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Letter to the Editor

Unshifted, asymmetric Stokes *V*-profiles: possible solution of a riddle

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Summary: We show that Stokes V-profiles originating in an atmosphere in which a magnetic field and a systematic velocity field are spatially separated along the line of sight are asymmetric with unshifted zero-crossings. Such a configuration is probably realized in the peripheral parts of magnetic flux concentrations in the solar photosphere: Since the magnetic field flares out with height, the line of sight traverses both a static magnetic region and a downdraft in the non-magnetic surroundings. V-profiles formed in these parts of the flux concentration will be strongly asymmetric but unshifted while the V-profiles from the central parts are symmetric and unshifted. The resulting mean V-profiles show the characteristics of the observed profiles, i.e. they are unshifted and asymmetric.

Key words: The Sun: magnetic fields – photosphere – faculae – Stokes profiles

1. Introduction

High precision Fourier Transform Spectrograph (FTS) measurements of Stokes V-profiles originating in small magnetic flux concentrations permeating the solar atmosphere (Stenflo et al., 1984) revealed that almost all of these profiles are asymmetric: Area and amplitude of one wing (the blue wing for observations near the center of the solar disc) are larger than those of the red wing. Indications for a net circular polarization in spectral lines had been provided earlier by broad-band polarization measurements of sunspots (Illing et al., 1974). These results led to the conjecture (Illing et al., 1975) that V-profile asymmetries are caused by gradients of velocity and magnetic field along the line of sight or, if the magnetic field is not parallel to the line of sight, by a velocity gradient alone (Auer and Heasley, 1978).

Since the presence of a systematic flow should also lead to a wavelength shift of the zero-crossing of the V-profile, it came as a surprise that measurements of the V-profiles of many spectral lines with high spectral resolution did not show significant shifts placing an upper limit of 250 $\mathrm{m\cdot s^{-1}}$ on the systematic velocity (Stenflo and Harvey, 1985; Solanki, 1986). Seemingly conflicting observations of zero-crossing shifts (Giovanelli and Slaughter, 1978; Wiehr, 1985) very probably are due to insufficient spectral resolution of asymmetric V-profiles (cf. Solanki and Stenflo, 1986) and neglect of the granular blueshift.

Because no zero-crossing shifts have been observed it appears difficult to maintain the interpretation of asymmetries in terms of velocity and magnetic field gradients. Indeed, Solanki and Pahlke (1988) have shown that in a 1D geometry it is impossible to reproduce the asymmetries without zero-crossing shifts using a variety of physically plausible magnetic field and velocity profiles, i.e. magnetic field decreasing and downflow velocity increasing with height. The same negative result was obtained by Ribes et al. (1985) for physically consistent Bernoulli flow models. Recently, Sanchez-Almeida et al. (1988) presented an example of an unshifted, asymmetric V-profile of a single spectral line assuming a quite improbable one-dimensional situation, i.e. a magnetic field *increasing* with height and a downflow velocity *decreasing* with height. Since in the particular case considered by the authors the wavelength range around the zero-crossing of the V-profile is formed at approximately the same height as the core of the intensity profile (Stokes I), such a configuration may lead to an asymmetric V-profile with little shift of the zero-crossing if the velocity decreases rapidly enough in the upper layers where the line cores are formed. However, it is quite improbable that any chosen velocity and magnetic field profile can simultaneously lead to unshifted, asymmetric V-profiles for *all* spectral lines irrespective of their strength, excitation potential and height of formation. Furthermore, it has been observationally demonstrated (Stenflo et al., 1987b; Zayer et al., 1988) that the magnetic field *decreases* with height, a physically quite plausible fact.

Besides stationary flows one may consider overstable oscillations as a source of the V-profile asymmetry. Since the FTS measurements have a low spatial and temporal resolution it is possible that they represent averages over many flux concentrations oscillating at random phases thus leading to small mean velocities. However, the convective origin of such oscillations leads to velocity-temperature correlations (cf. Hasan, 1985; Venkatakrishnan, 1985) which would cause wavelength shifts in the same way as granulation produces the well-known convective blueshift of spectral lines in the solar atmosphere. Again it seems not very plausible that this mechanism should produce unshifted V-profiles for *all* spectral lines, regardless of their various parameters.

As a kind of last resort, an NLTE effect, i.e. unequal population of Zeeman sublevels due to atomic orientation, has been proposed as a cause of the asymmetries (Kemp et al., 1984; Landi Degl'Innocenti, 1985). No quantitative calculation has been presented so far and it seems impossible that such a mechanism should apply to all spectral lines. Moreover, the observed sign change of the asymmetry for measurements of structures near the solar limb (Stenflo et al., 1987a) is difficult to reconcile with this idea.

All models discussed above assume a two-component atmosphere, i.e. the observed V-profile is thought to originate purely in the magnetic part of the atmosphere while the non-magnetic part does not contribute. However, this may not be the case in reality; van Ballegooijen (1985) has pointed out that an asymmetric V-profile will originate if the line of sight traverses both

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a static magnetic structure and a flow field in the surrounding, non-magnetic atmosphere. In fact, magnetic flux concentrations are situated in intergranular downflow regions and model calculations have shown that they drive and accelerate this downflow by thermal interaction with their surroundings (Deinzer et al., 1984). Since the magnetic field strongly decreases with height, flux concentrations flare out and, near solar disc centre, lines of sight at the periphery traverse static magnetic (upper part of the atmosphere) and downflowing non-magnetic (lower part of the atmosphere) regions. If the transition between the two regions is as sharp as indicated by theoretical arguments (Schüssler, 1986), model calculations (Knölker et al., 1988) and observations (Zayer et al., 1988) this leads to a situation in which for a significant part of the area covered by a magnetic flux concentration *magnetic field and velocity field are spatially separated along the same line of sight.* We will show that quite generally such a configuration leads to asymmetric V-profiles with unshifted zero-crossings.

2. The Model

Consider a planeparallel atmosphere which is divided into two parts: An upper region that is pervaded by a magnetic field of arbitrary structure and which includes no systematic flow with vertical components and a lower part with vanishing magnetic field and a systematic vertical flow. Without loss of generality we restrict the discussion to vertical incidence of the line of sight. It is our assertion that the Stokes V-profile of a spectral line emerging from this atmosphere will be asymmetric while the crossing of the zero line will occur exactly at λ_0, the wavelength of the line center in a static solar atmosphere. The sign of the asymmetry will depend on the sign of the vertical velocity (down flow producing a stronger blue wing) while the magnitude of the asymmetry will be determined by both height of the dividing boundary and magnitude of the flow.

To prove this assertion let us consider the solution of the transfer equation of both right- and left-handed circularly polarized radiation emerging from the atmosphere:

$$I_{r,l}(\lambda) = \int_0^\infty S(\tau_c) exp(-(\tau_{r,l} + \tau_c)) d\tau_c$$

with

$$\tau_{r,l}(\lambda, z_0) = \int_0^{z_0} \kappa_{r,l}(\lambda) dz$$

where $\kappa_{r,l}$ are the opacities of both radiations, S the source function which we assume to be identical for both radiations and τ_c the continuum optical depth. The opacities vary with geometrical depth, z. In the upper region κ_r and κ_l will be exactly symmetrical with respect to λ_0 because of the absence of a velocity component along the line of sight. Hence, at λ_0 both opacities will assume identical values. In the lower region, on the other hand, κ_r and κ_l will be shifted but identical for all wavelengths, hence at λ_0 they will have identical values, too. Therefore, at λ_0 both I_r and I_l will be identical because they only depend on the functions $S(\tau_c)$ and $\kappa(\tau_c)$. Since Stokes V is the difference between I_r and I_l it will vanish at λ_0. Thus the second part of our assertion is proven.

An asymmetry of the emerging Stokes profiles is bound to occur in an atmosphere with vertical gradients of both velocity and magnetic field (Illing et al., 1975). Moreover, Solanki and Pahlke (1988) showed that the asymmetry has the correct sign (blue wing stronger than red wing) provided the unequality holds:

$$\frac{\mathrm{d}|B|}{\mathrm{d}\tau}\frac{\mathrm{d}v}{\mathrm{d}\tau} < 0$$

with B the magnetic field strength and v the flow velocity (positive if downward). Strictly speaking these considerations may not be applied to our atmosphere since it has no finite gradients. However, discontinuous variations of B and v should have the same effects on the Stokes profiles as smooth gradients. So we expect Stokes V asymmetries to occur in our model and since B is larger at small depth than at large depth and the opposite is true for the velocity v we also expect the asymmetry to have the correct sign provided v is positive. Actually our expectations are borne out by the calculations described below.

We wish to emphasize that the proposed model differs qualitatively from previous attempts to explain asymmetric and unshifted Stokes V-profiles which were based upon two assumptions: (1) vertical gradients of both velocity and magnetic fields, and (2) vanishing velocity in those layers of the atmosphere where the central part of the line is formed. In our model we retain the first assumption but replace the second by asuming magnetic and velocity field to be spatially separated. It has proved nearly impossible to meet condition (2) for *all* spectral lines, weak and strong alike, without reducing the velocity field to the extent that it is no longer capable of producing the observed asymmetries. In our model, on the other hand, the shift of the V-profile zero-crossing *vanishes exactly for any spectral line.* Only the amount of asymmetry will depend on line properties.

3. Model Exploration

We expect our model - although of a simple 1-D geometry - to represent at least qualitatively the considerably more complex situation in the outer parts of a solar flux tubes. The *observed* Stokes V-profiles are spatial averages over the entire flux tube including the opaque inner parts; in order to compare them with model calculations in any detail a careful analysis is necessary which integrates over many lines of sight using the appropriate flow velocities in the vicinity of the flux tube. We plan to undertake such an analysis with new dynamic 2-D flux tube models. In the meantime we carried out a number of exploratory calculations with a thin flux tube model based upon a standard VAL-atmosphere fitted to the convection model of Spruit (1977), a Wilson depression of 100 km and a downward flow whose magnitude at the level $\tau_c = 0.1$ is a free model parameter. The flow is assumed to conserve mass. The other parameter is the optical depth τ_b of the boundary between the lower part where the magnetic field is simply switched off and the upper part where the velocity is set to zero. This model may be considered to represent a single vertical ray passing through the outer part of the flaring flux tube. Note that decreasing τ_b corresponds to moving away from the axis of the tube. In order to see if the Stokes V-profile asymmetries produced by this model are quantitatively compatible with the observations we computed the emerging Stokes profiles with the code which has been described in Grossmann-Doerth et al. (1988a), varying both model parameters. Using the Fe I 5250 line we obtained Stokes V-profile (relative) area asymmetries (for their definition see Solanki and Stenflo, 1984) from 1% to about 90% for τ_b in the range 0.5 to 0.03 and v_0 in the range 0.5 to 2 km/s. For purposes of illustration we show in Fig.1 the profiles of Stokes I and Stokes V for the case $\tau_b = 0.1$ and $v_0 = 1.0$ km/s.

For the infrared line FeI $\lambda 15648$ we obtained asymmetries which were nearly an order of magnitude smaller, in agreement with the observation of Stenflo et al. (1987b). We also explored the relationship between asymmetry and line strength by artificially varying the oscillator strength of the line. We found that the asymmetry invariably vanishes as the line strength approaches zero and that for τ_b about 0.1 the amplitude asymmetry levels off at large line strength. Both phenomena have been observed (Solanki and Stenflo, 1984).

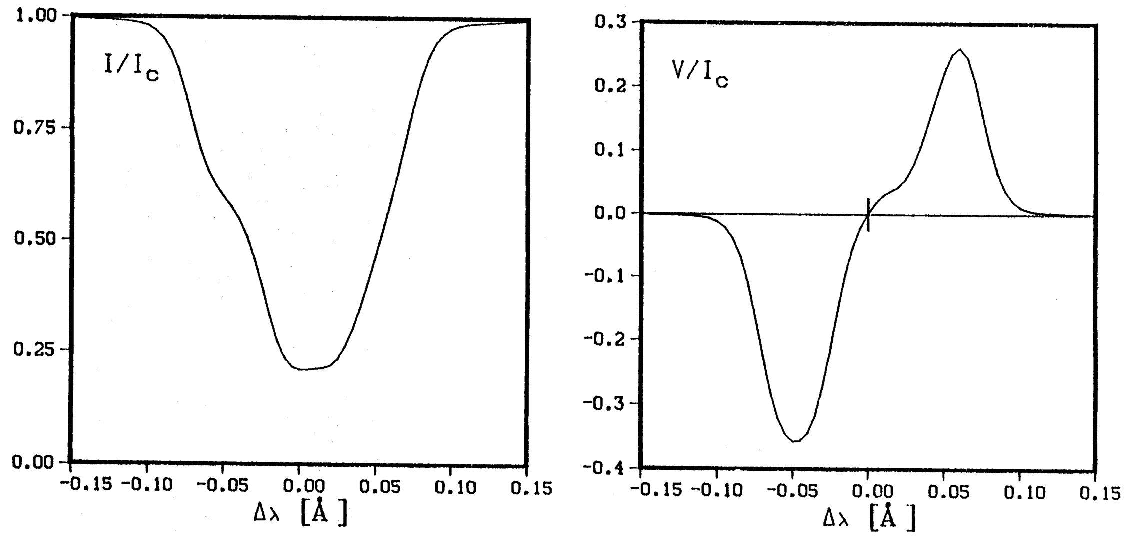

Fig.1. Stokes I- and V-profiles of the Fe I 5250.2 Å line emerging from a divided thin flux tube atmosphere (see text). Below $\tau_c = 0.1$ there is a downward flow (1 km/s at $\tau_c = 0.1$) but no magnetic field. Above that level there is no flow but the undisturbed flux tube magnetic field of about 1000 Gauss. Stokes I area asymmetry is 25%, the amplitude asymmetry 15%. There is no zero shift of Stokes V.

4. Conclusions

We have found strong evidence that the observed Stokes V asymmetries in the solar atmosphere have their origin in the peripheral parts of magnetic flux concentrations where lines of sight traverse both magnetic regions without systematic flow and a surrounding, non-magnetic downflow. We have shown that in such a situation a V-profile with strong asymmetry (of the observed sign) and exactly vanishing zero-crossing shift is formed. Independent support for this interpretation has been provided by Grossmann-Doerth et al. (1988b) who showed that the observed very broad V-profiles of the infrared line FeI λ15648 (Stenflo et al.,1987b) are caused by the contribution from the peripheral parts of the magnetic flux concentrations.

With the forthcoming analysis of new 2D flux sheet models (Grossmann-Doerth et al., 1988b) we will be in a position to fully use the rich information contained in the FTS spectra and actually probe the spatial structure of flux concentrations and their surroundings. Our results once more demonstrate the crucial effects of spatial structure in the solar atmosphere and the vital importance of 2- and 3D MHD-models for any sensible interpretation of observations of small-scale structures.

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