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QUANTITATIVE EXPLANATION OF STOKES *V* ASYMMETRY IN SOLAR MAGNETIC FLUX TUBES

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Abstract: Stokes profiles of four spectral lines with very different properties are calculated in a two dimensional flux tube model of a solar magnetic element. The model has empirically derived temperature and magnetic field strength values within the magnetic element and satisfies pressure balance. The considered model can reproduce the asymmetry between the blue and red Stokes *V* wings, as well as other line parameters observed near disk centre in solar active region plages and the network if it incorporates the following three features: 1) A downflow of 0.5–1.5 km s^{-1} in the immediate surroundings of the flux tube (but not inside it). 2) A 250–350 K lower temperature in the downflowing non-magnetic atmosphere than in the average quiet sun. 3) A longitudinal wave-like or oscillatory motion with an amplitude of between 1 and 3 km s^{-1} within the magnetic element. The Stokes *V* asymmetry is thus seen to be a natural outcome of the current picture of magnetic elements embedded in cool downflowing intergranular lanes and of the presence of relatively large amplitude non-stationary mass motions within magnetic elements. The observations also suggest that the upflowing and the downflowing phases of the waves differ in some important respects.

1. Introduction

One of the outstanding features of the Stokes *V* profiles observed in active region plages and in the quiet solar network is their pronounced asymmetry [e.g. Stenflo et al., 1984, Wiehr, 1985]. Near solar disk centre almost all spectral lines have Stokes *V* profiles whose blue wings are stronger than their red wings [e.g. Solanki and Stenflo, 1984, 1985], i.e. $\delta A > 0$ and $\delta a > 0$. δA is the relative area asymmetry defined as $\delta A = (A_b - A_r)/(A_b + A_r)$ with A_b and A_r being the absolute values of the areas of the blue and red wings of Stokes *V*. δa is the relative amplitude asymmetry defined as $\delta a = (a_b - a_r)/(a_b + a_r)$, where a_b and a_r are the absolute blue and red Stokes *V* amplitudes.

Until recently the source of this asymmetry was unknown. Although various mechanisms have been proposed to explain these observations, none has so far reproduced the data consistently within the framework of a physically reasonable model.

Van Ballegooijen [1985] first pointed out that downflows outside magnetic elements can produce a Stokes *V* asymmetry having the correct sign of δA if the expansion of the magnetic elements with height is taken into account. Grossmann-Doerth et al. [1988, 1989] have shown that in this model, when B and v are nowhere cospatial, Stokes *V* profiles can be asymmetric without exhibiting *any* zero-crossing wavelength shift, thus overcoming one of the key observational hurdles without compromising physical consistency. However, no attempt was made by the above authors to quantitatively reproduce, e.g., the asymmetry of more than one Stokes *V* profile, or the correct ratio of δa to δA. In the present paper I, therefore, attempt a first simple quantitative fit to the data with this model.

Non-stationary mass-motions within the magnetic elements have also been proposed as a source of the Stokes *V* asymmetry [e.g. Solanki and Stenflo, 1984], but their influence has never been studied quantitatively. I explore how the Stokes *V* asymmetry compares with the data, with the help of a very simple two time-components model of wave-like or oscillatory motions. Particular emphasis is placed on the combined effect of oscillations within the magnetic elements and downflows external to them. A physically much more consistent model of flux tube waves is investigated in greater detail in a separate paper [Solanki and Roberts, this volume].

2. Description of Model Flux Tube

The model is composed of a magnetic flux tube which expands with height. It is surrounded by and partly overlies a downflowing field free atmosphere.

The stratification of the magnetic field strength, B, within the flux tube is due to exact horizontal pressure balance, i.e. it is calculated using the thin tube approximation [e.g. Roberts and Webb, 1978, 1979]. $B = 2000$ G has been chosen at $\tau = 1$ within the flux tube, in accordance with observations [e.g., Zayer et al., 1989]. The atmosphere outside the flux tube is initially represented by a model of the quiet sun, the HSRASP [Chapman, 1979]. Later, other temperature profiles are also used. These are constructed by increasing or decreasing $T(\tau)$ of the modified HSRASP, without changing the temperature gradient. τ signifies the continuum optical depth at 5000 Å. The empirically derived network flux tube model of Solanki [1986] represents the atmosphere inside the flux tube.

The flow outside the flux tube is assumed to be purely vertical, independent of height and directed downwards. The influence of internal waves and oscillations is modelled in a very simple manner by assuming a two time-component model, one component each for the upflow and the downflow phases. The velocity is kept constant for the duration of each phase and is also independent of height in the atmosphere. Both phases have equal but opposite velocities.

The model is intersected at various distances from the symmetry axis by a number of vertical rays. Along each of these the continuum optical depth is determined and the Stokes profiles are calculated numerically in LTE, using a code based on the numerical method of solution of the Unno-Rachkovsky equations first described by Beckers [1969]. Next, each constituent profile is weighted according to the solar surface area represented by the ray along which it is formed and the average is calculated of all the profiles formed

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within a given radius from the centre of the flux tube. For a comparison with the data I have selected four of the spectral lines used in an earlier study of Stokes V asymmetry by Solanki and Pahlke [1988]. These include three Fe I lines (5083.3 Å, 5127.7 Å and 5250.2 Å) having similar (low) excitation potentials, but widely different equivalent widths in the quiet sun, so that they are strongly weakened by higher temperatures and exhibit very different amounts of saturation. In addition, Fe II line (5197.6 Å) has been selected which reacts quite differently to temperature due to its much higher combined ionisation and excitation energy. Solanki and Pahlke [1988] failed to even remotely reproduce the Stokes V asymmetry of these four lines with 1-D models which were otherwise consistent with observations, so that this set of lines is sufficiently sensitive to the atmospheric structure to allow at least some models to be ruled out.

The calculated line parameters are compared with observations obtained near solar disk centre using the Fourier transform spectrometer (FTS) and the McMath telescope in 1979. Stenflo et al. [1984] give a detailed description of the data. δA and $\delta a/\delta A$ values observed in an active region are listed for the four lines in Table 1.

3. Results of Models with Flows Outside the Magnetic Elements Only

In this section only those models are considered which have no velocities within the magnetic elements (i.e. $v_{\rm int} = 0$). First I consider a basic model which has a $T_{ext}(z) = T_{HSRASP}(z)$.

TABLE 1. Observed Stokes V Asymmetry

Ion	$\lambda_\odot$ (Å)	δA (%)	$\delta a/\delta A$
Fe I	5083.345	5.35 ± 0.84	3.64 ± 0.62
Fe I	5127.684	-2.06 ± 4.14	-1.79 ± 4.98
Fe II	5197.574	4.43 ± 0.97	4.17 ± 0.98
Fe I	5250.217	5.21 ± 0.42	1.84 ± 0.22

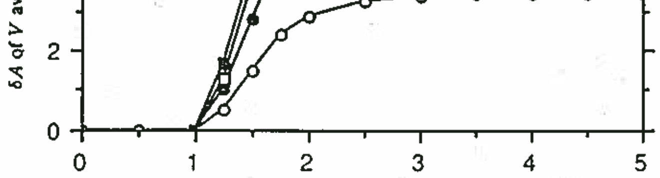

Fig. 1a. Relative area asymmetry, δA, of Fe I 5250.2 Å in % vs. r, the distance from the axis of the flux tube. The δA values plotted at any given r in the figure belong to the average of the Stokes V profiles formed between the axis of the tube and r. External downflow velocity, $v_{\rm ext} = 0.5$ km s^{-1} (open circles), 1 km s^{-1} (filled circles), 1.5 km s^{-1} and 3 km s^{-1} (open squares), and 2 km s^{-1} and 2.5 km s^{-1} (filled squares).

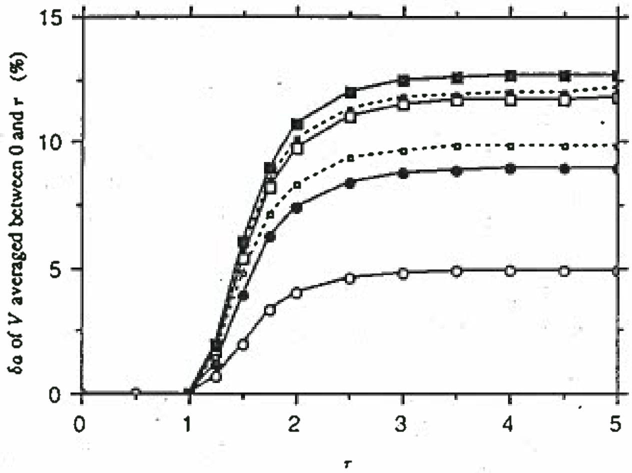

Fig. 1b. Relative amplitude asymmetry, δa, of the averaged Stokes V profiles of Fe I 5250.2 Å in % vs. r. The symbols refer to the same $v_{\rm ext}$ as in Fig. 1a. However, now the curves for $v_{\rm ext} = 2.5$ km s^{-1} and 3 km s^{-1} are plotted separately (dashed) with smaller symbols.

Fig. 1 shows various Stokes V line parameters of Fe I 5250.2 Å calculated with this model. In Fig. 1a the relative area asymmetry δA, and in Fig. 1b the relative amplitude asymmetry δa are plotted vs. radius r. The δA and δa values plotted at a given r belong to the area weighted mean Stokes V of all the profiles formed along rays between the flux tube axis and r. δA is shown for different values of $v_{\rm ext}$ (see Figure caption). δA increases steadily with $v_{\rm ext}$ up to $v_{\rm ext} \approx 2.25$, but decreases for larger $v_{\rm ext}$ (cf. Grossmann-Doerth et al. [1989] for a more detailed analysis of this effect).

δA also increases with increasing r. For Fe I 5250.2 Å the main contribution to δA comes in the range of radii between 1 and 2, reaching approximately 80% of the δA value at large r by $r = 2$. At a greater distance from the flux tube axis the contribution of any individual ray to Stokes V is extremely small, despite the large area represented by that ray, and δA becomes essentially constant. Even with reasonable values of $v_{\rm ext}$ ($0.5 \lesssim v_{\rm ext} \lesssim 1.5$ km s^{-1}) δA values comparable to the observations are produced, although only the "canopy" profiles are asymmetric. (The canopy refers to the part of the flux tube overlying field free regions.) This implies that the Stokes V profiles produced in parts of the canopy must be extremely asymmetric. Indeed, closer examination shows that individual Stokes V profiles can have δA and δa values of over 80% (for Fe I 5083.3 Å δA values of well over 90% are seen). Such profiles are almost completely composed of only one Stokes V wing.

As can be seen from Fig. 1b, δa shows a qualitatively similar behaviour to δA. For all the calculated cases $\delta a > \delta A$, but the ratio $\delta a/\delta A$ decreases markedly as $v_{\rm ext}$ is increased, being 1.42 for $v_{\rm ext} = 0.5$ km s^{-1}, but only 1.17 for $v_{\rm ext} = 3.0$ km s^{-1}. The major part of this decrease in $\delta a/\delta A$ occurs above $v_{\rm ext} = 1.5$ km s^{-1}. Although they are asymmetric, all the Stokes V profiles calculated in this section, where velocity within the tube is zero, have zero-crossing wavelengths corresponding to their rest wavelengths. This result has been rigorously proved by Grossmann-Doerth et al. [1988, 1989].

Although the observed δA and zero-crossing wavelength of a single Stokes V profile may be reproduced very simply with the "basic" model used so far, the δA of the four chosen lines cannot be reproduced by a single reasonable $v_{\rm ext}$ value. In addition, the calculated $\delta a/\delta A$ ratios for Fe I 5083.3, 5250.2 and Fe II 5197.6 Å are too small, as are the widths of the average Stokes V profiles of all four lines. Obviously the model must be modified if it is to explain the observations quantitatively.

One successful modification has been to change the temperature of the surroundings of the model flux tube in the manner described in Sect. 2. A series of models with ΔT_{ext} values ranging from -600 K to $+300$ K have been calculated. $\Delta T_{ext} = 0$ corresponds to the temperature structure of the HSRASP. The resulting δA of all four lines is plotted as a function of ΔT_{ext} in Fig. 2 for $v_{ext} = 1$ km s^{-1}. δA of each of the lines has a distinctive dependence on ΔT_{ext}. δa behaves quite similarly to δA, so that $\delta a/\delta A$ is not significantly affected by changing ΔT_{ext}.

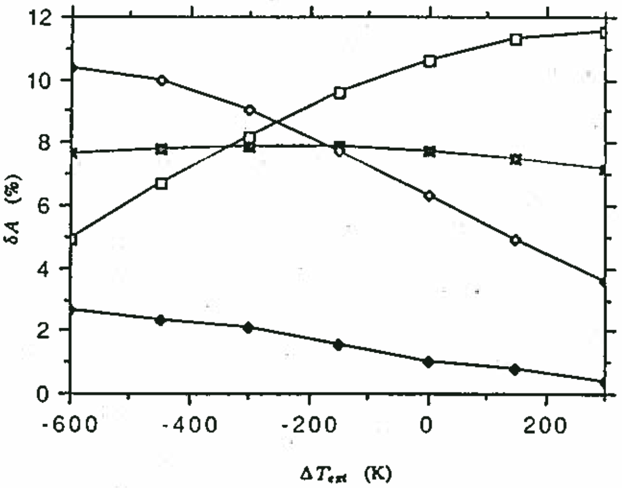

Fig. 2. δA in % of V profiles averaged between $r = 0$ and 4 (in the units used in Fig. 1) of Fe I 5083.3 Å (open squares), 5127.7 Å (filled diamonds), Fe II 5197.6 Å (filled squares) and Fe I 5250.2 Å (open diamonds) vs. ΔT_{ext}, the temperature difference between the non-magnetic atmosphere surrounding the flux tube and the HSRASP. $v_{ext} = 1$ km s^{-1}.

The best fit to δA of all four lines (within the observational uncertainty) is obtained for ΔT_{ext} between approximately -250 K and -350 K, i.e. when the surroundings of the magnetic elements are rather cool compared to the average quiet sun. This agrees well with the picture of magnetic elements being concentrated in dark intergranular lanes [e.g. Dunn and Zirker, 1974; Mehltretter, 1974; Title et al., 1987].

4. Results of Models with Velocities Inside and Outside the Magnetic Elements

In this section I investigate the influence of non-stationary mass-motions within the magnetic elements on the Stokes V asymmetry in combination with external flows. Only models with an external atmosphere having $\Delta T_{ext} = -300$ K are considered, in agreement with the results of Sect. 3.

A very simple two time-component model of a flux tube wave or oscillation, whose basics are described in Sect. 2. has been constructed. For the calculation of the line profiles the same atmosphere is used in both phases. However, when adding the two phases together to produce the time-averaged Stokes V (which is the proper Stokes V profile to compare with time averaged or low spatial resolution data), the profiles resulting from the two phases can be weighted differently to reflect, in a crude manner, e.g., differences in thermal structure between the upflowing and downflowing phases. It can be easily shown that adding two unequally weighted and shifted Stokes V profiles can easily produce a resulting Stokes V profile with a significant *amplitude* asymmetry δa, even if both the original profiles are antisymmetric. The calculations presented in this section should therefore influence δa considerably. The most important result of this section is illustrated in Fig. 3, where the ratio $\delta a/\delta A$ of Fe I 5250.2 Å and 5083.3 Å is plotted vs. the weight, w_u, given to the Stokes V profile resulting from the upflow phase. w_u is normalised such that the sum of the weights of both phases is always unity. The "wave amplitude" is 1 km s^{-1}, i.e. $v_{int} = \pm 1$ km s^{-1}, and v_{ext} is 0.5 km s^{-1}. The curves have only been plotted for those values of w_u for which $\delta a/\delta A \geq 0$ and $\delta A > 0$. Both lines exhibit the same qualitative behaviour, although $\delta a/\delta A$ of Fe I 5083.3 Å can be enhanced much more than of Fe I 5250.2 Å, in agreement with the data. The larger $\delta a/\delta A$ values are always produced when the upflow component is more strongly weighted.

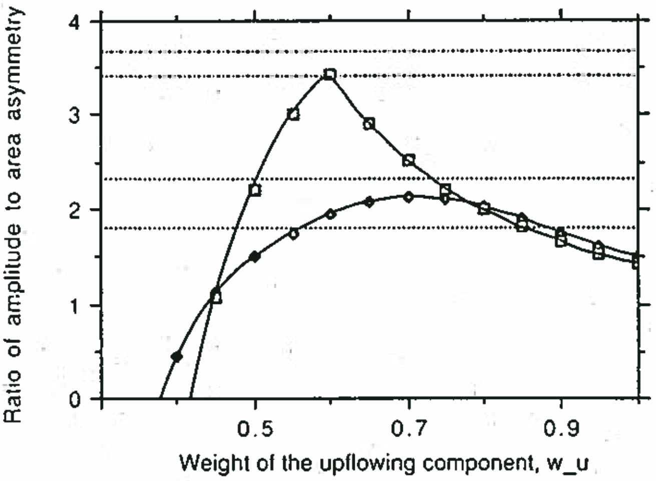

Fig. 3. The ratio $\delta a/\delta A$ of the Stokes V profile of Fe I 5250.2 Å (diamonds) and 5083.3. Å (squares) averaged between $r = 0$ and $r = 4$ vs. w_u, the weight of the internal upflow velocity component. $w_u = 1$ signifies that only an upflow is present, while $w_u = 0.5$ means that up- and downflows have equal weight. $v_{int} = \pm 1$ km s^{-1} and $v_{ext} = 0.5$ km s^{-1}. Only those points have been plotted for which both δa and δA are positive. The horizontal dashed lines represent the observations, in a plage and network region, of 5250.2 Å, while the dot-dashed lines mark the observations of 5083.3 Å.

The observations are represented by the horizontal dashed lines for 5250.2 Å and the dot-dashed lines for 5083.3 Å. The $\delta a/\delta A$ observations of both lines can be approximately reproduced by the chosen model parameters between $w_u \approx 0.55$ and $w_u \approx 0.65$. Unfortunately, the zero-crossing wavelength is no longer conserved when the up- and downflow phases are not equally weighted. However, zero-crossing wavelength shifts are minute when the weighting of the two phases is nearly the same. The observational upper limit of ±250 m s^{-1} on the zero-crossing shift [Solanki, 1986] implies that only calculations with w_u values between approximately 0.4 and 0.6 need be considered further, as far as a comparison with the observational data is concerned. For Fe I 5250.2 Å the profile with the $\delta a/\delta A$ value closest to the observations is blueshifted by approximately 150–250 m s^{-1} and lies just below the upper limit set by the observations. For Fe I 5083.3 Å, the blueshift of the corresponding profile is considerably smaller (50–100 m s^{-1}). As expected, the Stokes *V* line widths also increase with increasing "wave" amplitude. An external downflow of 0.5–1.5 km s^{-1} and an internal wave of amplitude between 1 km s^{-1} and 1.5 km s^{-1} with a weight of the upflow phase, w_u, of 0.55–0.6 are required to reproduce of the plage data best.

5. Conclusions

In the present paper the origin of the Stokes *V* asymmetry observed near disk centre in solar active regions and in the quiet network is studied with the help of a 2-D flux tube model of solar magnetic elements. It is shown that the observed relative area and amplitude asymmetry, the zero-crossing wavelengths and the widths of four Fe I and II Stokes *V* profiles belonging to lines with widely different properties can be reproduced relatively well within the framework of this model if it incorporates the following three features. Firstly, a downflow is present in the immediate surroundings of the magnetic elements. Secondly, this downflowing region is cooler than the quiet sun. Thirdly, an oscillatory or wave-like motion is present within the magnetic elements. Since the thermal and magnetic structures of the model are empirically derived, this implies that the same model effectively also reproduces a host of other line parameters (e.g. magnetic and thermal line ratios, Zeeman splitting of infrared lines etc.).

The following quantitative results are derived from the present calculations. The immediate surroundings of magnetic elements are approximately 250–350 K cooler than the average quiet sun and contain a downflow of 0.5–1.5 km s^{-1} near the walls of the magnetic elements. The waves or oscillations inside magnetic elements have a velocity amplitude of 1–1.5 km s^{-1}, derived on the basis of a simple two time-component model. It is expected that the true wave amplitude is larger, since it must compensate for the larger weighting of small velocities in a sinusoidal wave, so that more realistically the wave amplitude lies between 1 and 3 km s^{-1}. The observations also suggest that the upflowing and downflowing phases probably differ in some important respects.

The picture of solar magnetic elements emerging from the present use of the Stokes *V* asymmetry as a diagnostic is highly appealing, since it fits in very well with our present theoretical understanding of such structures [cf. Spruit and Roberts, 1983; Schüssler, 1986; Solanki, 1987, Roberts, this volume, for reviews].

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