*Proc. Workshop on Theoretical Problems in High Resolution Solar Physics*, Munich, Sept. 16 – 18, 1985.

# HIGH SPECTRAL RESOLUTION AND PROPERTIES OF SMALL MAGNETIC FLUXTUBES

**S.K. Solanki**

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

## Abstract

Some empirical results pertaining to properties of small magnetic fluxtubes are described. Using data obtained with an FTS it has been possible to set constraints on the temperature structure of fluxtubes, on the types of mass motions and velocities inside them, and on the magnetic field strength near their $\tau = 1$ level. The Stokes $V$ asymmetries observed in fluxtube spectra are also discussed and evidence is presented favouring the hypothesis that they are produced by velocities.

**Key words:** magnetic fluxtubes—magnetic field—Stokes parameters

## Introduction

Stokes $I$ and $V$ spectra obtained with a Fourier transform spectrometer (FTS), and having high spectral resolution together with a very broad spectral range, but with low spatial and temporal resolution, have been analysed in an attempt to obtain information on some properties of fluxtubes. The simultaneous measurement of Stokes $I$ and $V$ means that we also have data containing information on magnetic elements alone, which to a large extent overcomes the handicap of low spatial resolution.

Here we shall concentrate mainly on some of the results of this analysis, and shall discuss the applied methods only briefly.

## Temperature, magnetic field, and filling factor

One of the first results to emerge from the comparison of simple models to the data was that the temperature in the lower photospheric layers of network fluxtubes is approximately 400 – 600 K higher than in the same layers of plage fluxtubes.

We have now been able to determine the field strength in fluxtubes using different methods: from the line ratio of Fe I 5250 to Fe I 5247 (described by e.g. Stenflo, 1973), and from the statistical analysis of the line widths and depths of $I_V$ profiles of a large number of iron lines. Solanki and Stenflo (1984) give a detailed description of this method, and also give an exact definition of the $I_V$ profile. Suffice it to say that one obtains it by integrating Stokes $V$ over $\lambda$ and that it is a first order approximation of the Stokes $I$ profile formed inside the fluxtube. Both methods give fieldstrength values of around 1500 G (horizontally averaged across the fluxtube cross-section). It should be noted that the second method does not require the use of model calculations. Stenflo and Harvey (1985) have further shown that this value of the magnetic field strength is practically independent of filling factor.

It has also been possible to determine filling factors, $\alpha$, in a relatively model independent manner by considering many Fe I and II lines simultaneously. We feel it is important to state here that unless the amount of line weakening is known from observations, filling factors derived from the flux measured in a single line (e.g. in magnetograms of Fe I 5250) are extremely uncertain. Unfortunately, the amount of line weakening is itself coupled to the filling factor through the, mostly unknown, dependence of the fluxtube temperature on $\alpha$. Therefore, filling factors determined from only one line should be looked at as very rough estimates only.

## Velocity

So far we have used two methods to obtain velocity information from the Stokes $V$ observations: from the Stokes $V$

---

**Note:** The term 'rms macroturbulence velocity' has been wrongly used in the second paragraph of page 2 and in Fig. 2. The macroturbulence values quoted in the text and shown in Fig. 2 correspond to the $e$-folding width (or 'Doppler width') of the Gaussian macroturbulence profile.

zero-crossing shift and from the width of the $I_V$ profile. The results from the former method show essentially no shifts between Stokes $V$ and laboratory wavelengths for a large number of Fe I and II lines. These are absolute line shifts, determined without comparison with Stokes $I$. The absolute wavelengths were determined by comparing with telluric lines and correcting for the shifts induced by the earth's motion, solar rotation, and gravitational redshift. Both the scatter in the data and the uncertainty in the corrections are of the order of 250 m $\sec^{-1}$. We find no evidence for downflows or upflows larger than this value, as is evident from Fig. 1. There the mean Stokes $V$ shifts of Fe I lines are plotted vs. the line strengths of their Stokes $I$ profiles for four regions of varying filling factor. The shifts of the Mg Ib lines at 5172 Å and 5183 Å are denoted by arrows and also lie within this limit. The fact that the weak iron lines are not redshifted against the simultaneously measured strong Mg Ib lines is completely in contradiction to the results of Giovanelli and Slaughter (1978), who find the weak lines to be redshifted by 400–800 m $\sec^{-1}$ relative to the Mg Ib lines. This contradiction cannot be explained by invoking a mistake in our determination of the absolute wavelength, since it only depends on the relative shifts of lines of different strength.

Although we see no evidence for steady flows inside fluxtubes, models without any velocity have trouble explaining the data. They can either be made to reproduce the depths of the $I_V$ profiles, but then give too small widths, or if they are tuned to reproduce the line widths give completely wrong line depths. If, however, the $I_V$ profiles are broadened with a macroturbulence velocity this inconsistency disappears and both the depths and the widths of the $I_V$ profiles can be reproduced quite well. The rms macroturbulence velocity required can have a maximum value of upto 4-5 km/sec. The run of the rms macroturbulence velocity with Stokes $I$ line strength, for a model which fits our observations of a network region is shown in Fig. 2.

A possible explanation, for both the absence of Stokes $V$ zero-crossing shifts and the presence of line broadening velocities as evidenced by the $I_V$ linewidths, may be given in terms of oscillations or waves inside fluxtubes. A more extensive and detailed account of the work involving Stokes $V$ zero-crossings and macroturbulent $I_V$ line broadenings is in preparation.

## Stokes $V$ asymmetry

One of the most intriguing questions to emerge from our data is related to the sometimes quite large amplitude and area asymmetries present in the $V$ profiles: What causes their blue amplitudes and areas to differ from their red amplitudes and areas. Usually both the blue area and amplitude are larger than their red counterparts. We have gathered extensive observations of the Stokes $V$ asymmetry, and have also determined its dependence on a number of parameters. Thus, we have built up a substantial base of data to be reproduced by any model trying to explain the Stokes $V$ asymmetry. For example, we have determined the dependence of both area and amplitude asymmetry on line strength, excitation potential, Zeeman splitting, $\cos\theta = \mu$ (centre to limb variation), and the filling factor. An unexpected result to turn up in this context is that, although the relative amplitude asymmetry of the Fe I 5250 Å line decreases more or less steadily towards zero as one goes towards the limb, the relative area asymmetry changes its sign, so that near the limb the area of the red wing of Stokes $V$ becomes considerably larger than the area of the blue wing (cf. Stenflo et al., 1986).

Kemp et al. (1984) and Landi Degl'Innocenti (1985, this volume) have invoked atomic orientation to explain the Stokes $V$ asymmetry. Even though this process may play a role in creating the asymmetries, we feel that it will not be the dominant one. Firstly, producing atomic orientation with a radiation field requires it to be highly anisotropic, and secondly, it requires photon scattering to dominate over photon destruction. In other words, it is a process requiring large departures from LTE and one would therefore expect the resulting asymmetry to increase with line strength. However, the observations show that, at disk centre at least, the area asymmetry practically disappears for the strongest lines studied (Solanki and Stenflo, 1984, Fig. 12).

We also have strong indirect evidence from our observations for the hypothesis that mass motions are involved in creating the asymmetries. Fig. 3 shows the absolute amplitude asymmetry plotted vs. the Stokes $I$ line strength, $S_I$, (This is Fig. 3 of Solanki and Stenflo, 1985). Note the similarity between this figure and Fig. 2. Lines having a large asymmetry are also strongly broadened by velocity. This near proportionality between broadening and asymmetry of the $V$ profile strongly suggests that both effects are related, and that mass motions are responsible for both.

However, models involving mass motions also have their problems, and it is probable that simple stationary velocity gradients inside the fluxtube coupled with magnetic field gradients, as were first proposed by Illing et al. (1975) to account for the broadband polarisation of sunspots, will not be able to simultaneously reproduce both the strong Stokes $V$ asymmetry and the absence of a zero-crossing wavelength shift.

## Conclusions

In this paper some of the results to emerge from the analysis of Stokes $I$ and $V$ data have been briefly described. There is still an immense wealth of information locked up in this type of data, specially if one includes linear polarisation and centre to limb variation observations as well. However, these data have considerable limitations too, and in conclusion we would like to mention some of the fluxtube properties which cannot be determined with such observations, but which it may lie within the scope of SOT to obtain.

- Due to the limited spatial resolution of our data, we usually see ensembles of fluxtubes together and thus cannot say how strongly the properties of individual fluxtubes vary from the mean properties we determine.
- Since we cannot resolve individual fluxtubes we cannot say how large their diameters are, nor can we say anything on how different quantities, like the temperature, or the magnetic field, vary horizontally inside them.
- We can only get very limited information on the geometry of the magnetic field, although by including observations of linear polarisation this may be improved.
- Finally, our temporal resolution is too small to allow us to resolve dynamical events in fluxtubes, or to determine their lifetimes.

## Acknowledgements

It is a pleasure to acknowledge the help and guidance of Jan Stenflo. I would also like to thank Bruce Lites for some helpful remarks.

## References

Giovanelli, R.G., Slaughter, C.: 1978, *Solar Phys.* **57**, 255.
Illing, R.M.E., Landman, D.A., Mickey, D.L.: 1975, *Astron. Astrophys.* **41**, 183.
Kemp, J.C., Macek, J.H., Nehring, F.W.:1984, *Astrophys. J.* **278**, 863.
Landi Degl'Innocenti, E.:1985, in *Proceedings of the Workshop on Theoretical Problems in High Resolution Solar Physics*, this volume.
Solanki, S.K., Stenflo, J.O.: 1984, *Astron. Astrophys.* **140**, 185.
Solanki, S.K., Stenflo, J.O.: 1985, *Astron. Astrophys.* **148**, 123.
Stenflo, J.O.: 1973, *Solar Phys.* **32**, 41.
Stenflo, J.O., Harvey, J.W.: 1985, *Solar Phys.*, **95**, 99.
Stenflo, J.O., Solanki, S.K., Harvey, J.W.: 1986, in preparation.

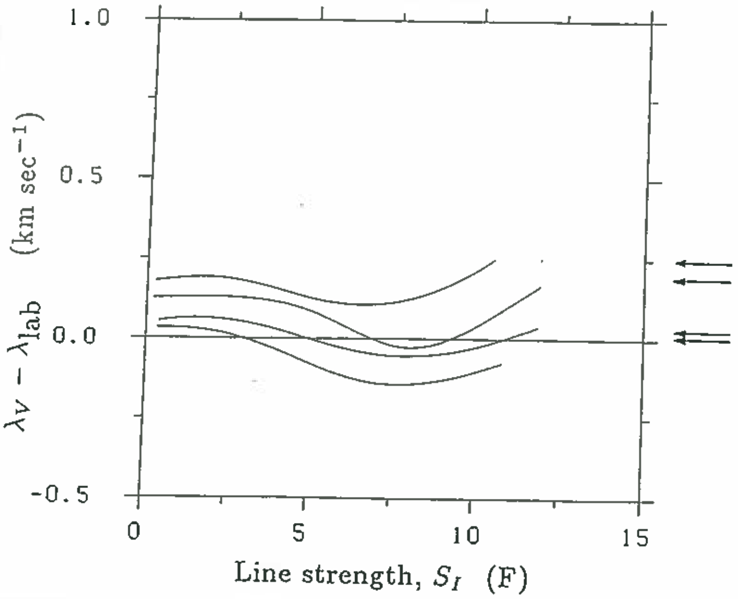

**Fig. 1:** Zero-crossing wavelength shift of Stokes $V$ profiles relative to laboratory wavelength, in km sec$^{-1}$, plotted against Stokes $I$ line strength, $S_I$. Mean curves of Fe I data from four different regions. The arrows denote the Stokes $V$ zero-crossing shifts of the Mg Ib lines at 5172 Å and 5183 Å of the two regions for which their spectral profiles were available.

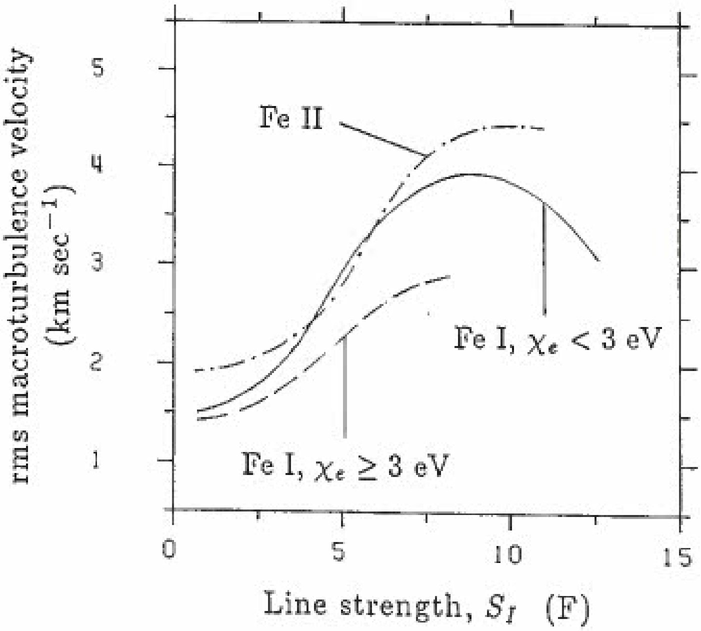

**Fig. 2:** RMS macroturbulence velocity inside the fluxtube, plotted vs. Stokes $I$ line strength, $S_I$. The plotted macroturbulence values were obtained by convoluting calculated iron line profiles with a gaussian macroturbulence distribution and subsequently fitting $I_V$ (integrated Stokes $V$) profiles observed in a network region. The solid curve represents Fe I lines with excitation potential, $\chi_e = 1.5$ eV, the dashed curve Fe I lines with $\chi_e = 4$ eV, and the dot–dashed curve Fe II lines.

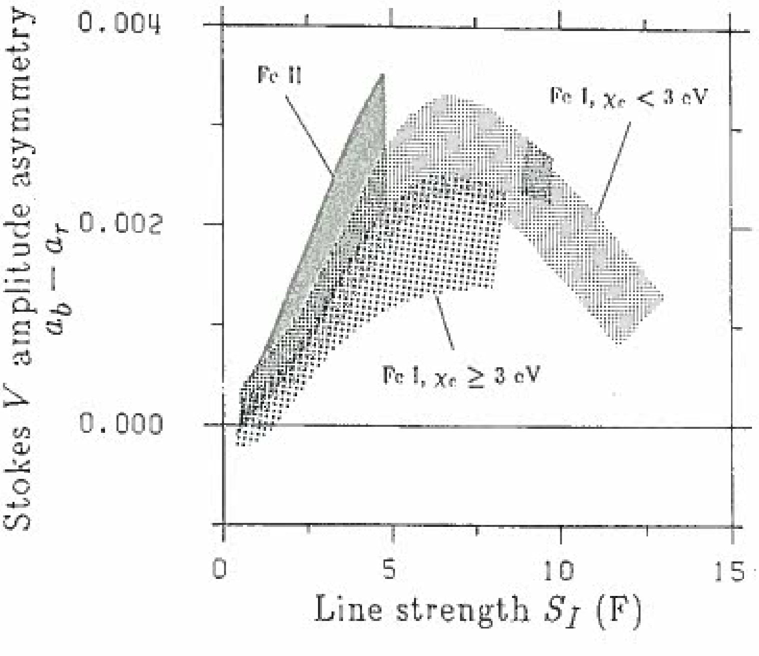

**Fig. 3:** Absolute amplitude asymmetry, $a_b - a_r$, for a network region. $a_b$ and $a_r$ are the amplitudes of the blue and red wings of Stokes $V$ in units of the intensity of the adjacent continuous spectrum. The lightly shaded portions indicate the location of Fe I lines with $\chi_e \geq 3$ eV, the intermediately shaded portions Fe I lines with $\chi_e < 3$ eV, and the darkly shaded portions Fe II lines.