STRUCTURE OF MAGNETIC FLUXTUBES AS DERIVED FROM OBSERVATIONS OF MODERATE SPATIAL RESOLUTION

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1. *INTRODUCTION*

The small scale structure of the magnetic field outside sunspots has been extensively studied over the last two decades, but progress has often been slow due to the small size of these structures, usually referred to as magnetic elements or fluxtubes. The diameters of most of them are known to be smaller than the best presently available spatial resolution of approximately 0.3″ (Ramsey *et al.* 1977). Although this property presently limits the success of direct methods of study (i.e. methods which attempt to spatially resolve the structures), it has stimulated the development of a number of powerful indirect (i.e. spectral) techniques. Almost without exception these methods rely on observations of the Stokes parameters, in general Stokes V. Therefore, before continuing, the Stokes parameters shall be described briefly.

A system of four quantities is required to describe light in an arbitrary state of polarization. An example of such a system are the four Stokes parameters I, Q, U, and V. Stokes I is the total intensity and can be measured without any polarization analyzing equipment, while

$$
\begin{aligned}
Q &= I_{\rm lin}(\varphi = 0) - I_{\rm lin}(\varphi = \pi/2), \\
U &= I_{\rm lin}(\varphi = \pi/4) - I_{\rm lin}(\varphi = 3\pi/4), \\
V &= I_{\rm circ}(\text{right}) - I_{\rm circ}(\text{left}).
\end{aligned}
$$

In the above equations $I_{\rm lin}$ denotes the intensity of linearly polarized light with azimuth φ, defined by the direction of the analyzer, while $I_{\rm circ}$ is the intensity of circularly polarized light.

Fig. 1 shows I, V, and Q of the Fe I 5250.2 Å line observed in an active region at $\mu = 0.28$ ($\mu = \cos\theta$ is the cosine of the heliocentric angle). This is just a small section of a much larger spectrum containing thousands of lines, which was obtained with a Fourier transform spectrometer (FTS). V is proportional to the line of sight component of the magnetic field, while Q and U increase as the magnetic field component perpendicular to the line of sight increases. Of great importance, as far as their diagnostic capabilities are concerned, is the fact that whereas Stokes I has contributions from both inside and outside the fluxtubes (since they cover only a small percent of the observed area, this means that I is formed mainly in the non-magnetic atmosphere), Q, U, and V are formed exclusively inside the magnetic elements. Therefore, by observing in polarized light, we can isolate the contribution from the fluxtubes even with moderate spatial resolution.

2. *COMPARISON OF DIFFERENT OBSERVATIONAL AND ANALYSIS PROCEDURES*

Ideally, observations should combine high spatial, temporal, and spectral resolution, and cover a large spatial, temporal, and spectral range simultaneously in all four Stokes parameters. In reality, due to the limitations set by seeing and instrumentation and in order to reach a reasonable signal to noise ratio, compromises have to be made. Therefore, two main types of observational polarimeter data exist. Firstly, those with high spatial and temporal resolution (both are required simultaneously due to the everchanging seeing) and one or two spatial dimensions, but with only very limited spectral information (magnetograph type, or spectra in one, or at the most a few

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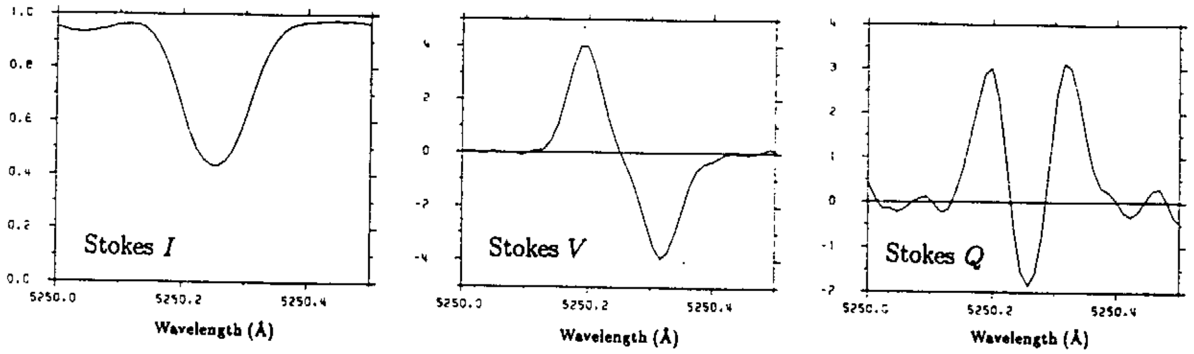


Fig. 1: Stokes I, V, and Q profiles of Fe I 5250.2 Å observed with an FTS in an active region plage at $\mu = 0.28$.

TABLE 1

	High spatial resolution in one spectral line	*Low spatial resolution FTS spectrum*
Internal horizontal variation of fluxtube parameters	NO (later ?)	PERHAPS[1]
Height variation of fluxtube properties	PERHAPS[2]	YES
Range of fluxtube properties	YES (between individual fluxtubes)	YES (between regions of varying α)[3]
Interaction of fluxtubes with their surroundings	YES (direct)	YES (bisectors)
Fluxtube diameters	YES ?	PERHAPS (indirect)[4]
Evolution of fluxtubes (lifetimes)	YES ?	NO
Waves, oscillations etc.	5-minutes: YES Rest: PERHAPS	YES (line widths)
Geometry	YES (model dependent)	Average: YES Individual: NO
User friendliness for quantitative interpretation	Modeller's nightmare, but doable[5]	Fodder for Ph.D. students

spectral lines). Secondly, those with high spectral resolution and a broad spectral range but with only moderate spatial and temporal resolution (as obtained for example with an FTS). Of course observations with properties intermediate to these two extremes exist as well.

Table 1 contrasts the two types of data to each other. Note that the table is based on present capabilities, and that future data or analysis procedures may be able to realise things now seemingly impossible. In the following a few remarks to the table are listed.

[1] The observation that the IR line Fe I 15648.5 Å has a Stokes V profile whose σ components are much broader than the complete I profile, may be due to a range of field strengths distributed horizontally across the fluxtube diameter (Stenflo *et al.* 1986b). However, at present this is not

the only possible explanation and much more work is required to decide this point.

[2] It may be possible to obtain information on the Height variation of fluxtube properties from observations at various distances from the limb, or by comparing IR with visible observations, etc.

[3] α is the filling factor.

[4] It may be possible to determine diameters of fluxtubes with low resolution data off disk centre when 2-D models are used, since the line profiles may depend strongly on the fluxtube diameter and angle of inclination (cf. Van Ballegooijen, 1985b).

[5] The work of Brants (1985a, b) is a good example of how such data can be quantitatively interpreted.

As is nicely illustrated by Table 1, we need both high and low resolution data in order to obtain a maximum of information on the fine scale structure of solar magnetic fields. We may also generalize from the table that high spatial resolution methods give information on the distribution, morphology, and evolution of magnetic features, while the low resolution spectra are more useful for determining their internal structure.

For the rest of this review we shall concentrate on data with moderate spatial resolution and on the internal structure of fluxtubes derived from such data. We shall also restrict ourselves to the solar photosphere. Some of the applications and limits of data with high spatial resolution are discussed by Title (1986) and Wiehr (1986). The raw data alone are not very useful, since the information, although present, is usually well concealed. The vital next step is therefore to consider the type of analysis to be carried out with such data. Once more there are basically two approaches. We shall call them the 'few line analysis' (using typically 1–10 spectral lines) and the 'many line analysis' (ideally involving hundreds of different spectral lines). The advantages and disadvantages of these two techniques are summarized in Table 2. From this table it is clear that the two analysis procedures complement each other, and should, if possible, both be used to make the maximum out of a given data set.

3. MAGNETIC FIELD

It is now observationally well established that the magnetic field in fluxtubes has a value of 1–2 kG at the level at which photospheric spectral lines are formed. First indications of a concentration of magnetic fields into smaller structures were found by Sheeley (1966, 1967) who observed fields ranging from 200 to 700 G in both active and quiet regions by direct high spatial resolution measurements of Stokes V. Using the same technique, Beckers and Schröter (1968a) found field strengths of the order of 600–1400 G in active regions. With the help of the line ratio of Fe I 5250.2 Å to Fe I 5232.9 Å, Howard and Stenflo (1972) and Frazier and Stenflo (1972) showed that over 90% of the magnetic flux was concentrated into strong fields, although they could not give a specific number for the field strength. Stenflo (1973), from the line ratio of Fe I 5250.2 Å to Fe I 5247.1 Å, discovered that the field strength of the strong field flux was of the order of 1–2 kG everywhere. For a horizontal field distribution in the shape of a Gaussian, the peak value turned out to be close to 2000 G. These observations were confirmed by Harvey and Hall (1975) (see also Harvey, 1977), who determined a field strength of 1200–1700 G directly from the splitting of the $g = 3$ Fe I 15648.5 Å line in the infrared (IR).

Tarbell and Title (1977) also derived fields ranging from 1000 G to 1800 G from Fe I 5250.2 Å, via a single line technique based on the Fourier transform of the line profile (see also Title and Tarbell, 1975 and Tarbell and Title, 1976). The line ratio technique of Stenflo (1973) was extended by Wiehr (1978) to include three spectral lines, and resulted in field strengths of 1500–2200 G for the high excitation lines Fe I 6302.5 Å. 6336.8 Å, and 6408.0 Å. From a statistical analysis of a large number of Fe I lines Solanki and Stenflo (1984) were able to isolate the influence of the Zeeman effect on their widths and depths. They found values of the field in the range 1400–1700 G. By determining the line ratio 5250/5247 for regions of different magnetic flux, Stenflo and Harvey (1985) discovered a weak dependence of the field strength on filling factor, with the field strengths being roughly 800–1000 G in the quiet network and 1100–1200 G in active region plages near disk centre. Finally Stenflo *et al.* (1986b) showed that the field strength decreases continuously with height from approximately 1400 G at the height at which Fe I 15648.5 Å is formed (somewhere near $\tau = 1$) to approx 1100 G at

TABLE 2

Few Line Analysis:

Advantages	Disadvantages
Coverage of many μ positions and α values. Short integration times $\Rightarrow$ also usable for observations with good spatial and temporal resolution.	The height variation of fluxtube properties is often not determinable.
No Fourier transform spectrometer is required. It is ideal for telescopes at Tenerife and La Palma.	Results are often model dependent. One line parameter may depend on many fluxtube parameters.
Empirical model calculations require little computer time. In particular 2-D models with many lines of sight can be calculated.	Results might depend on the lines chosen, due to blends, or because the chosen lines may be insensitive to the desired fluxtube parameters.

Many Line Analysis:

Advantages	Disadvantages
Detailed dependence on the spectral parameters (line strength, excitation potential, etc.) can be studied and the dependence of fluxtube properties on height determined.	Large data flow and long integration times. Few μ and α values can be sampled. Low spatial and temporal resolution.
Blends are no problem, since they only increase the scatter in the data.	A Fourier transform spectrometer (or an Echelle grating) are required.
With a regression analysis the influence of the different physical quantities can be partially separated. Leads to a certain model independence.	Empirical model calculations eat up immense amounts of computer time and force restrictive assumptions on the modeller.

the height of formation of Fe I 5250.2 Å (in the vicinity of $\tau = 10^{-2}$). However, they could not, in the framework of their simple analysis, give the true geometrical height scale needed for a proper comparison with theoretical models.

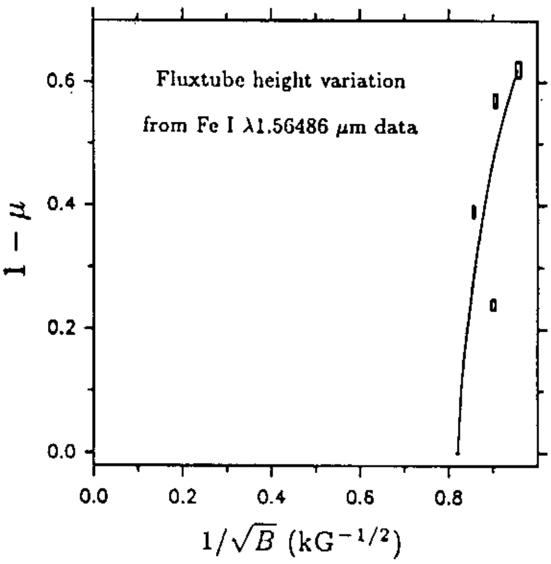
Fig. 2 shows the variation of fluxtube cross-section with height, as determined from the IR line, in somewhat unnatural units. $1/\sqrt{B}$ is proportional to fluxtube radius if we assume flux conservation with height and a horizontally constant field within the fluxtube, while $1 - \mu$ is a measure of height in the atmosphere, since lines are in general formed at greater height near the limb.

To obtain more quantitative information, we need more and better model calculations. Much of the work described above is based on calculations using the simple analytical Unno (1956) theory of line formation in a magnetic field, or even more primitive models. We therefore require numerical radiative transfer calculations, for example of the line ratio of 5250/5247 using the best presently available empirical fluxtube models, including velocity broadening of the lines and, wherever known, the inclination of the magnetic field. Finally, we refer the interested reader to the fine reviews by e.g. Harvey (1977) and Stenflo (1978), which contain more detailed discussions of the measurement of solar magnetic fields.

4. *TEMPERATURE*

A decade after the discovery of a decrease in the line depths of Fe I Stokes I profiles

Fig. 2: Height variation of fluxtube radius, as determined from the centre to limb variation of the field strength B resulting from the splitting of Fe I 15648.5 Å (cf. text for more details).



in faculae (so called 'line gaps') by McMath *et al.* (1956), Sheeley (1967) showed that the magnitude of this line weakening is correlated with the amount of magnetic flux. Chapman and Sheeley (1968) conclusively evinced that it can only be explained by a higher temperature in the magnetic elements. Harvey and Livingston (1969) used the ratio of the Stokes V profiles of Fe I 5250/5233 to determine the 'true' line weakening in fluxtubes, unaffected by the limited spatial resolution. This early work was mainly aimed at establishing the temperature at a single height in the atmosphere. Most of the later effort, as far as fluxtube temperature is concerned, has focussed on models of $T(\tau)$, i.e. the dependence of temperature on optical depth. In the following, a number of these so-called facular models are listed. They can be divided into two main families, the one-component models, which give the average temperature structure of faculae, and two-component models, which differentiate between the fluxtubes and their surroundings, supposing fluxtubes to cover a fraction α of the surface and the non-magnetic surroundings the rest, i.e., $1-\alpha$. Since α is usually small, the two-component models come much closer to describing the internal temperature of fluxtubes than the single-component ones, and we shall therefore only review the former.

The two-component models can be further subdivided into three main classes according to the type of data they are based on. A first class of models is derived from the centre to limb variation (CLV) of continuum intensity. Examples of such models are those of Rogerson (1961), Chapman (1970), Wilson (1971), Muller (1975), and Hirayama (1978). A second class of models is based mainly on the Stokes I profiles of usually a few spectral lines. Sometimes these models have also additional constraints imposed by continuum data (e.g. the continuum contrast at disk centre). Examples are the models of Chapman (1977, 1979), Koutchmy and Stellmacher (1978), Stellmacher and Wiehr (1979), and Walton (1986). The model of Stellmacher and Wiehr (1979) is actually a three-component model, since it differentiates between granule centres and intergranular lanes in the non-magnetic atmosphere. Walton's models include the effects of fluxtube expansion and the possible presence of more than one fluxtube along the line of sight when observing away from disk centre. Finally, there are the models of Stenflo (1975) and Solanki (1984, 1986), which are based on an analysis of Stokes V profiles.

In Fig. 3 we plot $T(\tau)$ of some of the models listed above. As a glance at the figure shows, there appears to be no consensus among the empirical modellers regarding the fluxtube temperature. The differences in $T(\tau)$ are mainly due to the differences in data that the various models are based on. The latest additions to this series of models are shown in Fig. 4 (Solanki, 1986). These models are based on the Stokes V profiles of a large number of Fe I and II lines. They are also compatible with the disk centre continuum contrast results of Muller and Keil (1983) for the network, and Frazier and Stenflo (1978) for active plages.

As visible from the figure, different models have been derived for the fluxtubes in active region plages

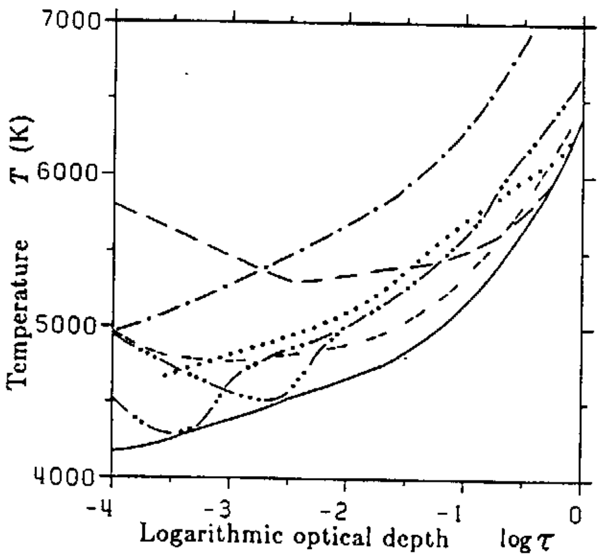


Fig. 3: Temperature T vs. optical depth at 5000 Å, τ_{5000}, of the quiet sun model HSRA (Gingerich *et al.* 1971) and of a number of fluxtube models. HSRA: solid line, Stenflo (1975): -- --, Hirayama (1978) model Z: · · · · ·, Chapman (1979): — —, Stellmacher and Wiehr (1979): — · —, Solanki (1984) model 6K: — · · —, model 6P: — · · · —.

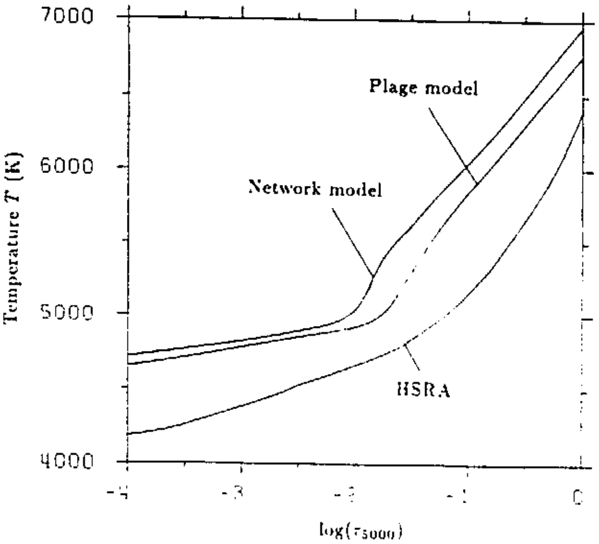
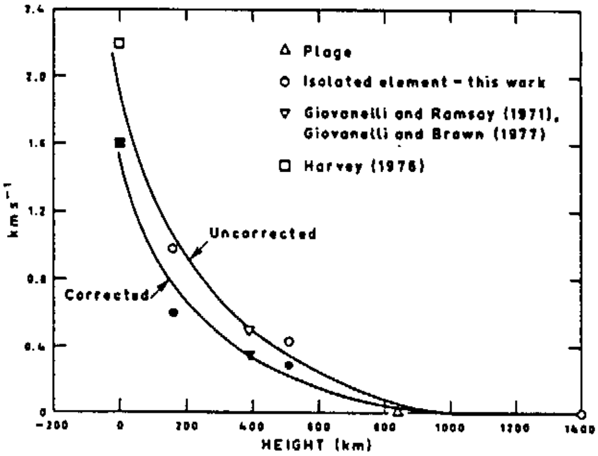


Fig. 4: T vs. τ_{5000} of the HSRA and a model each for network and plage fluxtubes, as derived from Stokes I and V data obtained with an FTS.

and in the quiet network, with the network model being hotter in its lower layers. This difference in temperature structure is suggested by our FTS data, which, however, only covers a few regions on the sun. A much larger sample of regions with different α is therefore required to test whether this difference in temperature is a universal property or not.

Each model depends critically on the data it is based on. As far as determining the internal structure of fluxtubes is concerned, both continuum contrast and Stokes I data have the disadvantage that the filling factor is a completely free parameter, and the empirically determined temperature structure depends critically on the value assumed for it, as has been shown by Walton (1986). In this respect the models based on Stokes V have a distinct advantage. However, in every model calculation assumptions, of often quite a drastic nature, have to be made. All empirical models so far assume LTE, most are only one-dimensional as well. So far only the models of Solanki (1986) take the quite sizable velocity broadening of the spectral lines inside the fluxtubes into account. An additional limitation is that the data the models are based on often cover only a limited height range, so that the temperature over some portion of τ only reflects the taste of the modeller. We can therefore safely conclude that the real temperature structure in fluxtubes may differ considerably from the temperature of the present generation of models in some layers.

Fig. 5: Downflow velocity, determined from the wavelength shift of Stokes V relative to I, as a function of height in the non-magnetic atmosphere (from Giovanelli and Slaughter, 1978). The upper curve represents the original data, the lower curve is obtained after subtracting the Stokes I blueshift due to granulation.



5. *DOWNFLOWS*

A correlation between magnetic fields and redshifts in Stokes I has been observed by many investigators (mostly with a Babcock type magnetograph used to measure the shift in the line wings) and has generally been interpreted as representing a downflow in the magnetic elements. A few random examples of such investigations are: Beckers and Schröter (1968a, b), Frazier (1970), Howard (1971), Simon and Zirker (1974), Skumanich *et al.* (1975), Tarbell and Title (1977), and Frazier and Stenflo (1978). The last mentioned authors suggest, via an indirect argument, that the downflows may be concentrated outside the magnetic elements themselves. Recent observations of full Stokes I line profiles in network and active regions by Miller *et al.* (1984) and Cavallini *et al.* (1984, 1986a, b), find no evidence for true downflows greater than 0.1 km sec^{-1}.

There have also been a number of measurements of the shifts of Stokes V, with varying results. Such investigations can be roughly divided into three camps. Those which show downflows, those which rule out downflows, and those which are inconclusive.

The observations of Giovanelli and Ramsey (1971) with the line centre magnetogram technique (LCM, which relies on the fact that for an antisymmetric V profile the signal from a single-slit magnetograph disappears when the slit is centred at the zero-crossing wavelength of the line), of Harvey (1977) of the zero-crossing wavelength of the IR line at 15648.5 Å, Giovanelli and Brown (1977) and Giovanelli and Slaughter (1978), both with the LCM technique, and most recently of Wiehr (1985) of the full line profile of Fe I 8468.4 Å show zero-crossing shifts of photospheric lines ranging from approximately 0.5 km sec^{-1} to over 2 km sec^{-1} with respect to Stokes I.

Fig. 5 shows the height dependence of the downflow velocity as derived from different lines by Giovanelli and Slaughter (1978). Of interest is the lower curve, which is obtained after correcting for the blueshift of Stokes I induced by the correlation of brightness and velocity in the granulation (Dravins *et al.* 1981, 1986). It is very difficult to explain the increase of the velocity with depth theoretically. From mass-conservation one would expect a decrease in velocity with depth due to the exponential increase in density, even for fluxtubes which flare out rapidly with height. As has been pointed out by Hasan and Schüssler (1985) and Schüssler (1986a), inflow of matter near the temperature minimum cannot explain these observations.

On the other side of the fence we have Stenflo and Harvey (1985), who have observed the V profiles of 5250 and 5247 for regions with varying α, Brants (1985b), who has analysed high spatial resolution spectra of Fe I 6302.5 Å, Solanki (1986) who has determined the shifts of hundreds of Fe I and II Stokes V profiles, and Stenflo *et al.* (1986a), who have studied the CLV of four lines near 5250 Å. These authors find no evidence for downflows greater than 0.2 km sec^{-1} inside magnetic fluxtubes from the difference between V and I wavelengths, after correcting for the Stokes I blueshift. In addition, Solanki (1986) has determined the Stokes V wavelength shifts relative to a laboratory wavelength scale. In Fig. 6 $v_V = c(\lambda_V - \lambda_{\rm lab})/\lambda_{\rm lab}$, the absolute shift of Stokes V (corrected for the different components of the motion between the observer and the observed solar region), is plotted

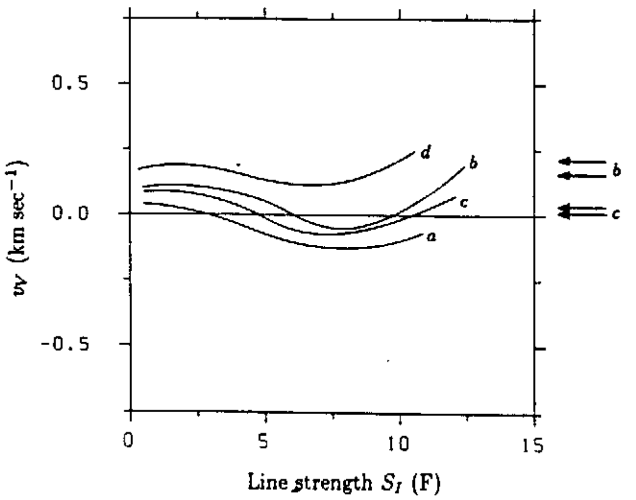


Fig. 6: Downflow velocity, v_V, as determined from the absolute wavelength shift of Stokes V vs. line strength, S_I, defined as the area of the lower half of the line. Plotted are the smoothed mean curves of the Fe I lines observed in two active region plages and in two network elements. The arrows denote the v_V values of the Mg I b lines at 5172.7 Å and 5183.6 Å in two of the regions.

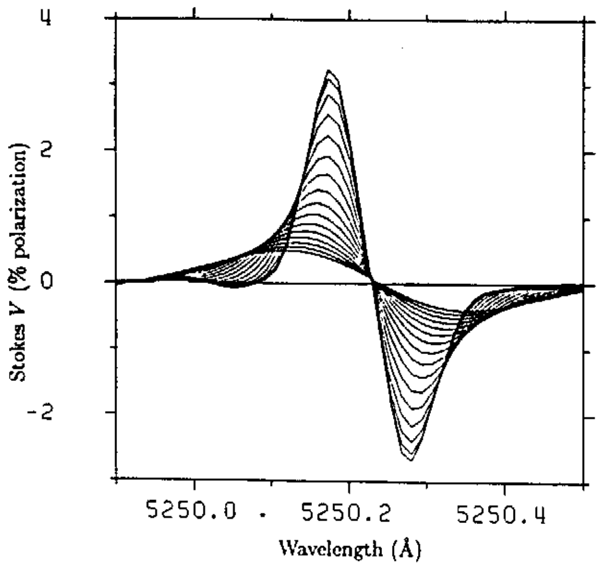
against the line strength, S_I, defined as the area of the lower half of the spectral line. Each of the curves in the figure represents the smoothed mean of the v_V values of the 150-200 Fe I lines in the spectrum of a particular region (marked by the letters a, b, c, and d respectively). The absolute accuracy of v_V is approximately 0.25 km sec^{-1}. Also indicated by arrows to the right of the figure are the v_V values of the Mg Ib lines at 5172.7 Å and 5183.6 Å for two regions. These observations are easily consistent with the sometimes quite large flows observed in the transition zone above photospheric active regions (10–20 km sec^{-1}, e.g. Dere *et al.*, 1981; Feldman *et al.*, 1982), even in the presence of magnetic canopies, whose presence has been reported by Giovanelli (1980), Giovanelli and Jones (1982), and Jones and Giovanelli (1983). See also the review by Jones (1985).

Finally, in the third camp, Scholier and Wiehr (1985) find that the Fe I 6301.5 and 6302.5 Å V profiles show sizeable redshifts in three regions and a blueshift in only one region. However, according to Pahlke and Wiehr (1986) the analysis of an additional seven regions results in an average shift of almost exactly zero relative to Stokes I for both lines. The other measurement which is inconclusive regarding the presence of downflows is the CLV of the zero-crossing of the IR-line at 15648.5 Å, which is redshifted by approximately 1 km sec^{-1} with regard to Stokes I (Stenflo *et al.* 1986b). Due to the absence of measurements of the absolute Stokes I wavelength it has not been possible to determine whether this redshift is due to a downflow in the fluxtube or if it is simply an artifact caused by a large convective blueshift of Stokes I. That the second explanation may be correct is suggested by the fact that the convective blueshift of Stokes I increases rapidly with increasing depth of formation of the line (Balthasar, 1985), and the IR line is formed at a level where the blueshift may approach 1 km sec^{-1}. However, measurements of the absolute shifts of either Stokes I or V in the IR region around 1.6μ are of critical importance to settle this question.

How can the differences between all these observations be reconciled? The interpretation proposed by Miller *et al.* (1984) for the Stokes I profiles is that no real downflows are present but rather the strength of the convection is reduced by the magnetic field. This leads to a decrease in the curvature of the line profile, so that measurements in the line wings (e.g. with a Babcock type arrangement) will lead to an apparant downflow. This interpretation is supported by the analysis of Cavallini *et al.* (1986a,b), who are able to reproduce the shapes and wavelengths, measured in an active region, of the line bisectors of three lines around 6300 Å by assuming no downflows in both the fluxtubes and their surroundings. They only assume an inhibition of convection in the surroundings. They are not able to reproduce their observations if they assume a downflow inside the magnetic elements.

The discrepancies between the observed Stokes V zero-crossing wavelength shifts may possibly be due to differences in the *spectral* resolution of the various measurements. A limited spectral resolution, when combined with the asymmetry of Stokes V (blue amplitude and area larger than red amplitude

Fig. 7: Stokes V profile of Fe I 5250.2 Å for different amounts of spectral smearing. The highest and narrowest profile is taken from the original FTS data. The other profiles have been convoluted with increasingly broader Gaussians representing instrumental smearing. The broadest Gaussian has $v = 150$ mÅ, where v is the e–folding width ('Doppler' width).



and area, cf. Sect. 7) gives rise to a fictitious redshift, as has been shown by Solanki and Stenflo (1986).

A simulation of how spectral smearing affects Stokes V is illustrated in Fig. 7, where the Stokes V profile of Fe I 5250.2 Å, observed in an active region plage with very high spectral resolution (the highest and narrowest profile in the figure), is plotted along with the same profile smeared with a Gaussian apparatus function having a 'Doppler width' $v = 10, 20, 30, \ldots, 150$ mÅ. Some of the effects of the smearing are clearly visible from the figure. The amplitude and area of each wing decreases, but also the zero-crossing wavelength shifts towards the red. Solanki and Stenflo (1986) were able to reproduce the magnitudes of the Stokes V shifts observed by various authors with the help of this effect, if they used the appropriate instrumental parameters.

6. *NON-STATIONARY VELOCITIES*

Although there are strong theoretical grounds for expecting non-stationary velocities to be present in fluxtubes, only a limited observational base for their presence exists at present. Tanenbaum *et al.* (1971) saw an oscillation of five minute period in the magnetic flux from an active region, when observing in the wings of Fe I 5250.2 Å with a Babcock type magnetograph. However, oscillations in velocity, temperature, or magnetic field may all contribute to the observed effect, so that the diagnostic potential of such an observation alone is quite limited. Using time series measurements with the LCM technique (cf. Sect. 5), Giovanelli *et al.* (1978) showed that 5-minute oscillations in the velocity are present in Stokes V with an amplitude of approximately 0.25 km sec^{-1} in photospheric lines. Wiehr (1985) also observed oscillations of a similar period and amplitude, in addition to some time dependent shifts and changes in the amplitude of Stokes V whose origin is not clear.

The widths of the I profiles inside the fluxtubes can also give information on the amplitudes of non-stationary motions. (A spatial resolution independent approximation of the I profile inside fluxtubes can be obtained by integrating Stokes V. See Solanki and Stenflo, 1984, 1985 for more details). Their analysis has yielded that unresolved motions with large amplitudes are present in fluxtubes (Solanki, 1986). However, in this manner, no direct information is obtainable on whether such motions are due to, e.g., oscillations, waves, or a mixture of up and downflows in different fluxtubes. Nor can anything be said on the frequencies or phases of such motions.

Fig. 8 shows the approximate velocity amplitudes derived by assuming macroturbulence to be the main broadening mechanism. It should, however, be noted that this is simply a convenient way of determining the velocity amplitude and does not imply the presence of truly turbulent motions

Fig. 8: $\xi^V_{\rm mac}$, the macroturbulence velocity inside fluxtubes, as derived from the integrated V profile vs. S_I. Microturbulence $\xi_{\rm mic} = 0$ is assumed. The curves represent both network and plage data. The $\xi^V_{\rm mac}$ values derived from Fe I lines with $\chi_e < 3$ eV are denoted by the solid curve, the $\xi^V_{\rm mac}$ values derived from Fe I, $\chi_e \geq 3$ eV lines by the dashed curve, and $\xi^V_{\rm mac}$ from Fe II by the dot-dashed curve. The Fe II curve is dotted between $S_I = 5$ and 9 F to indicate that it is interpolated in that region.

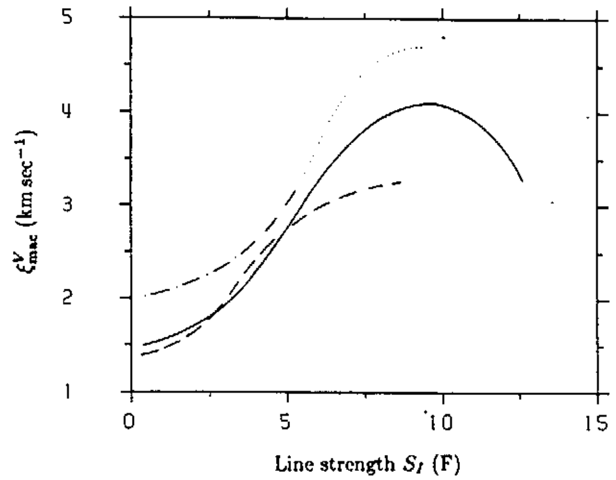
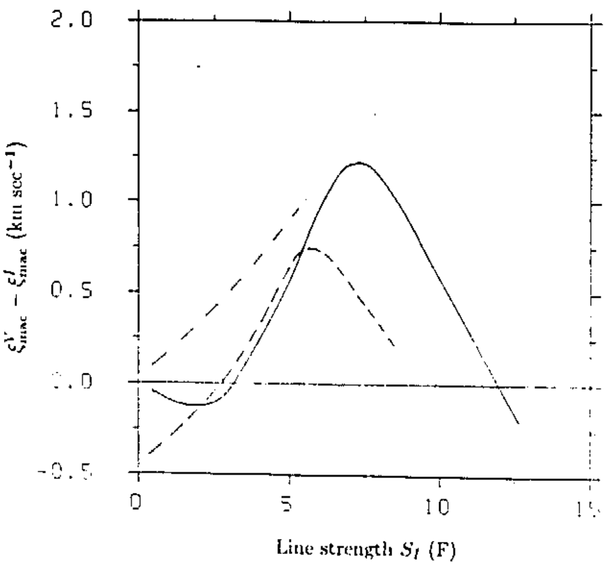


Fig. 9: $\xi^V_{\rm mac} - \xi^I_{\rm mac}$ vs. S_I, i.e. the macroturbulence excess in fluxtubes (from Stokes V data), as compared to the quiet sun (from Stokes I data). Symbols are the same as in Fig. 8.



inside fluxtubes. $\xi^V_{\rm mac}$ is the 'Doppler' width of the Gaussian macroturbulence distribution, S_I is the line strength. The solid curve represents Fe I lines with excitation potential $\chi_e < 3$ eV, the dashed curve Fe I lines with $\chi_e \geq 3$ eV and the dot-dashed curve Fe II lines (the dotted part of this curve indicates that no suitable Fe II lines are available in the given S_I range). Maximum $\xi^V_{\rm mac}$ values of 4-5 km sec^{-1} are derived. Note that the rms velocity is a factor of $\sqrt{2}$ smaller than $\xi^V_{\rm mac}$.

In Fig. 9, the difference, $\xi^V_{\rm mac} - \xi^I_{\rm mac}$, between the velocity amplitudes derived from Stokes V (fluxtubes) and Stokes I (observed in the quiet sun), is plotted vs. S_I. It is clear that the velocity amplitudes are in general larger for the fluxtubes than for the quiet sun.

The obvious question is, why do the line widths give such large velocity amplitudes while direct observations of time dependent Stokes V shifts give at best only equivocal evidence for any motions besides low amplitude five-minute oscillations. One possible answer may be that so far such time dependent measurements have not been able to isolate individual fluxtubes. Consequently only the global oscillations in which all the fluxtubes oscillate in phase are observed. Non-stationary motions excited locally in any one fluxtube (e.g. via the mechanism proposed by Hasan, 1984, 1985; or Venkatakrishnan, 1986), will most probably not be in phase with such motions in another fluxtube.

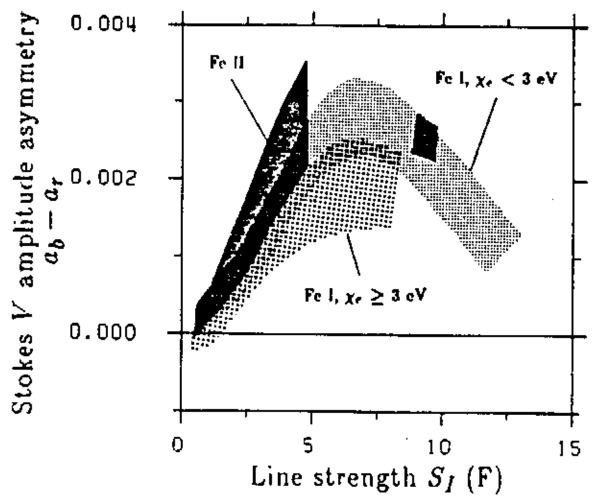


Fig. 10: $a_b - a_r$, the absolute amplitude asymmetry of Stokes V vs. S_I for an enhanced network region. a_b and a_r are the amplitudes of the blue and red wings of Stokes V in units of the adjacent continuum. The differently shaded portions of the figure represent Fe I and II lines of different excitation potential, as marked.

7. *STOKES V ASYMMETRY*

The Stokes V profile in both active region plages and the quiet network is now known to be asymmetric, with the amplitude and area of the blue wing being larger than the amplitude and area of the red wing. This asymmetry has been observed and analyzed by Stenflo *et al.* (1984), Solanki and Stenflo (1984, 1985), Stenflo and Harvey (1985), Wiehr (1985), Scholier and Wiehr (1985) and Stenflo *et al.* (1986a, 1986b). An example of such observations is shown in Fig. 10, where the amplitude asymmetry, $a_b - a_r$, of Fe I and II lines is plotted vs. S_I for an enhanced network region. The lines are grouped according to excitation potential and marked in the figure.

A number of mechanisms have been proposed to produce such asymmetries. Most of these proposals were originally intended to explain the broad-band circular polarization in sunspots observed by Illing *et al.* (1974a, b, 1975) and by Kemp and Henson (1983). However, they can also be applied to the observations outside sunspots. The first proposal was made by Illing *et al.* (1975), who suggested a combination of velocity and magnetic field gradient along the line of sight as the cause. Auer and Heasley (1978) noticed that if the angle between the line of sight and the magnetic field is not zero, then a velocity gradient alone is sufficient. However, a sizeable asymmetry is observed near disk centre, and since fluxtubes are thought to be almost vertical due to buoyancy (Schüssler, 1986a), one would expect this mechanism to play only a limited role, at least near disk centre. Pahlke and Solanki (1986) have shown with the help of model calculations that stationary downflows which reproduce the observed Stokes V asymmetry invariably also result in redshifts greater than approximately 1 km sec^{-1}, contradicting the newer observations of zero-crossing shift in fluxtubes. A steady flow therefore appears to be ruled out as the cause of such asymmetries. A somewhat modified version of the original proposal of Illing *et al.* (1975) was made by Solanki and Stenflo (1984), who suggested that instead of a steady flow an oscillation in velocity (with a height gradient) and a correlation with an oscillation in temperature and/or magnetic field is responsible. This proposal has the advantage that it need not necessarily give rise to large zero-crossing shifts like the steady flow gradient. On the other hand, it has not been worked out in detail yet.

A totally different approach was taken by Kemp *et al.* (1984) and Landi Degl'Innocenti (1985), who proposed that due to the anisotropy of the radiation field in a fluxtube, the different Zeeman sublevels are not equally populated, leading to a Stokes V asymmetry. This process requires that the lines be formed in NLTE and its description is quite involved, being strongly dependent on the details of the atomic transition.

Some indirect evidence exists that Stokes V asymmetry is closely related to the velocity structure inside fluxtubes (Solanki, 1985, 1986). This can be easily seen by comparing Fig. 8 with Fig. 10.

The marked similarity between the two figures suggests some relationship, and indeed the correlation coefficient between ξ^V_{mac} and $a_b - a_r$ is found to be of the order of 0.85. It therefore appears likely that velocity gradients are in some way responsible for Stokes V asymmetry, although it is by no means certain.

Let us summarize our present knowledge of velocities in fluxtubes. We expect no sizeable downflows, and in general only small amplitude 5-minute oscillations. However, motions with large amplitudes and probably a vertical velocity gradient are present in the fluxtubes or their immediate surroundings. The exact nature of such motions is unknown. Candidates are: stationary up- and downflows in different fluxtubes, so that on the average little vertical mass transfer takes place. Oscillations or waves in fluxtubes are another possibility, whereby these motions are not in phase in different fluxtubes. Finally, we should not forget that due to the geometry of the fluxtubes (expansion with height), it is possible that motions in their immediate surroundings may also affect Stokes V.

8. *FUTURE CONSIDERATIONS*

After this brief and incomplete review of the investigations carried out to data, there now follows an attempt at a very subjective preview of some of the work which needs to be done or is in the process of being carried out at the moment. Four main avenues come to mind.

Firstly, more data, both of high and of moderate spatial resolution are required in order to resolve a number of problems. Some examples of open questions which can be addressed with moderate spatial resolution data are listed in the following. *i*) Very little is known of the dependence of most of the fluxtube properties on filling factor α, the position on the solar disk, the age of an active region, the distance from a sunspot, etc.. A large sample of observations will be required to be able to determine these dependences with any measure of certainty. *ii*) The properties of both the deeper and the higher layers of fluxtubes are known only in their rudiments. This problem requires polarimetric data in chromospheric lines and in the IR near 1.6μ. *iii*) The data available to date are usually limited to Stokes I and V, but complete profiles of Stokes Q and U will also be required in future if we want to determine the geometry of the field and resolve the question of a possible inclination of the fluxtubes.

Additional data alone may not be sufficient to answer many of the presently open questions. Better diagnostic techniques are required as well. This is the second avenue which must be followed in future investigations. Although we already possess an impressive array of methods for obtaining information from polarized spectra, much of it is still hidden from us. In particular Stokes Q and U are almost virgin territory as far as fluxtube diagnostics are concerned (some exceptions are to be found in Hagyard, 1985). Besides being absolutely necessary for determining the direction of the field, Stokes Q and U are also capable of serving as diagnostics for the field strength, temperature, and perhaps even velocity inside the fluxtubes. In addition to new techniques, long established methods like the line ratio technique of Stenflo (1973) need to be studied further. In order to improve the diagnostics we also need to know the heights of formation of the spectral lines in fluxtubes. This may be done either with the method of Van Ballegooijen (1985a), or of Wittmann (1973, 1974). Such work is in progress.

So far all NLTE effects have been neglected in empirical models of fluxtubes, but in the long run they will have to be included. A few investigators have attempted to assess the influence of departures from LTE on line profiles in magnetic fluxtubes. Rees (1969) and Domke and Staude (1973) studied the general influence of NLTE on the Stokes profiles in a magnetic field. Later Stenholm and Stenflo (1977, 1978) and Owocki and Auer (1980) concentrated on the effects of 2-D radiative transfer in non-plane parallel geometry, as typifies fluxtubes. They found that 2-D effects can give rise to differences from 1-D profiles. However, Owocki and Auer (1980) showed that 1.5-D radiative transfer (i.e. radiative transfer along many parallel lines of sight, the profiles from all off which are summed to give the resultant) is often a sufficiently good approxiation. Finally, Solanki and Steenbock (1987) use empirical models of the fluxtube temperature and a realistic iron model atom to study departures from LTE and their influence on the empirically determined temperature and velocity.

Finally, future *empirical* models must combine a 2-D MHD model of a fluxtube (without energy equation, e.g. thin tube model, the expansion model of Pneuman *et al.*, 1986, or the exact solution of Steiner *et al.*, 1986) with radiative transfer along many lines of sight (1.5-D). Specially away from disk centre, the effects of limited fluxtube diameter should play a major role. 1.5-D calculations of Stokes I, in conjunction with fluxtube models of varying sophistication, have been carried out by e.g. Chapman (1970), Caccin and Severino (1979), Owocki and Auer (1980), Chapman and Gingell (1984), Deinzer *et al.* (1983, 1984b), and Walton (1986). Only Van Ballegooijen (1985a) has studied the influence of the fluxtube geometry (including expansion, and finite diameter) on all four Stokes profiles. An additional investigation, which compares the Stokes profiles resulting in plane parallel, slab and cylindrical geometry with each other, is in preparation.

However, with increasing sophistication of empirical models, it will become increasingly time consuming to test a sufficiently broad range of parameters. The interpretation of the results will also become increasingly involved. Therefore, radiative transfer calculations in plane parallel atmospheres will still be important when a first idea of the diagnostic contents of the data are required, to separate influences of different physical parameters on the line profiles, or simply when the profiles of a large number of lines have to be calculated. We therefore have a similar situation with regard to empirical models as exists for theoretical models (as has been discussed by Schüssler, 1986a). Simple calculations serve to map the terrain, show which effects are particularly important, and advance the basic understanding of the processes involved. They thus simplify the task of constructing comprehensive and realistic models, which must reproduce a maximum amount of data.

An alternative, and in the future possibly quite promising approach, is to calculate the line profiles resulting from the most comprehensive, self-consistent theoretical models, including an energy equation (e.g. the models of Spruit, 1976; Deinzer *et al.* 1984a, b; Knölker *et al.* 1985, 1986, Nordlund, 1985), and compare with the observations directly. This approach becomes increasingly feasible as the theoretical models continue to improve. See the review by Schüssler (1986b) for comparisons between such models and the observations.

We are now at an exciting stage in the investigation of fluxtubes. Although some progress has been made in recent years, many promising possibilities beckon the enterprising observer, and we can look forward to new discoveries and a better understanding of these structures in the near future.

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