Fluxtube model atmospheres and Stokes V zero-crossing wavelengths

L.R. Bellot Rubio, B. Ruiz Cobo, M. Collados
Instituto de Astrofísica de Canarias, E-38200, La Laguna (Tenerife), Spain

Received ______________; accepted ______________
ABSTRACT

First results of the inversion of Stokes I and V profiles from plage regions near disk center are presented. Both low and high spatial resolution spectra of Fe I 6301.5 and Fe I 6302.5 Å obtained with the Advanced Stokes Polarimeter (ASP) have been considered for analysis. The thin flux tube approximation, implemented in an LTE inversion code based on response functions, is used to describe unresolved magnetic elements. The code allows the simultaneous and consistent inference of all atmospheric quantities determining the radiative transfer with the sole assumption of hydrostatic equilibrium. By considering velocity gradients within the tubes we are able to match the full ASP Stokes profiles. The magnetic atmospheres derived from the inversion are characterized by the absence of significant motions in high layers and strong velocity gradients in deeper layers. These are essential to reproduce the asymmetries of the observed profiles. Our scenario predicts a shift of the Stokes V zero-crossing wavelengths which is indeed present in observations made with the Fourier Transform Spectrometer.

Subject headings: Line: formation — line: profiles — polarization — sun: faculae, plages — sun: magnetic fields — Radiative transfer
1. Introduction

A remarkable, still unexplained feature of the spectra emerging from facular and network regions in the solar photosphere is the conspicuous asymmetry exhibited by Stokes V profiles. At disk center, the peak and absolute area of the blue lobe are larger than those of the red lobe for the majority of Fe I lines (Solanki & Stenflo 1984). In addition, the red lobe has a more extended wing than its blue counterpart. A detailed analysis of the properties of high spatial resolution Stokes V spectra in plage regions can be found in Martínez Pillet et al. (1997).

The search of the processes that give rise to the area asymmetry of Stokes V has been one of the most vivid discussions of recent times in solar physics. Illing et al. (1975) first suggested that gradients of velocity and magnetic field along the line of sight may produce asymmetric V profiles. Originally, this mechanism was put forward to explain broad-band measurements of circular polarization in sunspots. Later, a series of papers refined this idea and settled down the physics involved (van Ballegooijen 1985; Sánchez Almeida et al. 1988; Grossmann-Doerth et al. 1988). In the current picture, the area asymmetry is produced by the combined (but otherwise spatially separated) gradients of magnetic field and velocity that photons traversing the tubes encounter at the boundary layer. These gradients are generated by the expanding walls of magnetic elements embedded in field-free surroundings. The canopy mechanism, however, does fail to explain the peak asymmetry of Stokes V spectra. Observationally, the peak asymmetry turns out to be several times larger than the area asymmetry. All attempts to reproduce the observations have invariably led to ratios of peak to area asymmetries of the order of unity.

A number of other scenarios have been invoked to solve this problem. They include NLTE effects (Kemp et al. 1984; Landi Degl’Innocenti 1985), linear oscillations (Solanki 1989) or longitudinal waves (Solanki & Roberts 1992) within the magnetic elements,
non-linear oscillations (Grossmann-Doerth et al. 1991) and, more recently, micro-structured magnetic atmospheres (Sánchez Almeida et al. 1996). None of these mechanisms has proven yet to be able to reproduce the observations. Non-linear, high-frequency oscillations inside the tubes have never been detected in spite of the observational efforts. Time series of Stokes V profiles at disk center analyzed by Fleck (1991), for example, did not reveal such motions. Micro-structured magnetic atmospheres, on the other hand, seem promising but still need further development.

The present state-of-the-art can be summarized as follows: no physical process is known to be able to generate a peak asymmetry significantly larger than the area asymmetry exhibited by Stokes V spectra in plage and network regions at disk center. In fact, some of the mechanisms above were proposed, without much success, as a very last attempt to explain the observations. It is our belief, however, that velocity gradients have not been completely exploited yet. A natural extension of the canopy mechanism might include mass motions in the magnetized plasma. Empirical evidence of such motions has been found repeatedly (Solanki 1986, 1989; Sánchez Almeida et al. 1990), but stationary flows were ruled out already in the earliest analyses as the dominant source of the asymmetries because they would generate Doppler shifts of the Stokes V zero-crossing wavelengths larger than the reported upper limit of ±250 m s$^{-1}$ (Solanki 1986). Some preliminary calculations, often involving one dimensional models, have confirmed this result (e.g., Solanki & Pahlke 1988). However, it could be possible that the small shifts of the zero-crossings are effectively produced by velocity gradients in the magnetic atmosphere. These gradients might explain the marginal dependence between the observed shifts and line strength that various analyses have revealed (Solanki 1986; Sánchez Almeida et al. 1989). If this is the case, stationary flows should be reconsidered again as a possible source of the asymmetries.

In order to proceed further, reliable 2-D fluxtube atmospheres have to be used.
Unfortunately, no such models exist. Numerical simulations (e.g. Steiner et al. 1995) are more intended to understand the interaction between magnetic elements and their convective surroundings than to explain the observed spectra. For this reason it is not strange that, despite their important results, they are not able to reproduce the asymmetries. On the other hand, empirical models fail to match the observations because they neglect the role of velocity gradients to diminish the complexity of the problem. Indeed, extracting the information contained in the Stokes spectrum is hampered by the intricate non-linear dependences of the radiative transfer equation on the various quantities defining both the thermodynamical and magnetic properties of the atmospheres. The trial-and-error method does not work in this case, and so inversion techniques come into play. Here we follow an empirical approach to investigate the capabilities of velocity-based mechanisms. As a first step, a new LTE inversion code of the radiative transfer equation particularized to the case of thin flux tubes has been developed. Applied to real observations, it carries out a simultaneous inference of the whole set of model parameters which reproduce the observed Stokes spectrum, thus ensuring self-consistency. The details of the procedure and numerical tests will be presented in a forthcoming paper, although a brief description of the method is given below.

This letter reports on fluxtube model atmospheres derived from the inversion of high spatial ($\sim 1''$) and temporal ($\sim 4$ sec) resolution Stokes I and V spectra of Fe I 6301.5 and 6302.5 Å from plage regions at disk center obtained with the Advanced Stokes Polarimeter (ASP, Martínez Pillet et al. 1997). For the first time, plausible model atmospheres are found that reproduce the whole shape of the ASP Fe I 6301.5 and Fe I 6302.5 Å Stokes spectra to a degree of accuracy never reached before. The recovered model atmospheres, in which stationary flows within the tubes were allowed, have been used to synthesize the Stokes profiles of a large number of spectral lines. The comparison of their zero-crossing wavelengths to observations made with the Fourier Transform Spectrometer (FTS, Stenflo
et al. 1984) reveals that the observed Doppler shifts are not randomly distributed and suggests that non-negligible mass motions within the magnetic elements do exist.

2. Inversion of Stokes profiles from solar magnetic elements and observations

The code we have developed is a generalization of a previous code by Ruiz Cobo & del Toro Iniesta (1992) which carries out the inversion of the radiative transfer equation by employing a Marquardt non-linear least squares fit. Information about how the emergent Stokes vector varies when the atmospheric parameters are changed is provided by the so-called response functions (Ruiz Cobo & del Toro Iniesta 1994). The use of response functions (RFs) accelerates considerably the iterative scheme, making it fully automatic.

The extension of the code to the case of unresolved magnetic elements implies the adoption of a model and the calculation of its RFs. We have adopted the thin flux tube approximation to describe small scale magnetic structures. Axisymmetric thin tubes are characterized by the radial constancy of the physical parameters within the tube and satisfy hydrostatic equilibrium, horizontal pressure balance and magnetic flux conservation. The model consists of two homogeneous atmospheres, namely the tube itself and the non-magnetic surroundings. To take proper account of the geometry, the emergent Stokes spectrum is computed as an average of vertical rays that pierce the tube at different radial distances. The inversion problem is kept tractable by considering the non-magnetic atmosphere horizontally constant, which is a reasonable assumption for high spatial resolution spectra. The free parameters of the model are the temperature and line of sight velocity stratifications inside and outside the tube, constant microturbulent velocities in both atmospheres, the radius and the magnetic field strength of the tube at a given height, the external gas pressure at that level and the same height-independent macroturbulence for both atmospheres. Contributions due to stray light have been included as well. The RFs
of the Stokes spectrum emerging from such a model were derived and their basic properties discussed by Bellot Rubio, Ruiz Cobo & Collados (1996).

The inversion code has been applied to averaged and spatially resolved ASP Stokes spectra of Fe I 6301.5 and Fe I 6302.5 Å from plage regions in NOAA 7197 (Martínez Pillet et al. 1997). Typical signal-to-noise ratios are of the order of 500-1000 in the continuum of Stokes I. The average profiles have been constructed from individual spectra whose degree of polarization integrated over a band in 6302.5 Å is larger than 0.4%. As a consequence, they are more representative of strong magnetic fields and/or high filling factor regions.

For comparison purposes, very high signal-to-noise, low spatial and temporal resolution FTS spectra from plage regions at disk center will be employed (Stenflo et al. 1984). These observations provide a huge number of lines for analysis which will allow us to draw statistically significant conclusions.

3. Results

The inversion scheme iteratively modifies a guess atmosphere until the best fit between synthetic and observed Stokes spectra is reached. The instrumental profile of the spectrograph (Martínez Pillet et al. 1997) is taken into account to eliminate spurious asymmetries and Doppler shifts. For both the magnetic interior and the surroundings, the HSRA model atmosphere (Gingerich et al. 1971) has been adopted initially. The magnetic field strength and the radius of the tube at the base of the photosphere (placed arbitrarily at \( z = -122 \) km) were taken to be 1500 G and 50 km. For both atmospheres the initial microturbulence was set at 0.6 km s\(^{-1}\), the macroturbulence at 1 km s\(^{-1}\) and the line-of-sight velocity at 1 km s\(^{-1}\). This particular choice of the guess atmosphere does not influence any of the results of this work, as different initializations lead to the same final
models.

Figure 1 shows the average ASP Stokes I and V spectra of Fe I 6301.5 and 6302.5 Å inverted as described above, and the results of the inversion. Error bars have been estimated by assuming the independence of all model parameters. Under this hypothesis, confidence limits in the inferred parameters turn out to be inversely proportional to linear combinations of the RFs. We emphasize, however, that only formal errors are taken into account; the possible inadequacies of the thin flux tube model, the approximations and the numerical limitations of the inversion algorithm are other sources of error whose influence is difficult to assess. In any case, the excellent fit obtained means that the simple thin tube model is able to mimic real observations. At this juncture we want to remark that, even for only two spectral lines, none of the previous attempts to reproduce the shape of Stokes profiles coming from active regions outside sunspots has been as successful as the inversions reported here. Also, it is important to note that we have not antisymmetrized the V profiles.

The relative Stokes V area asymmetries $\delta A$ of the average ASP Fe I lines at 6301.5 and 6302.5 Å turn out to be 2.8% and 4.0%, whereas the relative amplitude asymmetries $\delta a$ amount to 10.9% and 9.9% (for a definition of $\delta A$ and $\delta a$ see, e.g., Solanki 1989). These values are correctly reproduced by the combined action of downflows inside and outside the tubes. The synthetic spectra of 6301.5 and 6302.5 Å presented in Fig. 1 have $\delta A = 3.2\%$ and $\delta A = 2.2\%$. The corresponding values of $\delta a$ are 8.1% and 7.1%. In order to explain the full Stokes profiles and, in particular, their asymmetries, the velocity gradient recovered by the inversion procedure in the magnetic atmosphere is essential. This most important conclusion has been drawn after a large number of inversions in which no velocities within
the tubes were allowed.

The basic features of the model atmospheres that fit the average Stokes spectrum are still maintained by those inferred from the inversion of individual spectra. Figure 2 shows the Stokes profiles emerging from a number of adjacent pixels in a plage region of NOAA 7197 and the results of the inversions. Non-negligible differences between spectra coming from adjacent points exist, specially in Stokes $V$ and the continuum of Stokes $I$. These, however, are reproduced by models that share the same basic properties as the atmospheres determined from the average spectra. This strengthens the reliability of the procedure and validates the models to a large extent.

We want to remark that the internal downflows derived from the inversion of observed spectra are compatible, within error bars, with null velocities in high atmospheric layers; only in deep layers is an abrupt velocity gradient established. This implies a different view about how the asymmetries are generated. For convenience, we shall make a distinction between the cylinder inside the tube and the rest of the magnetic element (the canopy). While the canopy gives rise to pronounced positive amplitude and area asymmetries, the cylinder produces negative area and positive peak asymmetries. This results in a peak asymmetry significantly larger than the area asymmetry, in accordance with the observed behavior of Stokes $V$ at disk center. The role of the canopy is maintained in our scenario, but now the cylinder creates the necessary negative area asymmetry as to compensate the excess of area asymmetry produced by the canopy. Gradients of velocity ($v$) and field strength ($B$) are cospatial and negative within the tube. This leads to the condition

$$\frac{d|B|}{dz} \frac{dv}{dz} > 0$$

almost everywhere, which fully explains the sign of $\delta A$ in the magnetic cylinder (Solanki & Pahlke 1988).
4. Zero-crossing wavelengths of observed Stokes V profiles

It has been argued from long ago that stationary velocity fields within the magnetic elements cannot be considered as the main source of the asymmetries of Stokes V because the required motions would produce noticeable shifts of their zero-crossing wavelengths. An observed upper limit of about ±0.25 km s\(^{-1}\), which is only slightly larger than the estimated accuracy of current wavelength calibrations, has been set in different analyses (Stenflo & Harvey 1985; Solanki 1986).

The atmospheres presented in Sect. 3 successfully reproduce the observed profiles of two spectral lines. This means that both area and amplitude asymmetries, and zero-crossing wavelengths are also matched. But, do the recovered velocity fields generate Stokes V zero-crossing shifts compatible with the observations for a large number of spectral lines? In order to check this point we have used the models resulting from the inversion of the average profiles and a macroturbulence of 1 km s\(^{-1}\) to synthesize the Stokes spectra of 92 unblended Fe I lines with different excitation potentials and strengths in the range 4600-5450 Å. Their Stokes V zero-crossings have then been compared to FTS observations. Figure 3 summarizes the analysis and reveals a distinct similarity between observed and computed shifts. FTS wavelengths are not absolutely calibrated, but in any case the correlation found suggests that the velocity gradients derived by the inversion procedure are those required by the observations to be reproduced. Since the selected lines sample the whole photosphere, we conclude that mass motions within fluxtubes increase with depth, thus producing larger zero-crossing shifts for lines formed at deeper layers.

In view of the evidence presented here we believe that strong indications of velocity gradients in the magnetized plasma exist, and that these may be responsible for the
observed asymmetries of Stokes V in plage regions at disk center. Various mechanisms might explain the downflows, including convective collapse, gas entry into the magnetic structures and viscous drag induced by external convective motions (Steiner et al. 1995). Certainly, the origin of velocity gradients in the magnetic atmosphere deserves further theoretical work.

We gratefully acknowledge V. Martínez Pillet, B. Lites and A. Skumanich for providing their reduced ASP observations and for many useful discussions regarding the data. Thanks are also due to S. K. Solanki, who kindly allowed us to compare the FTS zero-crossing shifts with the predictions of our model and made valuable suggestions. This work has been funded by the Spanish DGICYT under project PB91-0530.
REFERENCES

Bellot Rubio L.R., Ruiz Cobo B., Collados M., 1996, A&A, 306, 960

Fleck B., 1991, Rev. Mod. Astron. 4, 90

Gingerich O., Noyes R.W., Kalkofen W., Cuny Y., 1971, Sol. Phys., 18, 347.

Grossmann-Doerth U., Schüssler M., Solanki S.K., 1988, A&A, 206, L37

Grossmann-Doerth U., Schüssler M., Solanki S.K., 1991, A&A, 249, 239

Illing R.M.E., Landman D.A., Mickey D.L., 1975, A&A, 41, 183

Kemp J.C., Macek J.H., Nehring F.W., 1984, ApJ, 278, 863

Landi Degl’Innocenti E., 1985, in: Theoretical Problems in High Resolution Solar Physics, Schmidt H.U. (ed), Max-Planck-Institut für Astrophysik, München, 162

Martínez Pillet V., Lites B.W., Skumanich A., 1997, ApJ, in press

Nave G., Johansson S., Learner R.C.M, Thorne A.P., Brault J.W., 1994, ApJS, 94, 221

Ruiz Cobo B., del Toro Iniesta J.C., 1992, ApJ, 398, 375

Ruiz Cobo B., del Toro Iniesta J.C., 1994, A&A, 283, 129

Sánchez Almeida J., Collados M., del Toro Iniesta J.C., 1988, A&A, 201, L37

Sánchez Almeida J., Collados M., del Toro Iniesta J.C., 1990, Ap&SS, 100, 31

Sánchez Almeida J., Landi Degl’Innocenti E., Martínez Pillet V., Lites D.W., 1996, A&A, 466, 537

Solanki S.K., 1986, A&A, 168, 311
Solanki S.K., 1989, A&A, 224, 225
Solanki S.K., Pahlke K.D., 1988, A&A, 201, 143
Solanki S.K., Roberts B., 1992, MNRAS, 256, 13
Solanki S.K., Stenflo J.O., 1984, A&A, 140, 185
Steiner O., Grossmann-Doerth U., Schüssler M., Knolker M., 1995, Sol. Phys., 164, 223
Stenflo J.O., Harvey J.W., 1985, Sol. Phys., 95, 99
Stenflo J.O., Harvey J.W., Brault J.W., Solanki S.K., 1984, A&A, 131, 333
Van Ballegooijen A.A., 1985, in: Theoretical Problems in High Resolution Solar Physics, Schmidt H.U. (ed), Max-Planck-Institut für Astrophisik, München, 177
Fig. 1.— Inversion of average ASP Fe I 6301.5 and 6302.5 Å spectra. Top panels: observed (open circles) and synthetic (solid line) Stokes profiles, and residuals. Bottom panels: models derived from the inversion. The magnetic interior and the external surroundings are represented by solid and dashed lines, respectively. The best estimates for the single-valued parameters of the model turn out to be $2.0 \pm 0.1$ km s$^{-1}$ for the macroturbulence; $90 \pm 3$ km, $2050 \pm 50$ G and $(3.47 \pm 0.06) \times 10^5$ dyn cm$^{-2}$ for the radius of the tube, the magnetic field and the external gas pressure at the base of the photosphere; $61 \pm 2\%$ for the stray light contamination and null microturbulences.
Fig. 2.— Inversion of 16 high spatial resolution ASP Fe I 6301.5 and 6302.5 Å spectra with maximum V signals larger than 0.05 and maximum Q and U signals lower than 0.002 (in units of the continuum of Stokes I). Top panels: observed spectra. The residuals below are representative of a typical fit. Bottom panels: models derived from the inversion. Solid and dashed lines represent the magnetic interiors and the external surroundings, respectively. The inferred macroturbulence ranges from 1.6 to 1.9 km s\(^{-1}\), the internal microturbulent velocity from 0 to 0.9 km s\(^{-1}\), and the stray light contamination from 21 to 30 %. The external microturbulence is always null. At the base of the photosphere, the radii of the tubes range from 95 to 107 km, the magnetic field strength from 2070 to 2430 G, and the external gas pressure from \(3.43 \times 10^5\) to \(3.80 \times 10^5\) dyn cm\(^{-2}\).
Fig. 3.— Predicted and observed Stokes V zero-crossing shifts for 92 unblended Fe I lines in the range 4600-5450 Å. Laboratory wavelengths from Nave et al. (1994) have been adopted because solar wavelengths are affected by convective blueshift. For comparison purposes, a straight line with slope equal to unity has been added. Dotted lines indicate the uncertainty of laboratory wavelengths and lie ±0.15 km s\(^{-1}\) apart.