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# Continuum intensity of magnetic flux concentrations: Are magnetic elements bright points?*

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**Summary.** We use the weakening of temperature sensitive spectral lines (Fe I $\lambda 5250.2$ and $\lambda 5247.1$) in a strong plage region to derive a lower limit ($\approx 1.4$ of the quiet photospheric value) for the continuum intensity in magnetic flux concentrations. This suggests an identification of magnetic elements with the observed photospheric bright points. We discuss the implications of this result for the quantitative determination of magnetic flux and propose a procedure for obtaining information on the physical structure of the non-magnetic surroundings of flux concentrations.

**Key words:** solar magnetic fields – faculae – fluxtubes – solar activity

## 1. Introduction

It has long been suspected that photospheric bright points found in white light pictures and filtergrams of very high resolution (e.g. Mehltretter, 1974; Muller, 1983) are spatially coincident with small magnetic flux concentrations ("magnetic elements"), which comprise more than 90% of the magnetic flux in the solar photosphere outside active regions (Frazier and Stenflo, 1972). Due to the fact that the size of these flux concentrations is below the spatial resolution of existing telescopes, a direct proof of this conjecture has not yet been possible. A definite cospatiality of magnetic and bright continuum intensity structures, however, would have severe consequences for the quantitative determination of magnetic flux and filling factors, quite independent of the adopted method (Grossmann-Doerth et al., 1987). Furthermore, the observed properties of bright points could then be safely taken as indicators of the characteristics of magnetic flux concentrations.

Due to their small size, the true continuum intensity of bright points can only be determined by deconvolution or extrapolation of spatially unresolved observations, a procedure that always involves some degree of arbitrariness. Disk centre values for $I_b/I_q$ ($I_b$: continuum intensity of bright points, $I_q$: mean continuum intensity of the quiet photosphere) given in the literature range between 1.2 (Frazier and Stenflo, 1978), 1.3 . . . 1.5 (Muller and Keil, 1983) and 2.0 (Koutchmy, 1977). MHD calculations for small flux concentrations (e.g. Spruit, 1976; Deinzer et al., 1984) predict continuum intensities in the same range. This suggests the identification of magnetic elements with continuum bright points.

In this contribution we present further evidence for this identification by giving a lower limit of the continuum intensity, $I_m$, of the concentrated magnetic structures. Section 2 describes a simple way to obtain an estimate for $I_m$ using the measured mean profiles of spectrum lines together with line profiles originating solely in the magnetic elements. The latter can be determined by integration of the Stokes $V$-profiles (Solanki and Stenflo, 1984) or from model calculations. The argument is based on the impossibility of reproducing the observed rest intensities of temperature sensitive spectrum lines (like Fe I $\lambda 5250.2$) in active regions without increasing the continuum intensity in magnetic structures above the quiet Sun level. In Sect. 3 the consequences and limitations of this result are discussed and possible extensions are sketched. Section 4 summarizes our conclusions.

## 2. The continuum intensity near disk centre

Let us consider a temperature sensitive line (e.g. Fe I $\lambda 5250.2$) and a two-component model of the solar photosphere: A magnetic component with area fraction ("filling factor") $\alpha$, continuum intensity $I_m$ (at $\lambda = 5250$ Å, say) and rest intensity $I_{rm}$ of the spectrum line together with a non-magnetic component with area fraction $1-\alpha$, continuum intensity $I_e$ and rest intensity $I_{re}$. In principle, the non-magnetic component may itself be subdivided into a cool region in the immediate vicinity of a flux concentration (see e.g. Deinzer et al., 1984) and the undisturbed "quiet" photosphere further away. However, only the average properties of the non-magnetic component enter into the following considerations. These properties are generally not equal to those of the quiet photosphere as will be discussed below.

Observations which do not spatially resolve the magnetic structures average over both components. The observed continuum intensity, $I_o$, and rest intensity, $I_{ro}$, are then given by

$$I_o = \alpha I_m + (1-\alpha) I_e, \tag{1}$$

$$I_{ro} = \alpha I_{rm} + (1-\alpha) I_{re} = \alpha I_m \varphi_m + (1-\alpha) I_e \varphi_e, \tag{2}$$

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where we have used the normalized intensities

$$\varphi_m = \frac{I_{rm}}{I_m}, \quad \varphi_e = \frac{I_{re}}{I_e}.$$

A short calculation based on Eqs. (1) and (2) shows that the observed normalized rest intensity $\varphi_o$ is given by

$$\varphi_o = \frac{I_{ro}}{I_o} = \varphi_e + \alpha\delta(\varphi_m - \varphi_e), \tag{3}$$

with

$$\delta = \frac{I_m}{I_o}.$$

Consequently, we have

$$\delta = \frac{\varphi_o - \varphi_e}{\alpha(\varphi_m - \varphi_e)}. \tag{4}$$

It is well known that network, faculae and plage regions are not observable in the true continuum at disk centre with low spatial resolution (3″–4″). Quantitatively, Foukal and Fowler (1984) and Hirayama et al. (1985) have shown that

$$\left|\frac{I_o - I_q}{I_q}\right| \lesssim 10^{-3},$$

where $I_q$ denotes the mean continuum intensity of the undisturbed photosphere. This is in agreement with the results of model calculations (Deinzer et al., 1984) which exhibit a cool, dark ring around the bright magnetic structure (cf. Spruit, 1977). Consequently, in what follows we may take $I_o = I_q$ and consider $\delta = I_m/I_q$, the intensity contrast between the magnetic flux concentration and the mean quiet photosphere.

Equation (4) shows that a lower limit for $\delta$ can be found by taking $\varphi_m = 1$, a reasonable upper limit for $\alpha$ and some estimate for $\varphi_e$ (e.g. $\varphi_e = \varphi_q$), the normalized rest intensity of the spectrum line in the undisturbed photosphere. As shown below, for Fe I $\lambda$5250.2 we find that $\varphi_e$ actually is similar to $\varphi_q$. Consequently, we can write

$$\delta \gtrsim \frac{\varphi_o - \varphi_q}{\alpha(1 - \varphi_q)}. \tag{5}$$

Let us take data obtained with the Fourier transform spectrometer (FTS) at Kitt Peak for Fe I $\lambda$5250.2 (Stenflo et al., 1984). We find $\varphi_q = 0.25$ for a quiet region and $\varphi_o = 0.48$ for a strong plage region with a reasonable upper limit of $\alpha = 0.25$ for the area factor. Equation (5) then gives

$$\delta \gtrsim 1.2.$$

Thus even if the spectrum line would vanish totally in the magnetic component, which obviously is not the case, we would need a significant increase of the continuum intensity within the magnetic structure in order to reproduce the observed average line weakening.

In using Eq. (4) to obtain a more precise value of $\delta$, we encounter the necessity of providing realistic values for $\varphi_m$ and $\varphi_e$. For $\varphi_m$ this can be achieved by using the atmopsheric structure derived by Solanki (1986) on the basis of the integrated Stokes $V$ profiles of many iron lines. Since Stokes $V$ originates exclusively in the magnetic structures the values for $\varphi_m$ obtained in this way can be considered reasonable.

In order to determine $\varphi_e$, the environmental component, we resort to the line ratio technique: Take two spectrum lines which do not differ in their sensitivity to thermodynamic properties, but do differ in their sensitivity to the magnetic field, as for example the "classical' pair Fe I $\lambda$5247.1 and Fe I $\lambda$5250.2 (Stenflo, 1973). Therefore, in the non-magnetic component we have for the ratio of the rest intensities (of Stokes $I$) of these lines (denoted by suffixes 1 and 2, respectively):

$$\frac{\varphi_{e,2}}{\varphi_{e,1}} = \frac{\varphi_{q,2}}{\varphi_{q,1}} = \beta, \tag{6}$$

where $\beta$ is the known ratio in the undisturbed atmosphere. Since $\alpha$ and $\delta$ are the same for both lines we find from Eqs. (4) and (6):

$$\frac{\varphi_{o,1} - \varphi_{e,1}}{\varphi_{m,1} - \varphi_{e,1}} = \frac{\varphi_{o,2} - \beta\varphi_{e,1}}{\varphi_{m,2} - \beta\varphi_{e,1}}. \tag{7}$$

We solve Eq. (7) for $\varphi_{e,1}$ and obtain:

$$\varphi_{e,1} = \frac{\varphi_{o,1}\varphi_{m,2} - \varphi_{o,2}\varphi_{m,1}}{(\varphi_{m,2} - \beta\varphi_{m,1}) - (\varphi_{o,2} - \beta\varphi_{o,1})}, \tag{8}$$

$$\varphi_{e,2} = \beta\varphi_{e,1}.$$

In this way we can actually determine the line depth in the non-magnetic component without prior knowledge of its thermal structure or its continuum intensity.

We again take quiet Sun and plage data from the FTS spectra and calculate $\varphi_m$ with the aid of the plage model of Solanki (1986). The field strength in the magnetic elements may be determined from the line ratio of the Stokes $V$ profiles. Using the detailed procedure outlined by Solanki et al. (1987) we fit the observed line ratio of this region using the thin tube approximation. This gives a field strength at the continuum level $B(\tau = 1) \approx 2150$ G. The resulting rest intensities are listed in Table 1 for the Fe I $\lambda\lambda$5247/5250 pair.

As visible from the table the non-magnetic component shows a normalized rest intensity similar to the undisturbed photosphere. This justifies a posteriori over previous assumption $\varphi_e \approx \varphi_q$.

We notice another, more serious, difficulty for the determination of $\delta$ from Eq. (4), namely the unknown filling factor $\alpha$. As will be discussed in Sect. 3, there is no method of determining $\alpha$ independently of $\delta$. All methods actually measure the product, $\alpha\delta$, which also appears in Eq. (5). We are thus left with the possibility of setting a *lower* limit on $\delta$ using a reasonable *upper* limit of $\alpha$. Recalling that the FTS observations have a spatial resolution of only 10″ and that great care was taken to avoid pores through visual inspection of the observed region, an upper limit of $\alpha \leq 0.25$ is adopted. This value corresponds to a mean field of $\lesssim 300$ G and a typical distance between magnetic structures of the order of their own diameter. Even larger filling factors seem unreasonable for the following reasons:

**Table 1.** Measured and calculated normalized rest intensities ($\varphi_q$: quiet Sun, $\varphi_0$: average plage, $\varphi_m$: magnetic component of plage, $\varphi_e$: non-magnetic component of plage)

| Line | $\lambda$(Å) | $\varphi_q$ | $\varphi_0$ | $\varphi_m$ | $\varphi_e$ |
|---|---|---|---|---|---|
| 1 | 5247.1 | 0.2450 | 0.4457 | 0.736 | 0.290 |
| 2 | 5250.2 | 0.2476 | 0.4761 | 0.818 | 0.293 |

a) The granulation structure would be much more disturbed than is observed below plages.
b) The supergranulation network structure would disappear, since the region would become too crowded with fluxtubes.
c) The area covered by plages typically is much larger than the area covered by sunspots, even in active regions with a single sunspot or a group of spots with the same polarity, where the same amount of magnetic flux must pass through the solar surface in the plages as in the sunspots.

If we insert the numbers listed in Table 1 into Eq. (4), we find

$\alpha\delta = 0.35$

and, with $\alpha \lesssim 0.25$

$\delta \gtrsim 1.4$.

Consequently, the observed weakening of the 5247/5250 line pair can only be understood if the continuum intensity in the magnetic regions is significantly larger than that of the undisturbed photosphere. Since photospheric bright points are the only structures observed so far that show continuum intensities about this value and are closely associated with magnetic structures, our results constitute strong evidence for the identification of magnetic elements with photospheric bright points.

Using $\alpha \lesssim 0.25$ we can also determine the continuum contrast, $\delta_e$, of the non-magnetic component

$$\delta_e \equiv \frac{I_e}{I_q} \approx \frac{I_e}{I_o} = \frac{I - \alpha\delta}{1-\alpha} \lesssim 0.9.$$

This low intensity is equivalent to a temperature reduction of a few hundred degrees with respect to the undisturbed photosphere. On the other hand, the result $\varphi_e \gtrsim \varphi_q$ (cf. Table 1) suggests that at the level at which the Fe I $\lambda$5250.2 line is formed the temperature in the non-magnetic surroundings has risen to approximately the same or even a slightly higher level than in the quiet atmosphere. This is consistent with the observations of Foukal and Duvall (1985) and Elste (1985), who report a smaller (spatially averaged) temperature *gradient* $dT/d\tau$ in facular regions. The observations of Worden (1975) are also best interpreted in terms of a decrease in the spatially averaged temperature gradient.

## 3. Consequences, limitations and possible extensions

The most important implication of the large continuum intensity derived in Sect. 2 is the possibility of identifying photospheric bright points with magnetic elements. However, this does not necessarily mean that *all* magnetic flux appears in the form of bright points at any given instant of time. The magnetic component considered might itself be a mixture of bright and dark regions, the bright ones contributing most of the signal. Therefore, long-lived magnetic structures with occasional brightenings (overstable oscillations?) are still compatible with our results. On the other hand, in this case the continuum intensity of the bright phase would have to be even larger than the value determined in Sect. 2.

Since brighter also signifies hotter, our result implies that the temperature near $\tau = 1$ is considerably higher in the magnetic elements than in the quiet photosphere. This places a significant constraint on present and future fluxtube models. The higher temperature in turn produces a stronger UV radiation field, which leads to a further overionisation of neutral species, e.g. Fe I, and consequently to larger departures from LTE in lines of these species (Solanki and Steenbock, 1987).

Our result has significant consequences for the quantitative determination of magnetic flux $\phi$ and area fraction $\alpha$ (filling factor) of magnetic regions. Since all methods obviously depend on the number of photons per unit area and time received from the magnetic region (if the latter is not spatially resolved), the quantities $\delta\phi$ and $\delta\alpha$ are effectively determined. This applies to the Babcock magnetograph and the center-of-gravity method (Rees and Semel, 1979) as shown by Grossmann-Doerth et al. (1987) and it similarly affects statistical methods applied to the Stokes $I$ and $V$ profiles of many spectral lines (cf. Stenflo and Lindegren, 1977; Solanki and Stenflo, 1984). We have derived the dependence of the Stenflo-Lindegren method on $\delta$, but do not present the derivation here to ensure brevity. Furthermore, Eq. (9) below illustrates that only the product $\alpha\delta$ may be determined from the integrated $V$ profile used by Solanki and Stenflo. All previous applications of these methods have tacitly assumed $\delta = 1$; thus their results must be revised according to the much larger value of $\delta$ suggested above. Apparent magnetic flux variations might appear less mysterious in the light of these considerations. The Robinson (1980) technique, which has been extensively used to determine magnetic filling factors on late type stars (Robinson et al., 1980; Marcy, 1984; Saar et al., 1985), is also subject to uncertainty due to $\delta$ and the filling factors on stars derived with this method are therefore to be regarded with some caution. A similar caveat also applies to techniques based on infra-red lines, which have been applied to e.g. a DMe flare star by Saar and Linsky (1985).

Unfortunately, as can be seen from Eq. (4), our method is not independent of $\alpha$. In fact, it also only yields a value of $\alpha\delta$. Furthermore, the result is not model-independent: we have calculated the profile $\varphi_m$ using the plage atmosphere model of Solanki (1986) and have determined the magnetic field from the Stokes $V$ line ratio of $\lambda\lambda$5250/5247 assuming the thin tube approximation to be valid.

We have tried to estimate the model dependence and the uncertainty of our result by testing the sensitivity of our lower limit of $\delta$ to the main parameters affecting it, namely noise in the data, uncertainty in the FTS continuum and zero-level, fluxtube temperature, magnetic field strength and magnetic field gradient. The noise in the data is extremely low, being of the order of $2.5\,10^{-4}$. It results in an uncertainty in $\delta$, which we name $\Delta\delta$, of approximately 0.02. A mistake in the continuum or zero-level of the FTS data of 1% (the true variation should be less than this value; Holweger, private communication) results in $\Delta\delta \approx 0.01$. If the temperature structure of the fluxtube is changed such that the line depth in the fluxtube $(1-\varphi_m)$ changes by $\leq 20\%$, then $\Delta\delta \lesssim 0.1$. A change in magnetic field strength by 100 G, which induces a change in the line ratio larger than the standard error in the data, also results in a similar $\Delta\delta$. Finally, the gradient of the magnetic field also plays a role, with a lower gradient giving a smaller $\delta$ (since the $V$ and $I$ line ratios correspond to different wavelengths in the line and thus different heights in the atmosphere). However, even a height independent magnetic field of strength 1240 G (which reproduces the line ratio) still gives $\delta \gtrsim 1.2$. Both observational and theoretical reasons exist for supposing the thin-tube approximation to be considerably closer to reality.

We have also been able to deduce the line depths in the non-magnetic surroundings of the magnetic elements. We now wish to discuss an alternative method of achieving this aim. For spectral lines which show small enough Zeeman splitting we could calculate $\varphi_m$ by integrating the Stokes $V$ signal $S = \langle V\rangle/\langle I_c\rangle$ (Solanki and Stenflo, 1984) which gives

$$\phi_m(\lambda) = 1 + \frac{1}{\delta\alpha\Delta\lambda_H}\int_{\lambda_1}^{\lambda} S(\lambda')d\lambda', \tag{9}$$

where $\lambda_1$ is a wavelength outside the $V$ profile, $\Delta\lambda_H$ is the Zeeman splitting and $\phi_m(\lambda)$ the line profile of the Zeeman $\sigma$-components formed in the magnetic element. The line profile in the magnetic region is then given by

$$\varphi_m(\lambda) = \tfrac{1}{2}(\phi_m(\lambda+\Delta\lambda_H) + \phi_m(\lambda-\Delta\lambda_H)) \tag{10}$$

in the case of a homogeneous, longitudinal field along the line of sight. In this way we can determine $\varphi_m$ in a model independent manner, since $\Delta\lambda_H$ can be obtained from the Stokes $V$ line ratio. However, in contrast to the calculation using a model atmosphere the quantity $\alpha\delta$ is now involved in the determination of $\varphi_m$. This suggests a method of determining $\varphi_e$ independently of $\alpha\delta$ for lines for which the line ratio technique cannot be used. By inserting Eqs. (4) and (9) into Eq. (10) we get

$$\varphi_e = \frac{\varphi_o(1-\varphi_m) + \varphi_m G}{1 - \varphi_m + G}, \tag{11}$$

where

$$G = \frac{1}{2\Delta\lambda_H}\left(\int_{\lambda_1}^{\lambda} S(\lambda'+\Delta\lambda_H)d\lambda' + \int_{\lambda_1}^{\lambda} S(\lambda'-\Delta\lambda_H)d\lambda'\right).$$

It is thus possible to determine $\varphi_e$ for a large sample of lines if $\varphi_m$ is taken from model calculations. Of course, Eq. (9) can also be used to fix $\alpha\delta$ by comparing with $\varphi_m$ values from model calculations, which is essentially the technique employed by Solanki and Stenflo (1984, 1985).

This procedure has one disadvantage, namely, Eqs. (4) and (9) give identical values of $\alpha\delta$ only if the field is aligned along the line of sight (or at least if the inclination of the field is well known), only one magnetic polarity is present in the resolution element and the telescope depolarization is compensated for. The line ratio technique carried out here is free from these disadvantages. However, if we do determine $\alpha\delta$ from Eq. (9) by comparing the integrated $V$ profiles of a large number of lines with the plage model of Solanki (1986), assuming a vertical field with a strength as determined from the $V$ line ratio and compensating for the calibration error of a factor of 2 discovered by Stenflo and Harvey (1985), then we obtain

$$\alpha\delta = 0.34,$$

which is quite close to the value derived in Sect. 2[1] Furthermore, an application of the Stenflo-Lindegren technique to the observed region gives $\alpha\delta$ values between 0.3 and 0.45 depending on the choice of average line weakening and field strength. The choice of both quantities is not so straightforward for the Stenflo-Lindegren technique as for the line ratio.

Finally, we would like to comment on the possibility of determining $\alpha$ and $\delta$ individually. As far as we can see there is no *direct* way of obtaining these quantities for unresolved magnetic structures. However, $\delta$ is indirectly contained in the structure of semi-empirical model atmospheres. Since existing examples are based on line profiles observed in the visible spectral range, they give almost no reliable information on the layers where the continuum is formed. On the other hand, Stenflo et al. (1987) have presented FTS data (Stokes $I$, $V$ and $Q$) in the infrared around 1.6 $\mu$m. If Solanki's (1986) model atmospheres could be reliably continued to the deep layers of the photosphere using infrared lines, this would allow for a determination of $\delta$ independently of $\alpha$. Together with the value of $\alpha\delta$ obtained in Sect. 2 this would leave us with consistent values for $\alpha$, $\delta$, $\Delta\lambda_H$ as well as the line profiles $\varphi_m$ and $\varphi_e$. Model calculations would then allow us to empirically determine the atmospheric structure of the non-magnetic surroundings of magnetic elements.

[1] This $\alpha\delta$ is more than a factor of two larger than the one determined from the same region by Solanki and Stenflo (1984), mainly due to a factor of 2 error in that paper, but also partly due to the improved model used here.

## 4. Conclusions

We have presented a method for placing a lower limit on the continuum intensity of magnetic elements. The main assumption is a reasonable upper limit to the filling factor $\alpha$. Applying this method to data from a strong active region plage and assuming that $\alpha \leq 0.25$ we find that the continuum intensity of the magnetic flux concentrations near disk centre is at least 1.4 times higher than that of the quiet photosphere.

The main implication of this result is that the photospheric bright points observed in white light pictures can indeed be identified with magnetic elements, as has often been implicitly assumed in the past. Another important consequence is that the temperature near the $\tau = 1$ level in the magnetic elements is considerably higher than in the quiet photosphere. This contradicts those models of magnetic elements or fluxtubes which have temperatures similar to their surroundings *at equal* $\tau$ near $\tau(5000\,\text{Å}) = 1$. A higher continuum brightness also results in larger departures from LTE. Finally, a higher continuum intensity means that filling factors have generally been overestimated in the past, since we know of no method of determining $\alpha$ based on unresolved observations which does not involve the continuum contrast of the magnetic elements. This last point applies equally to observations of magnetic filling factors on late type stars.

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