G.

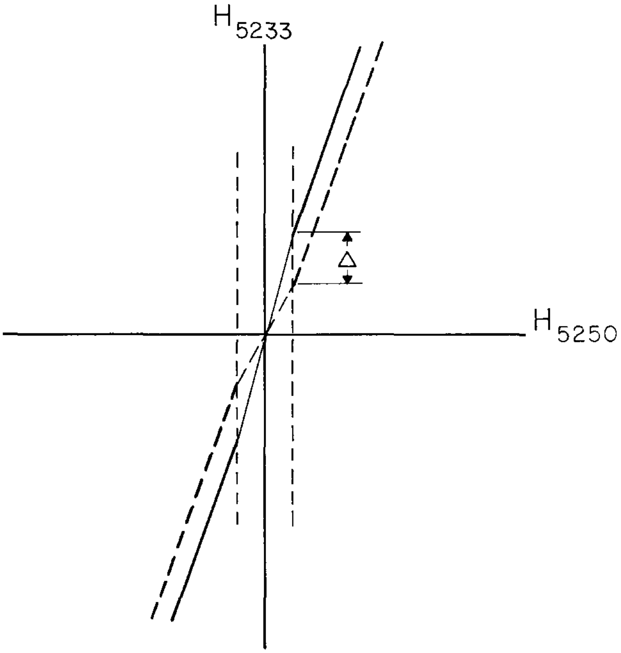

Fig. 3. A schematic version of Figure 2 to illustrate the effects of interfilamentary fields on such a plot.

4.1.2. *Lifetime of the Filaments*

The slope derived from the points in Figure 2 as a function of field strength in H_{5250} is shown in Figure 4. For fields apparently stronger than 10 G the slope is constant, in agreement with the results of Harvey and Livingston (1969) and Frazier (1970). The slope decreases suddenly, however, by a large amount for the fields below 10 G. Part of the reason for this decrease could be the presence of an interfilamentary field H_f, which contributes more when the recorded field is weak. If the interfilamentary field dominated the contribution to the recorded field in the 0–5 G interval, the true slope there would be 1.0. Since we earlier estimated the upper limit for H_i to be 3 G, the filamentary fields should give a significant contribution even in the 0–5 G interval, and the true slope should thus be larger than 1.0. The slope in the 0–5 G interval is however 0.5 according to Figure 4. What could be the explanation for this effect?

A mismatching of the two magnetograms may have a larger effect in the case of the weak fields since only a few filaments may be inside the scanning aperture. We feel, however, that the observed decrease of the slope by more than a factor 2 cannot be explained in this way.

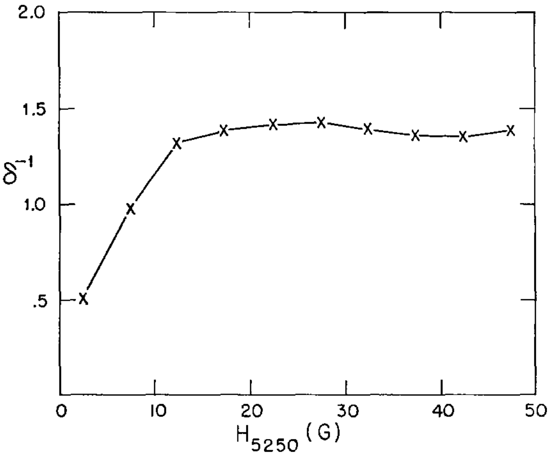

Fig. 4. A plot of the slopes determined at various field strengths in Figure 2. Both positive and negative field strengths are included.

The decrease of the slope can easily be explained, however, if the lifetimes of individual filaments are less than the time separation of a few hours between the two successive magnetograms. For an area including a large number of filaments it is likely that we have some kind of equilibrium with filaments being formed at roughly the same rate as others are being dissolved. This large-scale pattern will therefore have a much longer life-time. For instance, Janssens (1970) determined the lifetime of the chromospheric network to be about 21 hr. When only a few filaments are inside the aperture, it will make a great change to the magnetograph signal if one filament dissolves or is formed. This indication of a lifetime of the filaments not more than a few hours is consistent with the determination by Bray and Loughhead (1961) of the lifetime of bright chromospheric mottles which they found to be 2 hr.

4.1.3. *Comparison of Isogauss Maps*

As mentioned above, we shall not determine the absolute value of the slope from Figure 2 due to the problems of getting perfect matching between the pairs of magnetograms. The full value of δ or $1/\delta$ and its center-to-limb variation can, however, be determined by direct comparison of isogauss maps obtained in the two lines, such as those presented in Figure 1. For this purpose we picked out three pairs of magnetograms obtained on July 11, 14, and 16, 1970. The isogauss contour levels for the 5250 plots were, 5, 10, 20, 40, 80, and 160 G. For the 5233 recordings we produced plots with various settings of the first isogauss level: 5, 6, 7, ..., 14 G. Each higher isogauss level was always a factor two larger than the previous level. By a careful comparison of which λ5233 maps agreed best with the corresponding λ5250 map for various heliocentric distances, δ would be determined as a function of center-to-limb distance. These results will be illustrated below in Figure 6 together with the results for ϱ. We shall however mention one important point here: According to the weakened line profile for the magnetic filaments given in Figure 3 in the paper of Harvey and Livingston (1969), $1/\delta$ would be about 3.2 at the disk center for the exit slits used in the Mount Wilson magnetograph. Our determination of $1/\delta$ has, however, given the value 1.8 for the center of the disk. We feel that this large discrepancy is due to the fact that Harvey and Livingston interpreted their results entirely in terms of line weakenings, but did not account for the saturation occurring from the function $f_\lambda(H)$ in (1), which should also play an important role.

4.2. THE DETERMINATION OF ϱ

The magnetic flux was determined in each magnetogram for each polarity separately for different field strength intervals and in concentric rings corresponding to intervals in $\sin\theta$ of 0.0–0.1, 0.1–0.2, 0.2–0.3, ..., 0.9–1.0, where θ is the heliocentric angle. We found that less than 10% of the total flux is in the field strength interval -5 to $+5$ G. Since we estimated the upper limit for $|H_f|$ to be about 3 G, the interfilamentary fields would only give an appreciable contribution to the total flux for apparent field strengths smaller than about 5 G. Also, part of the flux that we find in the -5 to $+5$ G interval must be caused by noise. Accordingly this indicates that more than 90% of the total flux is channeled through the filaments. This result is relatively independent of the zero-line errors that occur (see below).

The mean field strength as a function of $\cos\theta$, i.e., the net flux in each ring divided by its area for all 26 days of observation taken together, is shown in Figure 5. The rapid fluctuation with $\cos\theta$ of the mean field is caused by active regions, which have most of their contribution to the mean field between $\sin\theta = 0.1$–0.6. Both spectral lines show the same fluctuations, but there is a systematic separation between the curves of about 2.4 G. This can hardly be explained in terms of physical properties of solar magnetic fields but must be caused by an instrumental zero-line displacement, which is different for the two spectral lines. Such errors in the zero-line occur frequently for all kinds of magnetographs (Stenflo, 1968a, 1970), but their cause is poorly

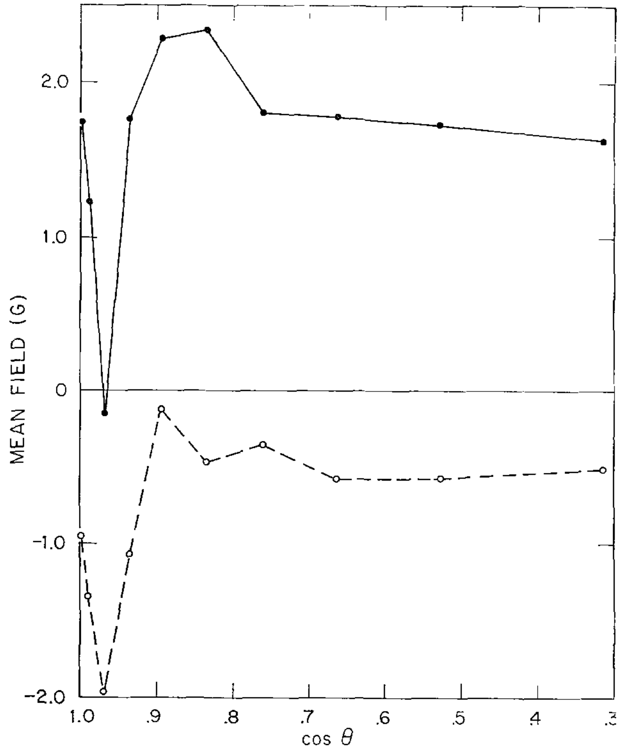

Fig. 5. Mean field strength as a function of cos θ for all the 26 days of data. The filled circles and solid line refer to the 5233 Å line, and the open circles and dashed line refer to the 5250 Å line.

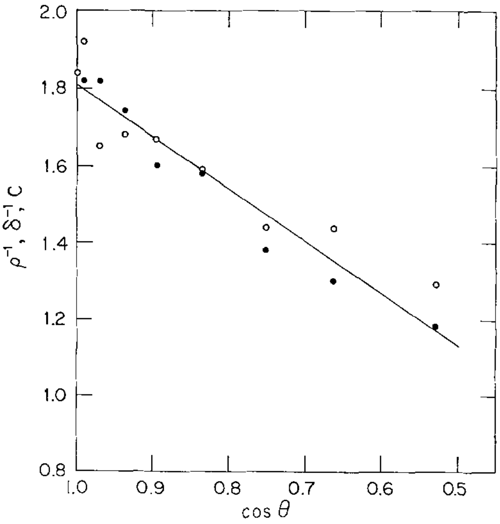

Fig. 6. δ^{-1} (filled circles), ϱ^{-1} (open circles), and C (straight line) as a function of cos θ.

understood. As the line-of-sight component is generally small compared to the total magnitude of the field close to the limb, it is likely that the mean field averaged over the 26 days of observation should be close to zero, although it need not, of course, be precisely zero. Figure 5 then indicates that the error in the zero-line was considerably larger for the recordings in the 5233 Å line than for the recordings in the 5250 Å line.

Instead of using the net flux, which is very sensitive to the accurate position of the zero-line, we use the total flux $|F_+|+|F_-|$, which is unaffected by an error in the zero-line, and determine ϱ according to (8). Our results are shown in Figure 6, which gives δ^{-1} and ϱ^{-1} as a function of $\cos\theta$.

We should point out that the magnetic flux from sunspots may have an effect on the value of ϱ that we determine. The contribution to the total flux (not the net flux) from spots may be estimated to be about 10% from the flux distribution. If the value of δ in sunspots were greater than unity, then we should increase ϱ^{-1} by some factor to correct for this effect. However saturation of the signal due to the shape of the line profile should be more important for 5250 than for 5233, and as a consequence δ may be less than unity. This produces some uncertainty in the determination of ϱ – but this uncertainty should be less than 10%. If the sunspot correction were appreciable it would show up in the value of ϱ determined at the disk center in Figure 6. Spots will have very little influence within $\frac{1}{10}\,R_\odot$ of the disk center. The absence of any effect on this point is evidence that spot fluxes do not influence ϱ to a significant degree.

4.3. THE CENTER-TO-LIMB VARIATION OF δ AND ϱ

When calibrating the magnetograph, the average quiet-region line profile near the center of the solar disk is used. This average profile is, of course, mainly formed in the interfilamentary medium, since the filaments occupy only a small fraction of the surface. The line weakening that enters into δ in (3) represents the weakening of the line profile in the filaments relative to the *local* average line profile at the same heliocentric distance. A weakening of the average line profile will therefore also contribute to a reduction of the magnetograph signal. If the center-to-limb variation is different for the 5250 and 5233 Å lines, this will influence the values of δ and ϱ.

The center-to-limb variation of the line depth for the two lines used was estimated with the Mount Wilson magnetograph in the following way. With the exit slits centered in the line wings as they are in a normal magnetograph observation, the solar image was scanned across the aperture, and intensity readings were made. The exit slits were then moved to the adjacent continuous spectrum, where a new intensity scan was made. The difference between the continuum intensity, I_c, and the line intensity, divided by I_c is a measure of the line depth. This is normalized to unity at the center of the disk to give the relative variation of the line depth. The results show no systematic variation within about 5% out to $\sin\theta \approx 0.9$. Accordingly, δ and ϱ need not be corrected for the center-to-limb variation of the average line profiles.

One important feature of Figure 6 is that δ is equal to ϱ within the limits of error of the two quantities. This would mean formally from (6) that the fraction R_i of the total flux that is carried by the interfilamentary fields is zero; because of the uncertainties mentioned above we may conclude that R_i is less than about 10%. This is consistent with our earlier estimates.

Further, the decrease of δ^{-1} towards the limb may have important implications. The immediate conclusion is that δ increases with height in the solar atmosphere. This can have several different causes:

(a) The line weakenings in the filaments become less pronounced higher up in the atmosphere. This would be the case if the higher layers are heated *less* than the lower layers, contrary to what is assumed in curreut plage models.

(b) The field strength decreases rapidly with height in the atmosphere which reduces the influence of the saturation effects on δ caused by the function $f_\lambda(H)$. This case would correspond to the 'mushroom effect' mentioned in the introduction.

4.4. CORRECTION FACTOR FOR EARLIER MOUNT WILSON MAGNETOGRAPH DATA

We feel that point (b) is the most likely explanation.

Since the effect of center-to-limb variation of the average line profile and the contribution of the interfilamentary field to the total flux both appear to be negligible, (3) can be written

$$H_{5250} = \delta A_f H_f , \tag{9}$$

where the line weakening in δ is now with respect to the average line profile at the center of the disk, which is used for calibration of the magnetograph. The true average field strength is

$$H = A_f H_f \tag{10}$$

Accordingly the true field can be derived from the apparent field strength measured in the 5250 Å line from the relation

$$H = C H_{5250} \tag{11}$$

where the correction factor $C = \delta^{-1}$ is a function of heliocentric distance. This function may be written

$$C = 0.48 + 1.33\,\mu \tag{12}$$

where $\mu = \cos\theta$. $C(\mu)$ is given by the solid curve in Figure 6 and has been determined from the points in the diagram by a least mean square fit with a linear dependence in μ. This relation is valid only for $\mu > 0.5$. Since the same exit slits as were used in this investigation have been used since June 1967 at Mount Wilson, and the recordings have been made in the 5250 Å line, the $C(\mu)$ function should be used to correct all earlier Mount Wilson magnetograph data over that period.

5. Conclusions and Discussion

From our analysis of a large amount of magnetograph data obtained in the 5250 and 5233 Å lines, we draw the following tentative conclusions:

(a) No more than 10% of the magnetic flux of the Sun can exist in the form of weak interfilamentary fields that may be observed with a 17 by 17 arc sec aperture.

(b) The magnitude of this observed interfilamentary field is less than 3 G on the average.

(c) The magnetic-field lines in a filament are confined to a small area in the photosphere, but spread out with height in the atmosphere.

(d) The correction factor for recent Mount Wilson magnetograph measurements varies from about 1.8 near the center of the disk to a smaller value near the limb.

We may imagine a model in which weak interfilamentary fields form from the dissolution of filaments, and conceivably also by rising from below the surface. These fields are relatively quickly swept by supergranular motions to cell boundaries where they form filaments again. The lifetime of the filaments and the speed with which the field lines are swept up are such that in the equilibrium situation that results only a very small fraction of the flux is in the form of interfilamentary fields at any one time. We cannot conclude from this study whether or not any new flux rises to the surface in the form of interfilamentary fields.

The 'mushroom effect' in the bright chromospheric mottles and in the magnetic filaments is a reasonable thing to expect because the lateral dimension of the filament should be determined by a balance between the magnetic pressure of the filament and the gas pressure and dynamic forces of the surrounding medium. Since the pressure falls off rapidly above the photosphere, one would expect the field strength within the filament to decrease by enlarging the filament until there is a pressure balance.

The correction $C(\mu)$, which has been derived for the Mount Wilson magnetograph measures, depends on the choice of exit slits. Thus one would not expect this correction to apply in general to other instruments. It is of interest to note that because of the dependence of the correction C with μ, magnetic fields measured near the limb with the 5250 Å line will appear strong relative to what one would expect by applying the $\cos\theta$ factor to the fields measured near the center of the disk. In other words, from the appearance of magnetograms one might be tempted to conclude that because the field strengths do not decrease near the limb, as one would expect for vertically oriented filaments obeying a $\cos\theta$ law, the field lines are more or less uniformly oriented in direction. However, our results allow a predominantly vertical orientation of the filaments in the photosphere.

A natural extension of the analysis of this paper would involve similar observations using exit slits at various positions in the line. This would enable us to examine the variation of δ over the line profile, and thus to gain information about the strength of the magnetic field in the filaments. In addition, observations with other lines, such as those of ionized metals, would be of interest.

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