DEPENDENCE OF THE PROPERTIES OF MAGNETIC FLUXTUBES ON AREA FACTOR OR AMOUNT OF FLUX

J. O. STENFLO

Institute of Astronomy, ETH-Zentrum, CH-8092 Zürich, Switzerland

and

J. W. HARVEY

National Solar Observatory, P.O. Box 26732, Tucson, AZ 85726, U.S.A.*

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Abstract. Stokes I and V line profiles with high signal-to-noise ratio of the 1 Fe I $\lambda\lambda$5247.06 and 5250.22 Å lines have been recorded in a number of regions with different amount of magnetic flux near disc center, from 'non-magnetic' regions to strong plages. The objective has been to study how the intrinsic fluxtube properties may depend on the amount of flux concentration, i.e., on the magnetic area factor. Indirectly, the area factor should be related to the average fluxtube diameter.

The intrinsic kG field strength is found to vary only slowly, by at most a few hundred G, when the area factor increases by a factor of 6. The statistical spread in the values is quite small.

The wavelength positions of the V profiles do not indicate any downdrafts within the fluxtubes. The well-known association of redward line shifts and magnetic features probably arises from motions in the field-free region adjacent to the fluxtubes. There are strong asymmetries of the Stokes V profile always in the sense of a 20–30% stronger blue peak, which indicate that there must be important mass motions with a vertical gradient within the fluxtubes.

Most of the recordings have been made with a grating spectrometer, but two recordings with a Fourier transform spectrometer have provided an important check of the instrumental effects of limited spectral resolution and straylight in the spectrometer data. These effects modify the I and V profiles substantially, and can for instance result in fictitious redshifts derived from the Stokes V profiles.

1. Introduction

The magnetic fluxtube is the fundamental entity in solar magnetohydrodynamics. It is the key to a unified understanding of a variety of solar phenomena, like sunspots, plages, network, spicules, etc. (Spruit and Roberts, 1983).

Unfortunately these basic units are generally too small to be spatially resolved, but using the so-called line-ratio technique (reviewed in Stenflo, 1976), it has been possible to derive intrinsic properties of the fluxtubes independent of the spatial resolution actually used. Before this technique had been applied, it was believed that there must exist all kinds of magnetic fluxtubes on the Sun, from those with very weak fields to those with kG field strengths like sunspots. It therefore came as a surprise when the line-ratio technique showed that more than 90% of the total magnetic flux seen by magnetographs occurs in strong-field form (Howard and Stenflo, 1972; Frazier and Stenflo, 1972), and that the field strength outside sunspots is 1–2 kG, the precise value

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depending on the assumed shape of the magnetic cross section (Stenflo, 1973). The line-ratio data indicated that the statistical spread in the intrinsic fluxtube properties, like field strength and temperature structure, is very small, and that regions so different in appearance as the quiet network and active-region plages seem to be made up by practically the same type of fluxtubes (Frazier and Stenflo, 1972). For example, Wiehr (1978) found field strengths, for assumed rectangular cross sections, ranging from 1500–2200 G for features ranging from quiet network to pores.

As the fluxtubes (apart from the sunspots) cannot be spatially resolved, at least not by ground-based instruments, we cannot determine their diameters reliably. Although white-light observations may partially resolve facular and network bright points (Muller and Keil, 1983), the diameters of the brightness elements may not represent the diameters of the corresponding magnetic-field concentrations. Therefore it is at present not feasible to determine the intrinsic field strength or interior mass motions as a function of fluxtube diameter. Due to such practical limitations, we have to replace the diameter as a direct physical parameter with the more indirect parameters area factor or, equivalently, magnetic flux.

Magnetic flux is the integral over a horizontal plane of the vertical component of the magnetic field. We assume that the magnetic field within a fluxtube is of constant strength and vertical. Thus, the amount of magnetic flux crossing a horizontal surface is proportional to the area covered by magnetic field provided that all the field is unipolar. We divide the area covered by magnetic field by the total area of the horizontal resolution element to obtain an area factor α, and we divide the flux by the same total area to obtain a mean magnetic field $\langle B \rangle$. Near the disk center, $\langle B \rangle$ is proportional to the circular polarization amplitude in a spectral line, so we can for our practical purposes consider polarization amplitude, magnetic flux, or area factor as equivalent parameters. We need only the factors of proportionality to convert one to the other.

Within the assumptions just discussed, a larger area factor may be due to two factors: (a) The fluxtubes are more densely packed (higher number density). (b) The fluxtubes have larger diameters. In our observations we cannot distinguish between these two cases, but it is natural to expect that with larger area factor, the average fluxtube diameter will also be larger (although in addition the fluxtube number density is expected to be higher). When the fluxtubes are densely packed, smaller fluxtubes would tend to coalesce to larger ones. We would accordingly expect that the fluxtube intrinsic properties would be functions of the area factor or amount of flux concentration, but no study has yet been performed to determine how large this variation actually is.

To derive the intrinsic field strengths and other properties we apply the line-ratio technique to the well-proven line pair 1 Fe I $\lambda\lambda$5247.06 and 5250.22 Å. In contrast to previous uses of the line-ratio technique, when only the line-wing polarizations were recorded with a Babcock-type magnetograph, we use spectral scans of the complete Stokes I and V profiles, which greatly enhances the information content.

The effects of limited spectral resolution and straylight in the recordings with the grating spectrometer have been monitored by comparing with corresponding, unaffected recordings using a Fourier transform spectrometer.

2. Observations and Data Reduction

The recordings were made with the 13.7-m vertical grating spectrometer of the Kitt Peak McMath telescope, September 24–25, 1979, as well as with the Fourier transform spectrometer (FTS) of the McMath telescope, April 29–30, 1979.

The recordings with the FTS have been extensively described before (Stenflo *et al.*, 1984). A circular entrance aperture with a diameter of 10 sec of arc was used. Due to the high spectral resolving power of the FTS, the instrumental broadening can be regarded as zero for any practical purpose. Further, there is no spectral straylight with the FTS.

In the case of the grating spectrometer, an image slicer allowed us to use a square entrance aperture of 5×5 sec of arc. The spectral resolution was about 20 mÅ. Further, we acknowledge the presence of spectrometer straylight (estimated at about 8% in previous studies). To record the intensity and circular polarization (Stokes I and V/I), a piezoelastic modulator followed by a linear polarizer was used in front of the image slicer at a modulation frequency of 50 kHz. The I and V/I spectra were scanned over the range 5246.0 to 5251.6 Å by rotating the grating. The signal-to-noise ratio was enhanced by repeating the scans at least 40 times, which was achieved in 3–4 min. Thus a noise level around 0.04–0.08% in the degree of polarization was reached.

An aim of the observing program with the grating spectrometer was to cover the broadest possible range of non-sunspot magnetic features. Accordingly we made the spectral scans in a series of regions near disk center of various magnetic-flux levels, from the most quiet regions with no visible magnetic flux, to strong plages with large Zeeman-effect polarization. Thus 18 different regions were covered.

Two of our FTS recordings of April 1979 covered the 5247–5250 Å range. One was made in a weak plage ($\mu = 1.00$), the other in a strong plage ($\mu = 0.92$). Using these FTS data we have been able to check to what extent the instrumental broadening and straylight affect our results with the grating spectrometer data.

For both the FTS and spectrometer data, the telescope polarization was not fully compensated in front of the analyzer. The remaining uncompensated instrumental polarization was eliminated in the data analysis by shifting the polarization zero line to make it coincide with the apparent continuum polarization (since we can safely assume that Stokes V has no significant sources in the continuum). After this correction, V/I was multiplied by I to give us the Stokes V spectrum, normalized to the intensity I_c of the continuous spectrum. For more on this procedure, see Stenflo *et al.* (1984) and references therein.

An uncertainty in the polarization amplitude scale has previously been noted in observations with the McMath telescope (Stenflo *et al.*, 1983a, b). Such an uncertainty will appear as an error in the scale of the area factors. We will discuss this problem more extensively in Section 3.

In the diagrams presented in Section 3, the results (line ratios, line asymmetries, line depths, etc.) have been plotted as functions of the recorded polarization amplitude in the 5250 Å line. This Stokes V amplitude can be regarded as a measure of area factor or magnetic flux. Let us now try to elucidate somewhat the relation between those three quantities and their dependence on the spatial resolution used.

For a two-component model, the average field strength $\langle B \rangle$ of vertically-oriented fluxtubes observed near disk center can be written

$$\langle B \rangle = \alpha B , \tag{2.1}$$

where α is the fractional area covered by fields of strength B (the fraction $1 - \alpha$ being field free). As Stokes V (normalized to the intensity of the adjacent continuous spectrum) is $\sim \langle B \rangle$, and as the intrinsic field strength B does not vary much with area factor (see Section 3.1 below),

$$\alpha \sim V \tag{2.2}$$

in a first approximation, *independent of the spatial resolution used.* Thus the polarization scale can be regarded as a scale for the area factor α as well, the constant of proportionality between α and V being the same for the FTS and grating spectrometer data, in spite of the fact that different spatial resolutions were used.

If we however regard Stokes V as a measure of magnetic flux ϕ, the scale becomes dependent on the spatial resolution being used. If the area of the sampling aperture is A,

$$\phi = \langle B \rangle A , \tag{2.3}$$

so that

$$\phi \sim AV . \tag{2.4}$$

As A for the FTS data is larger by a factor of π as compared with the grating spectrometer data, the Stokes V amplitudes recorded with the FTS have to be multiplied by a factor of π to be brought on the same *magnetic-flux scale* as the grating spectrometer data. This should be kept in mind when comparing the results of the FTS with those of the grating spectrometer in Section 3.

3. Results

3.1. Intrinsic Field Strengths

Figure 1 illustrates one of the FTS recordings (in a strong plage) over the wavelength range of interest. A striking feature of the Stokes V profiles is their pronounced asymmetry, in the sense that the blue (positive) polarization peak is significantly larger than the absolute value of the red (negative) polarization peak. As a measure of the magnetic flux (or area factor α) we therefore use the average of the polarization peaks in the blue and red line wings, and denote it $V_{\max,\,5247}$ and $V_{\max,\,5250}$ respectively, for our two Fe I lines of interest. The conversion between area factor α and polarization is not well determined, largely due to an as yet unidentified calibration error, which makes all our Stokes V values too small by a factor of two. Our analysis in Section 3.3 in

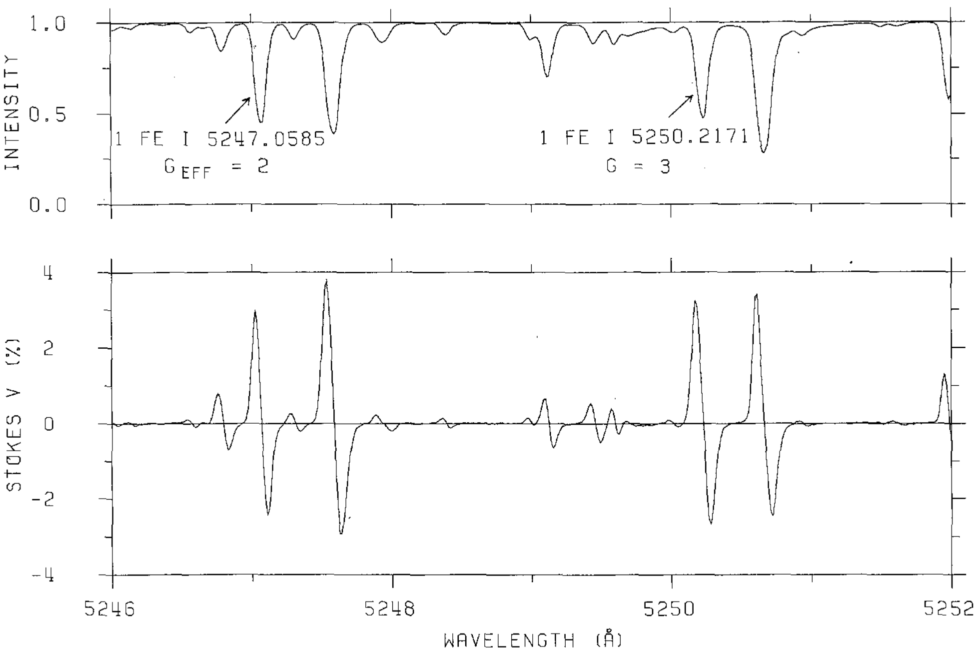

Fig. 1. Stokes I and V spectra in the wavelength range of interest, recorded in a strong plage near disk center with a Fourier Transform Spectrometer.

connection with Figure 7 suggests however that the relation is approximately given by $\alpha\,(\%) \approx 7.6\; V_{\max,\,5250}\,(\%)$. Throughout the present paper, the observed Stokes V represents the polarization *uncorrected* for a possible calibration error. Fortunately, an error in the polarization scale does not affect the conclusions in the present paper, since they are scale independent, as we shall see.

If the magnetic fields were intrinsically weak, the ratio between $V_{\max,\,5250}$ and $V_{\max,\,5247}$ would be the same as the ratio between their Landé factors, 3 : 2. The $V_{\max,\,5250}$ would equal 1.5 $V_{\max,\,5247}$. The plot of $V_{\max,\,5250}$ vs 1.5 $V_{\max,\,2547}$ in Figure 2a shows however that the points line up neatly along a line that has a smaller inclination than 45°. This representation of the data is the same as the scatter-plot diagrams of apparent field strengths in these two lines used by Stenflo (1973) and Frazier and Stenflo (1978). The value of the slope of the line gives us the intrinsic field strength B of the spatially unresolved fluxtubes.

It is the absence of much spread around this line that has led to the concept of 'unique' fluxtube properties. With sufficiently noise-free data, as in our present case, we can however begin to look for local deviations in the slope along the curve. This is done in Figure 2b, where we have plotted the ratio $V_{\max,\,5250}/(1.5\; V_{\max,\,5247})$ as a function of $V_{\max,\,5250}$. We have omitted the points with $V_{\max,\,5250}$ less than 0.4%, since the remaining noise will be too much amplified when dividing by a small number. The one-sigma error bars are due to random noise in the data but do not include possible systematic errors (instrumental drifts, variable seeing).

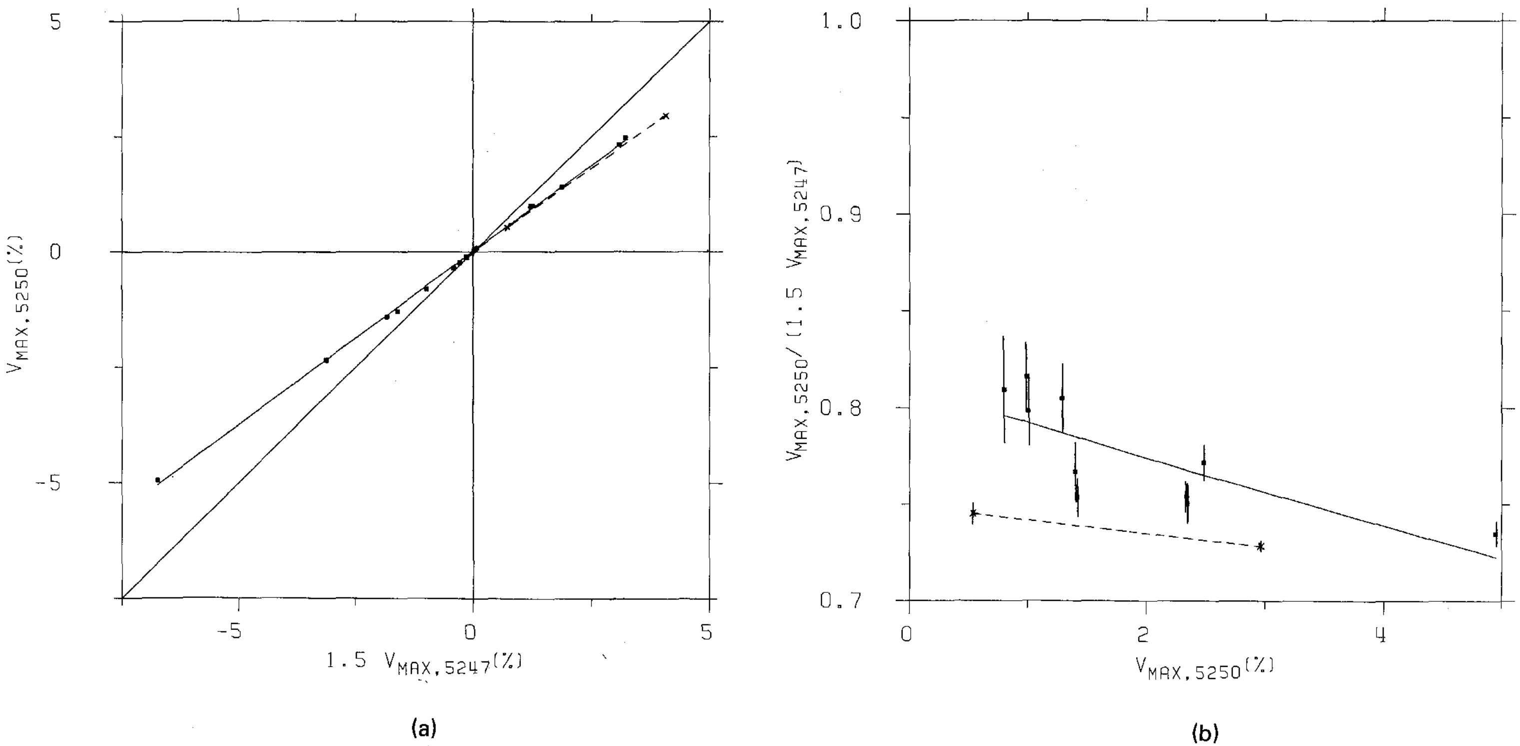

Fig. 2. (a) Polarization amplitude in the 5250 Å line vs 1.5 times the polarization amplitude in the 5247 Å line. If the fields were intrinsically weak, the points would fall along the 45° line. The spread around the line indicates the spread in intrinsic field strengths. (b) Ratio of polarization amplitudes in the two lines vs polarization amplitude in the 5250 Å line, indicating a slow increase of the intrinsic field strength with area factor. The points with a polarization amplitude below 0.4% have been omitted, since the noise becomes too amplified when dividing by a small number. Filled squares and solid curve (cubic spline fit): spectrometer data. Crosses and dashed line: FTS data.

We first notice in Figure 2b the conspicuous deviation of the points from the weak-field value (unity). The larger the deviation, the stronger is the intrinsic field. Secondly we notice the slight trend in the sense that the deviation (or the intrinsic field strength) increases with the area factor. Thus the 5250/5247 ratio decreases from about 0.80 to 0.72 when the area factor increases by a factor of 6, according to our spectrometer data. Thirdly we notice the effect of spectral resolution: The two FTS points lie substantially lower in the diagram. Thus spectral broadening may lead to underestimated values of B. If we however would convert the $V_{\max,\,5250}$ values to a common *magnetic-flux* scale (see Section 2), the discrepancy between the FTS and the grating spectrometer data would be greatly reduced.

To convert the 5250/5247 polarization ratio into intrinsic fluxtube field strength B, we need to use the theory of line formation in a magnetic field. The model dependence can be described mainly as a dependence on the assumed line strength and line width. The line strength and line width parameters can be adjusted in the radiative-transfer problem to fit the observed intensity profile. The problem is however that the intensity profile within the fluxtubes is not directly accessible through observations, since the fluxtubes cannot be spatially resolved. In the fluxtubes the intensity profile is different due to temperature weakening and reduced turbulent broadening. Therefore a more detailed analysis is relatively involved (cf. Stenflo, 1975; Frazier and Stenflo, 1978). Further, the field strength in the fluxtubes is of course not single-valued, but varies across the fluxtube and with height. The shape of the field-strength cross-section is still unknown, but to explore the magnitude of the effects, we will assume a rectangular cross section with a single-valued field B.

In Figure 3 we illustrate the main model dependence of the conversion procedure by plotting the 5250/5247 polarization ratio as a function of field strength B, using a Milne–Eddington model atmosphere, primarily characterized by the two parameters η_0, the ratio between the absorption coefficient at line center and in the continuum, and $\Delta\lambda_D$, the Doppler width. With $\eta_0 = 4.4$, $\Delta\lambda_D = 25.25$ mÅ, and 0.25 as the value of the damping parameter in the Voigt function, we obtain an optimum fit to the FTS intensity profile of the 5250 Å line in a non-magnetic region. In the fluxtube model of Stenflo (1975), the 5250 Å line depth would be 74% of the value in the non-magnetic atmosphere if the Landé factor were zero. A reduction of η_0 from 4.4 to 1.72, keeping the other parameters fixed, would reproduce this non-magnetic line weakening. We therefore regard the curve in Figure 3 with $\eta_0 = 1.72$ as the nominal one, to be used as a reference.

As the Zeeman saturation effect depends on the ratio between Zeeman splitting and line width, and as the line width scales with $\Delta\lambda_D$, the derived value of B will also scale with $\Delta\lambda_D$. Therefore the value of B is very sensitive to the assumed value of $\Delta\lambda_D$, but fortunately the difference in Doppler width between the fluxtube interior and exterior is not expected to be very large (cf. Stellmacher and Wiehr, 1971).

The dependence on the line-strength parameter η_0 is much smaller. The difference between the dashed and nominal curves in Figure 3 is not very large, although the corresponding values of η_0 differ by more than a factor of 2.5. The difference increases with increasing Zeeman saturation.

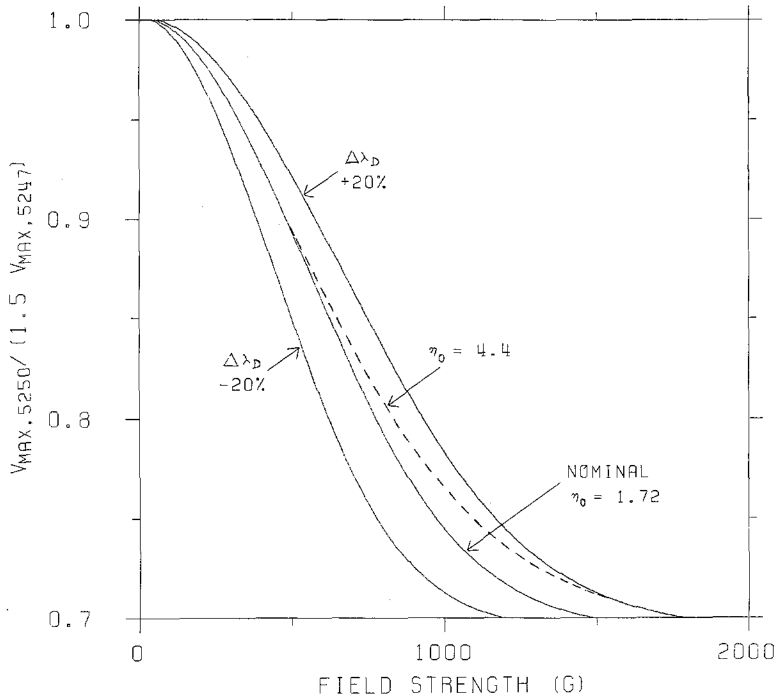

Fig. 3. Ratio of polarization amplitudes in the 5250 and 5247 Å lines vs field strength B, calculated for a Milne–Eddington model as described in the text. The different curves indicate the model dependence in the determination of B.

Using the nominal curve in Figure 3 for the conversion, the trend in Figure 2 that the polarization ratio decreases from 0.80 to 0.72 means that B increases from 800 G to 1140 G when the area factor increases by a factor of 6. Notice however that these B values are uncorrected for spectral resolution. The FTS data show a substantially larger B: It varies from 1000 G to 1100 G when the area factor increases by a factor of 6.

These values are in agreement with the results of Frazier and Stenflo (1978), who found from their data $B \approx 960$ G for a rectangular magnetic cross section. For any other shape of the cross section, the magnetic-field amplitude is naturally higher, as demonstrated in detail in Stenflo (1973) and Frazier and Stenflo (1978).

The validity of our procedure of interpreting the 5250/5247 polarization ratio in terms of Zeeman saturation and intrinsic field strengths can be appreciated when we have the behaviour of the full polarization profiles before us. To illustrate this we show to the left of Figure 4 the polarization profiles V_{5250} and 1.5 V_{5247} in the blue line wings, for the two FTS recordings (weak and strong plage). We notice that the effect of the kG fields is not only to suppress the maximum of the 5250 polarization curve, but also to change its shape, mainly by broadening it, in full agreement with theoretical expectations.

Instead of just giving the ratio between the polarization maxima, we can determine the ratio $V_{5250}/(1.5\ V_{5247})$ at each wavelength within the line profile. The result of doing

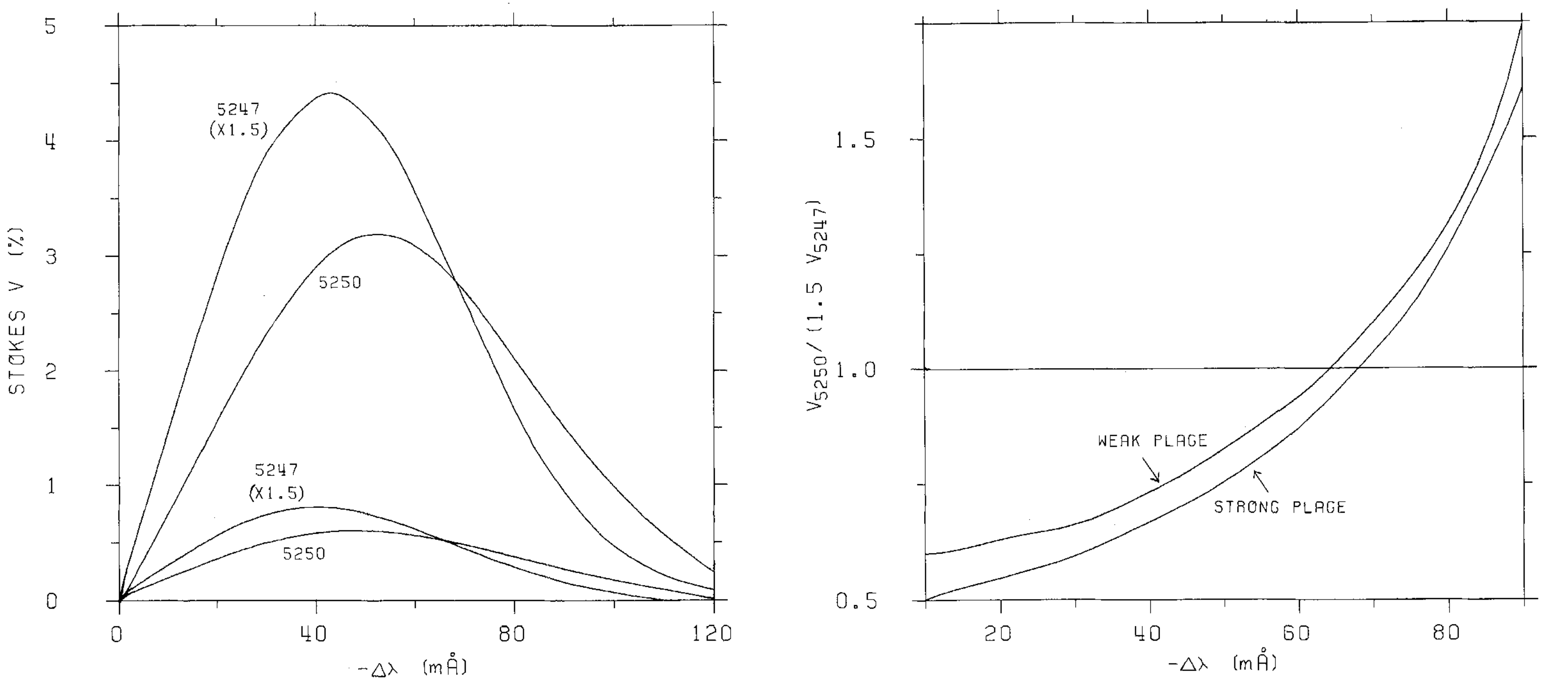

Fig. 4. Left diagram: Stokes V profiles in the blue line wings of the 5250 and 5247 Å lines, recorded in a strong (upper two curves) and in a weak (lower two curves) plage near disk center with the FTS. Right diagram: ratio between the curves in the left diagram, as a function of distance from the line center.

so is shown in the right diagram of Figure 4 for the two FTS recordings. We notice that the ratio increases steeply when we move out in the line wing, and becomes larger than unity in the far wings (beyond the points where the profiles in the left diagram of Figure 4 cross each other). The same type of curves is obtained from the observations with the grating spectrometer, except that the steepness is less than for the FTS curves due to the averaging effect of the limited spectral resolution.

Precisely this behaviour of the line ratio with wavelength is predicted from theoretical calculations of the Zeeman saturation effect (Stenflo, 1975; Frazier and Stenflo, 1978), which is the reason why there has been such a confidence in the results derived from the line-ratio technique.

Although the general behaviour of the ratio curves in Figure 4 is well understood, the detailed shape of the curves contains important information for more sophisticated fluxtube modelling, which however is outside the scope of the present paper.

3.2. Mass motions

Evidence of mass motions inside the fluxtubes has been provided by Giovanelli and Slaughter (1978), who used the wavelength position of the zero crossing of the Stokes V profile as a measure of the Doppler shift of the line profile inside the fluxtubes. At the level in the photosphere where the 5247–5250 Å lines are formed, they reported downdrafts of about 0.5 km s^{-1} relative to the quiet Sun. The downdraft velocity seems to steeply increase with depth (reaching 1.6 km s^{-1} according to corrected measurements of Harvey and Hall, 1975), in apparent conflict with the concept of mass conservation, since the density increases exponentially with depth. To resolve this conflict, it was necessary to postulate an extremely efficient mechanism of bringing matter from the outside into the interior of the fluxtube (Giovanelli, 1977).

We have applied the same method to our data, to measure the position of the V zero crossing, using the position (center of gravity) of the unpolarized intensity (Stokes I) profile as the zero point of our velocity scale. The results displayed in Figure 5 for the 5250 Å line show consistently smaller apparent downdrafts than found by Giovanelli and Slaughter (1978). The FTS data give apparent downdrafts of the order of 0.1 km s^{-1} only. The grating spectrometer data show somewhat larger values, $\sim$0.3 km s^{-1}, for small area factors, decreasing to about zero for the largest area factors. The error bars are due to random noise but do not include possible systematic errors (instrumental drifts, variable seeing). Part of the spread in the data is however likely to be of solar origin.

Now it should be remembered that the wavelength position of the unpolarized intensity profile does not represent the true zero velocity. Due to the well-known brightness-velocity correlation in the solar granulation, there is a net blue shift of the spectral lines, although the average velocity is zero. For a moderately strong Fe I line like 5250, this blue shift is around 0.3 km s^{-1} for the center of gravity of the lower half of the line (Dravins *et al.*, 1981). When we subtract this actual velocity zero point from our Stokes V data in Figure 5, we find small *outward* velocities in the fluxtubes. How could our results differ so from those of Giovanelli and Slaughter (1978)?

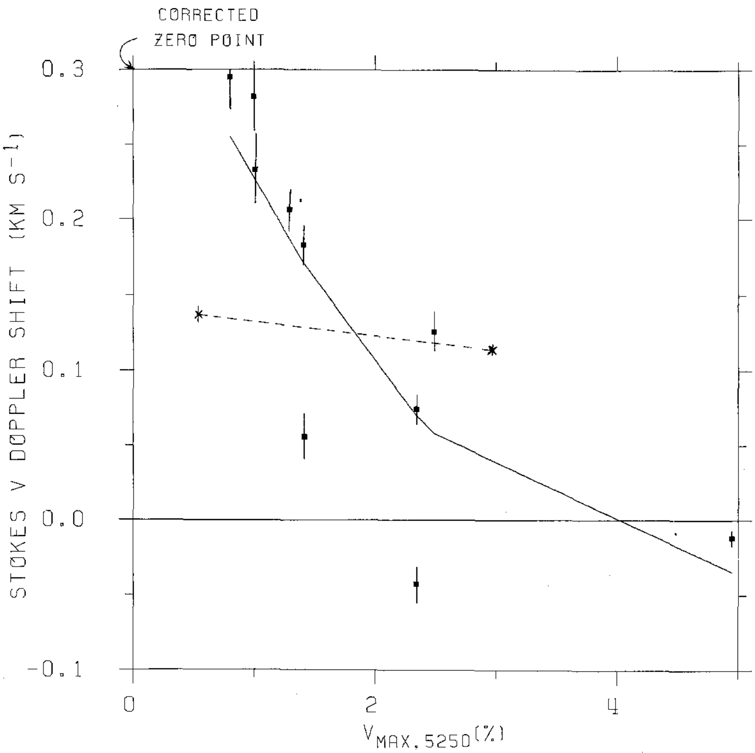

Fig. 5. Apparent Doppler shift of the zero-crossing point of the Stokes V profile, relative to the position of the unpolarized intensity profile. Filled squares and solid curve (cubic spline fit): spectrometer data. Crosses and dashed line: FTS data. Since the unpolarized line profiles are blueshifted by about 0.3 km s^{-1} due to velocity-brightness correlations in the solar granulation, the zero point of the velocity scale has to be shifted upwards, as indicated in the figure. As was the case in Figure 2b, the points with polarization amplitudes below 0.4% have been omitted, since the uncertainty in the V Doppler shift becomes too large.

Part of the answer may be that our velocity reference (Stokes I profile) lies spatially very close to the fluxtubes, while Giovanelli and Slaughter used the distant quiet Sun as a reference. Since there is evidence that convection (and thus the convective blue shift) is reduced in the vicinity of magnetic flux (e.g. Livingston, 1982), our reference may be systematically redshifted compared to the quiet Sun. It is more certain that at least part of the discrepancy between our results and those of Giovanelli and Slaughter lies in the large asymmetries in the Stokes V profiles. In Stenflo *et al.* (1984) it was noted that these asymmetries may cause considerable fictitious redshifts of the apparent zero-crossing point of the Stokes V profile, if the line profiles are not completely spectrally resolved. The actual V asymmetries in our data are illustrated in Figure 6, which shows the ratio of the red and blue wing polarization peaks with error bars due to random noise as a function of $V_{max,\,5250}$ or area factor. The blue polarization peak is always 20–30% larger than the red peak. Thus the asymmetry index is around

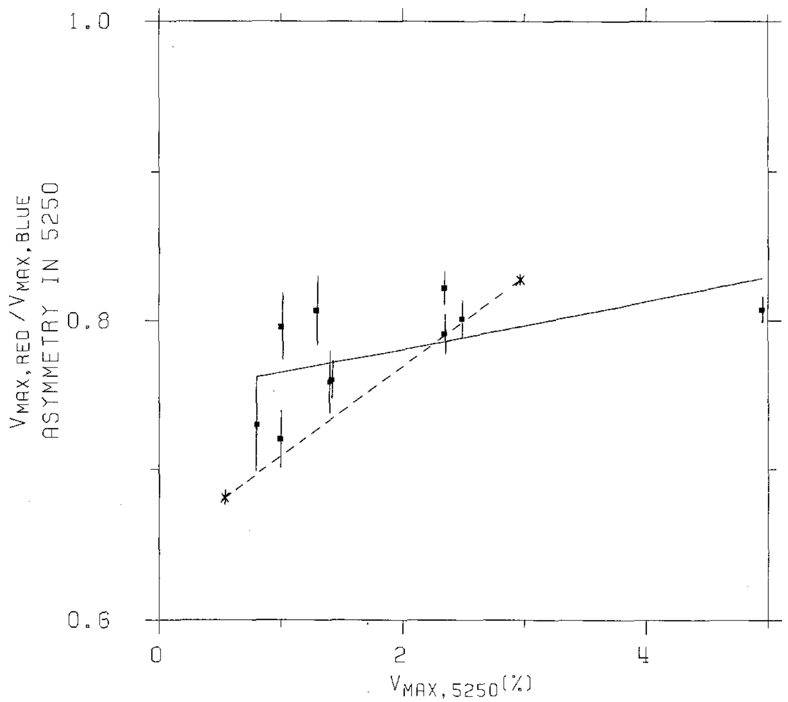

Fig. 6. Asymmetry of the Stokes V profile as a function of polarization amplitude in the 5250 Å line. Filled squares and solid curve (cubic spline fit): spectrometer data. Crosses and dashed line: FTS data. The points with a polarization amplitude below 0.4% have been excluded, since the corresponding V asymmetries become too uncertain.

0.7–0.8, increasing relatively steeply with area factor for the FTS data, the increase being more washed-out for the spectrometer data.

As the asymmetry is so much larger when the area factors are small according to the FTS data, one would expect the fictitious downdrafts also to be larger for small area factors. This may explain why our spectrometer data show excess redshifts for small area factors in Figure 5.

In conclusion, we find no evidence for a net downdraft inside the fluxtubes from our V zero-crossing data. However, as pointed out in Stenflo *et al.* (1974), the V asymmetries can only be explained within the framework of *dynamical* fluxtube models, including a height gradient of the vertical velocity v and magnetic field B (Auer and Heasley, 1978; Semel *et al.*, 1980). Accordingly we must have mass motions within the fluxtubes, although it is not yet clear of what type.

In addition to the asymmetry expressed by the red and blue V *amplitudes*, the FTS data also exhibit an area asymmetry in the sense that the area of the blue V peak is larger than the red peak area (Stenflo *et al.*, 1984). Horizontal gradients and brightness-velocity correlations are unable to generate such an area asymmetry, but vertical gradients are needed.

The recent theoretical analysis of asymmetries in Stokes profiles by Landi Degl'Innocenti and Landolfi (1983) does not apply to our observed asymmetries, since in their calculations the Stokes V asymmetry vanishes when the magnetic field is directed along the line of sight. The reason for this is that they only considered velocity gradients, with the magnetic-field gradient being zero. Our observed Stokes V asymmetries however require the presence of *correlated* vertical magnetic-field and velocity gradients.

3.3. Changes in the unpolarized line profile

Inside the fluxtubes, the unpolarized Stokes I profiles are drastically changed, due to a variety of effects. (a) The large Zeeman splitting. (b) The different temperature-density structure. (c) Different turbulent broadening. (d) Correlations between macroscopic velocities and the other parameters. The contributions of these fluxtube effects to the observed intensity profile increase in proportion to the area factor, i.e. to the amount of 5250 polarization.

To isolate the Zeeman broadening effect from the other thermodynamic effects we have plotted in Figure 7 the relative difference in line width w between the 5250 and 5247 Å lines, or $(w_{5250} - w_{5247})/(w_{5250} + w_{5247})$. The line width w that is used here is

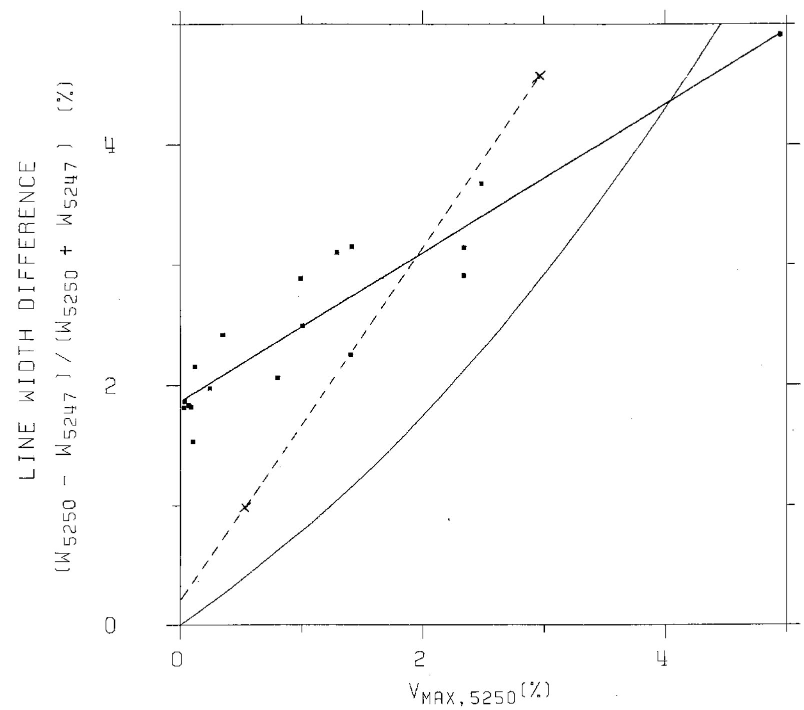

Fig. 7. Relative line-width difference between the 5250 and 5247 Å lines, as a function of polarization amplitude in the 5250 Å line. Filled squares and thick solid line (cubic spline fit): spectrometer data. Crosses and dashed line: FTS data. Thin solid line: theoretical curve, assuming a calibration error that makes the observed Stokes V too small by a factor of two.

not the half width but the chord length higher up in the line profile, 70% of the distance from the line bottom to the continuum (cf. the definitions in Figure 2 of Stenflo and Lindegren, 1977). If we use chord lengths deeper down in the line profile, the results are similar, but the scatter of the points becomes larger.

The magnetic broadening of the line profile is small, not exceeding a few percent, which explains why the scatter of the points looks large, although it is only a fraction of a percent. The fitted curve is a cubic spline assuming that the standard deviation of the points is 0.3%.

Since the spectra were recorded with a precision close to 0.01%, the error bars due to random noise are smaller than the symbol size in Figure 7. This also applies to the following figures. Most of the scatter in these diagrams thus seems to be of solar origin.

If there are no weak blends that would contribute to the line-width difference between the 5250 and 5247 Å lines, we would expect the difference to go to zero when the area factor goes to zero, assuming that there is no 'hidden' magnetic broadening left. Such a hidden magnetic flux would exist if a chaotic or turbulent magnetic field would fill the photosphere, with locally mixed polarities such that no net magnetic flux, and therefore no net polarization effect, is left when we integrate over the spatial resolution element. The area factor that we use is proportional to the net magnetic flux that we see. With this practical definition, the area factor is zero for any turbulent field, regardless of its strength and of the extent to which it fills the volume.

From the data with the grating spectrometer, one gets the impression that there is a remaining magnetic broadening of as much as 2% in the 'non-magnetic' areas, which would correspond to a turbulent field as strong as about 410 G. The FTS data on the other hand indicate that the remaining effect does not exceed 0.2%, corresponding to a turbulent field of about 130 G, which could also be zero in view of the uncertainties involved.

When comparing the results with the FTS and the grating spectrometer, one has to bear in mind that not only instrumental broadening but also straylight affect the grating intensity data significantly. In a first approximation the straylight may be thought of as a smooth background, but in a more complete picture the straylight also has spectral features, since it arises from the particular pattern of grating ghosts. Such effects may contribute to an apparent line-width difference between two intrinsically identical lines.

There is strong reason to suspect that all the polarization data in the present as well as in previous papers, in which the McMath FTS and spectrometer have been used, are subject to a calibration error, leading to polarization values that are too small by a factor of two. Such a factor is required to explain observations in the infrared of sunspot umbrae, as well as the too small polarization amplitudes found in the analysis of linear polarization near the solar limb (Stenflo *et al.*, 1983a, b). The origin of this scale error has not yet been identified, but further evidence for it is obtained when trying to introduce a theoretical curve in Figure 7. For these calculations we have used a two-component model with the nominal Milne–Eddington line parameters that were used for Figure 3 (i.e., with $\eta_0 = 1.72$, and $B = 1000$ G). If we assume that all Stokes V values in the theoretical calculations should be reduced by a factor of two due to a calibration error, we obtain the thin solid line in Figure 7, which gives a fair agreement with the slope of the FTS data. A better fit may be obtained with a more sophisticated model, using a distribution of field strengths. However, if we had not assumed the calibration error of a factor of two, the theoretical curve would have been much shallower, and even very drastic changes of the model would not have allowed the data to be fitted.

If there were no calibration error, our two-component model would predict the relation between area factor α and $V_{\max,\,5250}$ to be $\alpha = 3.80\ V_{\max,\,5250}$. With the presumed calibration error, the relation that we have to use becomes $\alpha = 7.6\ V_{\max,\,5250}$. In any case one should use the α and $\langle B_{\parallel} \rangle$ scales with great care. This is the reason why we have avoided to quote absolute values of α in the present paper, but instead have discussed how the fluxtube properties change when the area factor increases by a factor of 6. In this way the discussion becomes independent of the polarization scale. Note also that the line-ratio technique is scale independent.

While the line-width effects are small, the effect on the line depth is drastic. Figure 8 shows that the variation with area factor is well defined, the spread of the points being quite small. The line depths measured with the FTS are systematically much larger than those measured with the spectrometer, due to the absence of instrumental broadening

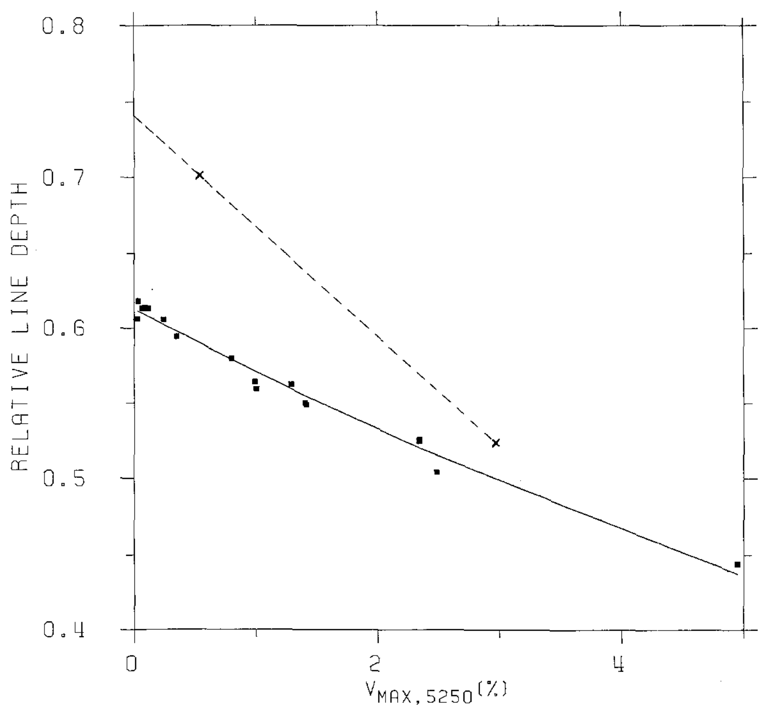

Fig. 8. Line depth (in units of the continuum intensity) as a function of polarization amplitude in the 5250 Å line. Filled squares and solid curve (cubic spline fit): spectrometer data. Crosses and dashed line: FTS data.

and straylight. The strong reduction in line depth with increasing area factor is partly due to the Zeeman splitting, partly to temperature weakening inside the fluxtubes.

Since the line-depth effects are much larger than the line-width effects, we would expect that the *equivalent width* of the line should exhibit a large decrease with increasing area factor. As it is difficult to integrate the line profile accurately in the far line wings due to the increasing influence of neighbouring lines, we use as a line-strength parameter the area S of the part of the profile that is below the half-level chord (cf. the definition in Figure 2 of Stenflo and Lindegren, 1977). S is roughly proportional to the equivalent width.

Figure 9 shows how the line strength S decreases strongly with area factor. Due to straylight, the spectrometer data have a large offset with respect to the straylight-free

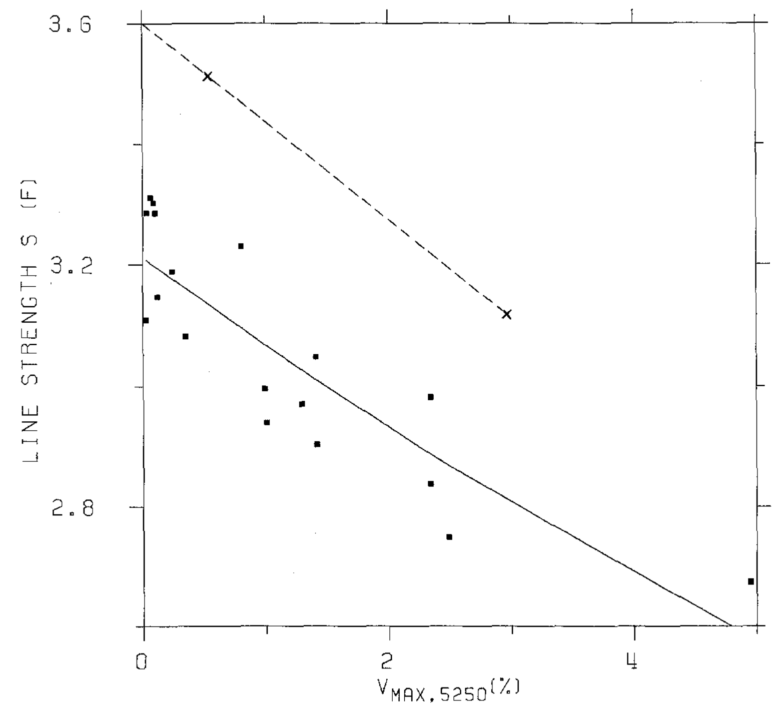

Fig. 9. Line strength S, expressed in Fraunhofer (F), as a function of polarization amplitude in the 5250 Å line. Filled squares and solid curve (cubic spline fit): spectrometer data. Crosses and dashed line: FTS data.

FTS data. The scatter of the points is much larger than for the line-depth data, which has to do with a correspondingly larger scatter in the line-width data.

Figures 8 and 9 imply that there must be a correlation between line depth and line strength. Figure 10 shows that this is indeed the case. Again, the FTS data indicate how important instrumental effects are for this relation.

We have plotted in Figure 10 the results for both the 5247 and 5250 Å lines, to allow a comparison of the relations. Whereas the two lines agree with each other for small

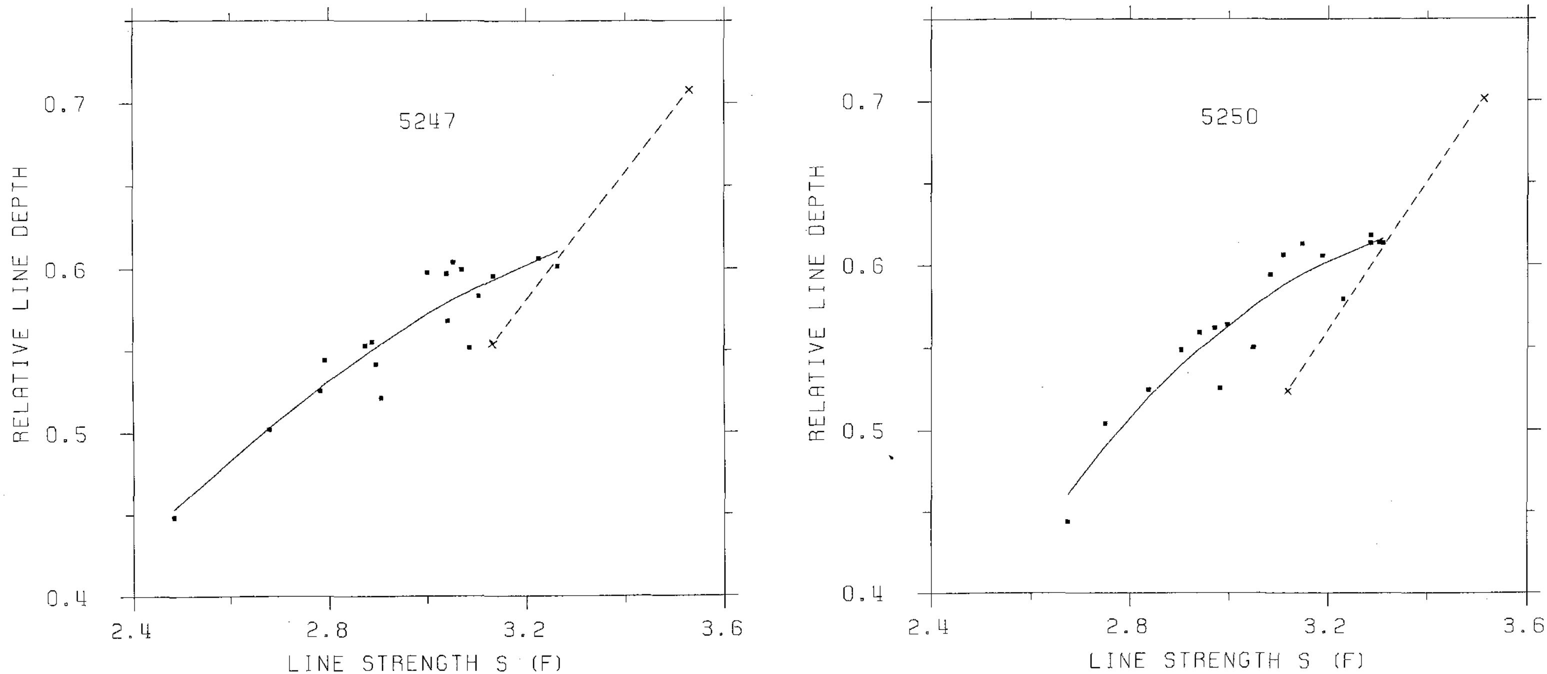

Fig. 10. Relative line depth vs line strength S (F), for the 5247 (left diagram) and the 5250 Å (right diagram) lines. Filled squares and solid curve (cubic spline fit): spectrometer data. Crosses and dashed line: FTS data.

area factors (upper right portion of the curves in the diagrams), they increasingly disagree when the magnetic flux is increased (lower left portion of the curves). This is an effect of the difference in Landé factor. The larger Zeeman splitting of the 5250 Å line contributes to enhancing the line strength (magnetic intensification), and pushes the points to the right in the diagram with respect to the corresponding points for the 5247 Å line. Such a comparison of a line pair makes it possible to separate the thermal fluxtube effects from those due to the Zeeman splitting.

The observed changes of the unpolarized line profiles provide additional constraints on the fluxtube models, partly independent of the polarization information. A more detailed interpretation of the material presented is however outside the scope of the present paper.

4. Conclusions

We observed the Stokes I and V profiles of the 5247 and 5250 Å lines formed in magnetic fluxtubes near disk center and interpreted the measurements in terms of a simple, two-component model atmosphere. The magnetic field is assumed to be constant and vertical across a fluxtube so that area factor, α, average magnetic field strength, $\langle B \rangle$, and circular polarization strength, V, are linearly proportional to each other. If the intrinsic magnetic field were weak, the ratio of $V(\Delta\lambda)$ for 5250 to 5247 Å would be 1.5. Instead, we find a considerably smaller value that indicates an intrinsically strong field (~ 1 kG) within fluxtubes. The discrepancy from the weak field case is, to a first approximation, independent of flux or area factor, supporting the concept of unique fluxtube properties. To a second approximation, however, and after allowance for limited spectral resolution and significant spectral scattered light, there seems to be an increase of B by about one hundred G when α varies by a factor of 6.

Measurements of the wavelength of the zero crossing of the Stokes V profile relative to the center of the I profile show smaller apparent downdrafts than previous results. The reason for this seems to be the superior spectral resolution of the present results combined with a persistent asymmetry of the V profiles. After a somewhat uncertain correction for convective blue shift of the I profiles, we find no clear evidence for net downdrafts within fluxtubes. The asymmetry of the V profiles is always in the same sense: The polarization amplitude in the blue line wing is always larger than that in the red wing by about 20–30%. This asymmetry cannot be explained within the framework of magneto-hydrostatic fluxtube models, but requires correlated height gradients of the vertical velocity and magnetic field.

Although there may not be systematic downdrafts *within* the fluxtubes, it is quite clear from previous investigations that downdrafts are statistically *associated* with fluxtubes. As a matter of fact this type of velocity structure can explain the large discrepancy between observations and model in Figure 3 of Frazier and Stenflo (1978). Their observations showed the same velocity-magnetic field regressions in the 5247 and 5250 Å lines, which can only occur if the entire downdrafts take place in the *field-free* region adjacent to the fluxtubes. The velocity cross section that was used in their model, however, implied a downdraft maximum at the center of the fluxtube. Therefore their model was unable to reproduce the velocity data. A determination of the true nature of velocities within fluxtubes is however beyond the scope of the present paper.

Due to an as yet unidentified calibration error, the polarization values given are probably too small by a factor of two. Accordingly one has to be careful in converting the polarization amplitudes to area factors. Scale errors however do not affect the line-ratio technique, and do not cause differential effects, like Stokes V asymmetries. If the asymmetry were due to some instrumental distortion, it would be in the opposite sense when the magnetic polarity is reversed, but our data show that the asymmetry is polarity independent.

The line depth, d, and line strength, S, of the unpolarized Stokes I profiles are strongly decreasing functions of increasing α. This suggests that searches for magnetic fields on other stars similar to the Sun should employ line depth and strength variations as well as line width variations.

The comparison between the results with the FTS and the grating spectrometer has demonstrated the large effects due to limited spectral resolution and straylight in spectrometer observations. Accordingly it would be important to use the FTS more extensively as a polarimeter, for the sampling of Stokes profiles in various types of regions on the Sun. This would provide us with 'clean' statistical material free from instrumental effects (apart from instrumental polarization), which would help us to find out how unique the fluxtubes really are (i.e., how large the intrinsic solar spread of the values around the various relations we have studied here really is).

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