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CAN VELOCITY GRADIENTS EXPLAIN THE OBSERVED STOKES V ASYMMETRY IN THE ABSENCE OF LARGE ZERO-CROSSING SHIFTS ?

In the absence of mass-motions and strong departures from LTE, the Stokes V profile of a spectral line is expected to be strictly antisymmetric with respect to its zero-crossing wavelength (Auer and Heasley, 1978). Observations show, however, that a distinct asymmetry is present with its blue amplitude, a_b, being larger than its red amplitude, a_r, and the area of its blue wing, A_b, being larger than the area of its red wing, A_r (e.g. Stenflo et al., 1984; Solanki and Stenflo, 1984, 1985; Stenflo and Harvey, 1985; Wiehr, 1985). We define the amplitude asymmetry as a_b/a_r and the area asymmetry as A_b/A_r.

In the present paper we present first results of a quantitative test of the hypotheses of Illing et al. (1975) and Grigorjev and Katz (1975) which attempt to explain the observed asymmetry by assuming a combination of vertical velocity and magnetic field gradients. We compare observed Stokes V profiles recorded at solar disk centre (see Stenflo et al., 1984 and Scholier and Wiehr, 1985 for a description of the data), with the results of LTE calculations, carried out with two slightly different approaches and using two different codes. However, both sets of calculations are based on one-dimensional fluxtube models containing a steady flow with a vertical gradient. We also test whether this mechanism produces profiles which are in agreement with the observed values of other parameters of Stokes V, in particular with the zero-crossing wavelength λ_V, whose values have been found to lie close to the values expected in the absence of steady flows inside fluxtubes, λ_0 (Stenflo and Harvey, 1985; Solanki, 1985, 1986).

We wish to note that only the combined *gradients* of B and v are important for the reproduction of the asymmetry. In particular, the absolute value of v has no effect on the asymmetry, so that we can write

$$v(\tau) = v_0 + v_1(\tau) = v(\tau_0) + (v(\tau) - v(\tau_0))\,, \tag{1}$$

with the contribution function of the line being approximately zero at optical depth τ_0 and $v_0 = v(\tau_0)$ being an arbitrary constant velocity as far as the asymmetry is concerned. In order to reproduce the observed asymmetry we need

$$\frac{\mathrm{d}|B(\tau)|}{\mathrm{d}\tau}\frac{\mathrm{d}v(\tau)}{\mathrm{d}\tau} < 0 \tag{2}$$

in the region of the formation of the line. The fact that only the absolute value of $B(\tau)$ is important, while the sign of $v(\tau)$ also plays a role is due to the different ways in which v and B affect the line profile.

Grid of parameterised models

Radiative transfer calculations of Fe I 6302.5 Å, for a grid of parameterised models have been carried out (with the code described by Wittmann, 1974) and compared to the observed values of a_b/a_r, A_b/A_r (which are in general smaller than the values of a_b/a_r), and λ_V for this line. Each model has a velocity and magnetic field structure of the following simple forms

$$v(\tau) = v_i\tau^a - v_i \tag{3}$$
$$B(\tau) = B_i\tau^b\,, \tag{4}$$

where a and b are dimensionless quantities, which together with v_i and B_i constitute the four free parameters per model. The second term on the right hand side of Eq. (3) has been introduced in order to minimise the resulting redshift of the calculated profiles (this term makes $v(\tau = 1) = 0$).

We restrict ourselves here to presenting the results of one grid of models for which $b = 1.0$, $B_i = 1500$ G, $-1.75 \le a \le -0.5$, and $v_i = 1.0$ km sec^{-1} (curve 1), 0.75 km sec^{-1} (curve 2), 0.5 km sec^{-1} (curve 3). For each set of parameters the calculations have been carried out using three different fluxtube temperature structures as marked in Figs. 1, 2, and 3.

The results of this grid are shown in Figs. 1 (a_b/a_r), 2 (A_b/A_r), and 3 (redshift, i.e. $\lambda_V - \lambda_0$). b, B_i, and v_i are kept constant along each curve, while a is varied. The shaded areas in Figs. 1 and 2 denote the range of the observations. They cover the average value $\pm$ one standard deviation of a_b/a_r (resp. A_b/A_r) of 14 Fe I 6302.5 profiles taken from the data set of Scholier and Wiehr (1985).

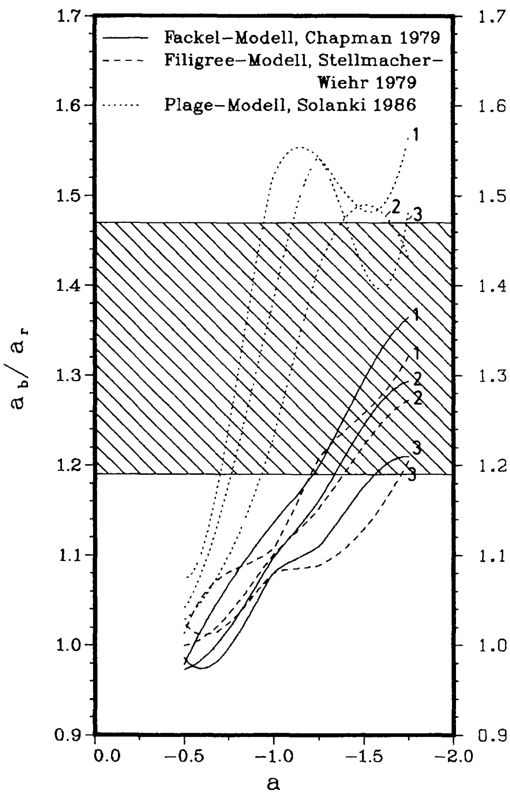

Fig. 1: Amplitude asymmetry a_b/a_r of Fe I 6302.5 Å vs. the parameter a (see Eq. 3). Shaded area denotes the range of the observations. See text for the labeling of the curves.

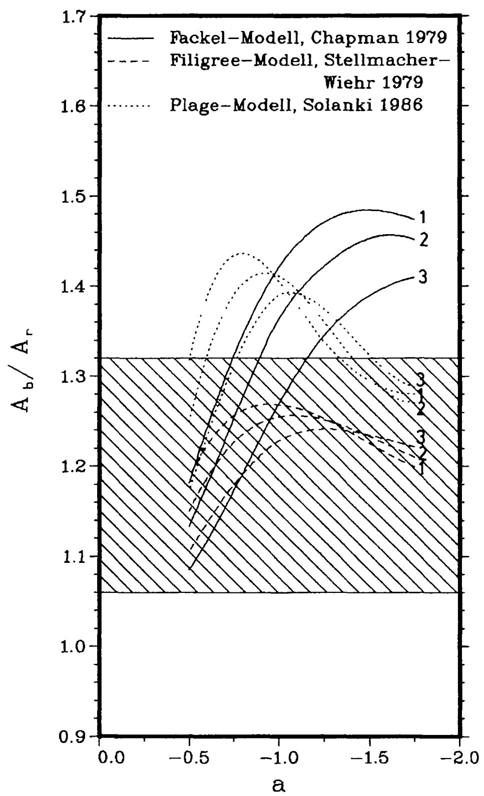

Fig. 2: Area asymmetry A_b/A_r vs. a. Otherwise the same as Fig. 1.

We wish to note that the model calculations require for $b > 0$ (i.e. $\mathrm{d}|B(\tau)|/\mathrm{d}\tau > 0$) and $v_i > 0$ (i.e. downflows), that $a < 0$ (i.e. $\mathrm{d}v/\mathrm{d}\tau < 0$) in order to reproduce the asymmetry, in accordance with Eq. 2. For the grid described above, the temperature structure of Stellmacher and Wiehr (1979) reproduces the observations the best (for $-1.25 \lesssim a$). If we also take into account the results of other calculated parameter grids, we find that the unpublished temperature stratification of Solanki reproduces the observed amplitude and area asymmetries most frequently, followed by the model atmosphere of Stellmacher and Wiehr (1979). However, none of the three models has so far been able to reproduce the observed asymmetries and zero-crossing wavelength for any single set of parameters.

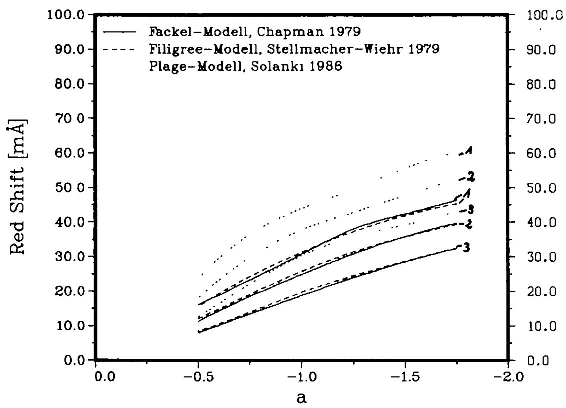

Fig. 3: Redshift ($\lambda_V - \lambda_0$) of the model Fe I 6302.5 Å profiles vs. a. The observations place upper limits of approximately 5 mÅ on the redshift.

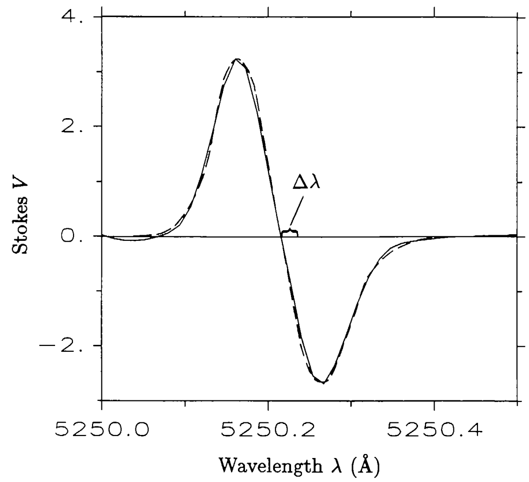

Fig. 4: The profile of Fe I 5250.2 Å observed in a plage (solid line) and calculated (dashed line). $\Delta\lambda$ is the amount by which the calculated profile has been artificially shifted in order to match the observed line.

Models reproducing the complete line profile

In this section we summarize some of the results of calculations carried out with the radiative transfer code of Beckers (1969) and aimed at reproducing the complete observed line profile by specifying the model atmosphere point by point at various depths. For each of the different temperature models tested the magnetic field is assumed to have some fixed depth dependence, and the velocity variation with depth is changed in an attempt to make the calculated profile match the observed Fe I 5250.2 Å profile (data from Stenflo et al., 1984). Often no velocity structure is found for the given $B(\tau)$ which reproduces the data including the zero-crossing wavelength. In such a case the $B(\tau)$ structure is varied as well until a good fit of the *shape* of the Stokes V profile is achieved. We have been able to reproduce the shape for all the temperature structures tested. We find that only models with $v(\tau)$ structures which contain negative as well as positive values (i.e. up- as well as downflows) at different heights in the atmosphere can correctly reproduce both the shape of the Stokes V profile and its zero-crossing wavelength accurately. Such a velocity structure presents severe problems of interpretation, and is certainly not compatible with our initial aim of producing the asymmetry with *steady* flow gradients. We therefore impose the physically reasonable constraint on the velocity that it should possess the same sign over the whole photospheric height range (in the present paper we restrict ourselves to positive $v(\tau)$). In order to minimise the zero-crossing shift induced by the velocity within this constraint, we assume that $v(\tau)$ is zero just below the height at which the line becomes sensitive to the velocity. Then for no combination of $T(\tau)$, $B(\tau)$, and $v(\tau)$ have we been able to reproduce the zero-crossing wavelength simultaneously with the correct profile shape.

Fig. 4 shows an observed and a calculated profile of Fe I 5250.2 Å. In order to facilitate the comparison between the shapes of the two profiles, the latter has been shifted by -1.1 km sec^{-1} (i.e. towards the blue, the shift is marked by $\Delta\lambda$ in the figure), so that their zero-crossings are made to artificially lie at the same wavelength. For the network a fit of similar accuracy can be achieved, but again the calculated profile exhibits a redshift of approximately the same magnitude as for the plage. For other $T(\tau)$ and $B(\tau)$ functions, the best fit profiles have somewhat different redshifts. However, these have been always found to lie within the range $+0.9$ km sec^{-1} and $+1.6$ km sec^{-1}, for the minimal redshift models described above.

Conclusions

First results of our calculations show that the observed shape of the line profile of Stokes V (including its asymmetry), can be reproduced by models containing velocity and magnetic field strength gradients (at least for the two lines discussed here). However, it has so far not been possible to simultaneously reproduce the observed asymmetry as well as the zero-crossing wavelength with such models.

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