Astron. Astrophys. 221, 338–341 (1989)

ASTRONOMY AND ASTROPHYSICS

Stokes V asymmetry and shift of spectral lines

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Received April 4; accepted April 21, 1989

Summary. We give further evidence for the interpretation of the observed unshifted and asymmetric Stokes V profiles in the solar atmosphere in terms of a magnetic flux concentration expanding with height and surrounded by a downflow. A general proof is given that a V-profile originating in an atmosphere in which magnetic field and flow are spatially separated along the line of sight has a zero-crossing wavelength which is unshifted with respect to the rest wavelength of the line center. Heuristic considerations for the dependence of the asymmetry of Stokes V on Zeeman shift, Doppler shift, line width and strength are described and confirmed by exploratory calculations.

Key words: The Sun: magnetic fields – radiative transfer – Stokes profiles

1. Introduction

The Stokes parameters of solar photospheric lines, notably Stokes V, are the most important carriers of information on the structure of the magnetic field in the solar atmosphere. Among the most conspicuous properties of the observed Stokes V profiles are their asymmetry and the absence of any significant wavelength shift, i.e. the blue wing normally has a larger amplitude and area than the red one yet the point of zero-crossing is practically unshifted with respect to the rest wavelength of the line center. In the present paper we deal with both of these features. In Sec. 2 we generalize the proof given in Grossmann-Doerth et al. (1988) that a Stokes V profile originating in an atmosphere with spatially separated magnetic and velocity fields has an unshifted zero crossing. Sec. 3 contains a discussion of the dependence of the asymmetry of Stokes V on the relative magnitudes of Doppler shift, Zeeman splitting, width and strength of the spectral line.

2. The zero-crossing shift of Stokes V

Since the strong asymmetry of Stokes V is taken as signature of a significant flow velocity in the region where the line and its Stokes parameters are created (Illing et al., 1975; Auer and Heasley, 1978) the absence of a shift of Stokes V (Stenflo and Harvey, 1985;Solanki, 1986) is surprising. It is not possible to explain these observational facts in terms of 1D models incorporating at least some physical realism, as has been shown by Solanki and Pahlke (1988). Also the attempt to solve the problem by invoking non-LTE processes (Kemp et al., 1984) has met with difficulties. Recently the present authors proved that an *asymmetric and unshifted* Stokes V profile emerges from an atmosphere in which magnetic field and velocity field are spatially separated (Grossmann-Doerth et al., 1988). Such a configuration presumably prevails in the outer parts of flux tubes and the problem seemed to be solved. However, our proof is valid only for the case that the magnetic field is parallel to the line of sight because only then the radiation transfer equations for both circularly polarized components decouple to allow their representation by a simple integral. Here we shall generalize our previous result by proving that whenever magnetic field and velocity are spatially separated the zero crossing of Stokes V is unshifted regardless of angle between magnetic field and line of sight. We base our argument upon the Unno-Rachkovski equation for Stokes V:

$$\frac{\mathrm{d}V}{\mathrm{d}\tau} = (1+\eta_I)V + \eta_V I + \rho_U Q - \rho_Q U \qquad (1)$$

Here τ is the continuum optical depth at the wavelength of the center of the line considered. Expressions for the quantities η_i and ρ_i (relative absorption coefficients and magneto-optical parameters, respectively) may be found in Landi Degl'Innocenti (1976). For the present purposes we note that η_I is a function of wavelength which is symmetric with respect to $\lambda_0 + \Delta\lambda_v(\tau)$ while η_V, ρ_Q and ρ_U are antisymmetric. Here λ_0 is the rest wavelength of the line center and $\Delta\lambda_v(\tau)$ is the shift induced by a flow velocity. The symmetry, respectively antisymmetry of the coefficients is due to the symmetry of the Zeeman splitting pattern combined with the symmetry of the Voigt function and the antisymmetry of the Faraday-Voigt function[1]. We shall now proceed by showing that if for any optical depth Stokes V is zero at line center it remains so along an optical ray provided the flow velocity v is zero wherever the magnetic field is non-vanishing and vice versa. Our assertion is obviously true in areas

[1] The exact symmetry relations are valid with respect to frequency, but due to the very limited range covered by a spectral line, they are also valid to a very high degree with respect to wavelength.

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with vanishing magnetic field because there all the coefficients in Eq. (1) vanish except η_I. So Eq. (1) reduces to

$$\frac{dV}{d\tau} = (1+\eta_I)V, \tag{2}$$

from which it is immediately apparent that, for any wavelength, Stokes V remains zero if it was zero when the ray entered the area. Next we consider the case that there is a magnetic field but no flow. Now the 2nd, 3rd and 4th terms on the right-hand-side of Eq. (1) vanish at *line centre* because of the antisymmetry of the coefficients and the fact that $\Delta\lambda_v$ is zero (no flow). Therefore, for $\lambda = \lambda_0$ Eq. (1) reduces to Eq. (2) here as well. Hence if Stokes V was zero at $\lambda = \lambda_0$ it remains so during passage of a ray through this area. Other cases, e.g., light passing from a medium with $v \neq 0$ and $B = 0$ into one with $B \neq 0$ and $v = 0$, or light passing in the opposite direction, or more general cases can always be reduced to the above two cases.

The proposition that the Stokes V profile retains an unshifted zero-crossing wavelength whenever magnetic field and flow velocity are spatially separated has thus been proven.

3. Stokes V area and amplitude asymmetry

Observed Stokes V profiles of spectral lines in the solar atmosphere typically show a relative *area* asymmetry $\delta A = (A_b - A_r)/(A_b + A_r)$ of a few percent and a relative *amplitude* asymmetry $\delta a = (a_b - a_r)/(a_b + a_r)$ which is somewhat larger (e.g. Stenflo et al., 1984; Solanki and Stenflo, 1984; Wiehr, 1985). Here $A_{b,r}$ are the unsigned areas of the blue and red wings of the V-profile, respectively and $a_{b,r}$ their (unsigned) amplitudes. An *amplitude* asymmetry may easily be produced by adding several symmetric profiles which are Doppler-shifted with respect to each other - as it happens with observations of limited spatial resolution. However, an *area* asymmetry of a line with symmetric Zeeman pattern formed in LTE can only arise if the *saturation* is different in both wings which requires a flow with a velocity gradient along the line of sight (Auer and Heasley, 1978). If the magnetic field is parallel to the line of sight, a magnetic field gradient is necessary as well (Illing et al., 1975; Solanki and Pahlke, 1988). Since the Zeeman shift of the left and right hand circularly polarized components (i.e. the two wings of the V-profile) is of opposite sign while the Doppler shift has the same sign, the combined effect of a height gradient of both shifts is a different width of the profiles of the absorption coefficient forming the two wings of the V-profile. This leads to a different amount of saturation and, consequently, to an area asymmetry or net circular polarization of the line as a whole. At the same time, an *amplitude* asymmetry of generally the same sign as the area asymmetry is produced. Solanki and Pahlke (1988) have discussed these relations on the basis of a simple two-layer model.

From the above considerations one is led to the expectation that the magnitude of the asymmetry for a given spectral line depends on the relation between the total *change* of Zeeman shift ($\Delta\lambda_H$) and the *change* of Doppler shift ($\Delta\lambda_D$) over the height range of formation (width of the contribution function) of the V-profile. More precisely, δA and δa are expected to be largest when the change in Doppler shift is equal to the change in Zeeman shift thus leading to a compensation of both shifts for one of the wings of the V-profile. The situation is slightly more complicated, however, since most solar spectral lines have a half width $\Delta\lambda_L$ (determined by the thermal Doppler width, the damping wings and the amount of saturation) which is of the same size or larger than the Zeeman shift. Since in this case the V-profile is approximately proportional to the derivative of the I-profile with respect to λ (cf. Stenflo et al., 1984), the Stokes V maxima are located roughly at $\pm\Delta\lambda_L$ from line center and not at $\pm\Delta\lambda_H$ as in the case of strong Zeeman splitting. Consequently, in this case the asymmetry is expected to be largest for $\Delta\lambda_D \approx \Delta\lambda_L$. Altogether we would expect that *the Stokes V- profile asymmetry is largest when $\Delta\lambda_D$ is of the same magnitude as the larger of $\Delta\lambda_H$ and $\Delta\lambda_L$.*

Since the zero crossings of the observed V-profiles are nearly unshifted, flow and magnetic field must be spatially separated in the case of magnetic elements in the solar photosphere. Therefore it seems reasonable to test our proposition using an atmosphere with the temperature and density structure of the VAL model which is divided into two parts: For $\tau < 0.1$ the atmosphere is static and pervaded by a constant magnetic field while for $\tau > 0.1$ the atmosphere is non-magnetic with a downflow of constant velocity. If the contribution function for Stokes V covers both regions of the model, the *changes* in Zeeman and Doppler shift are equal to the shifts themselves in the respective parts of the atmosphere.

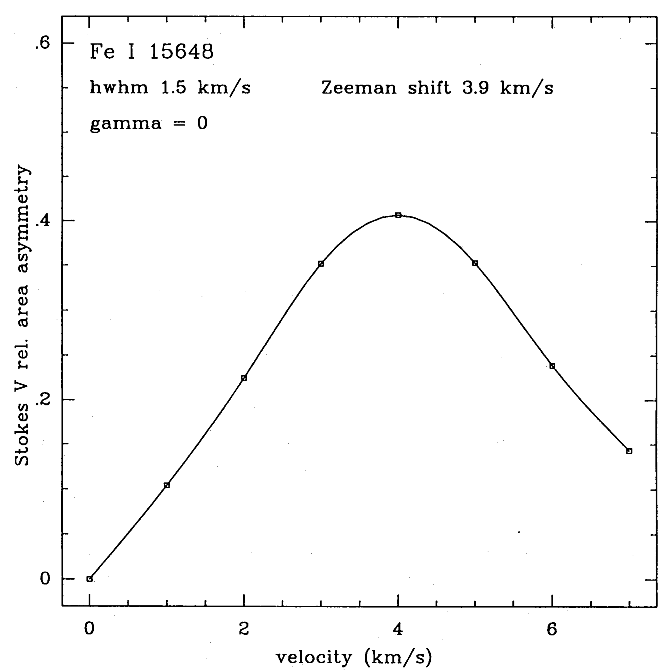

Fig. 1. Stokes V relative area asymmetry $\delta A = (A_b - A_r)/(A_b + A_r)$ for the infrared line FeI $\lambda15648$ as function of downflow velocity in the lower part of the two-component model described in the text for a constant Zeeman shift of 3.9 km/s (velocity units) which corresponds to 600 Gauss. δA reaches a maximum for $\Delta\lambda_D \approx \Delta\lambda_H$. The magnetic field is parallel to the line-of sight.

Fig. 1 shows the relative area asymmetry δA for the infrared line FeI $\lambda15648$ as function of Doppler shift (in units of the downflow velocity in the lower part of the model) for a given Zeeman shift (in the upper part of the model) of 3.9 km/s in velocity units (corresponding to 600 Gauss) which is much larger than the half-width of the line (1.5 km/s in velocity units). As we predicted the area asymmetry reaches a maximum for $\Delta\lambda_D \approx$

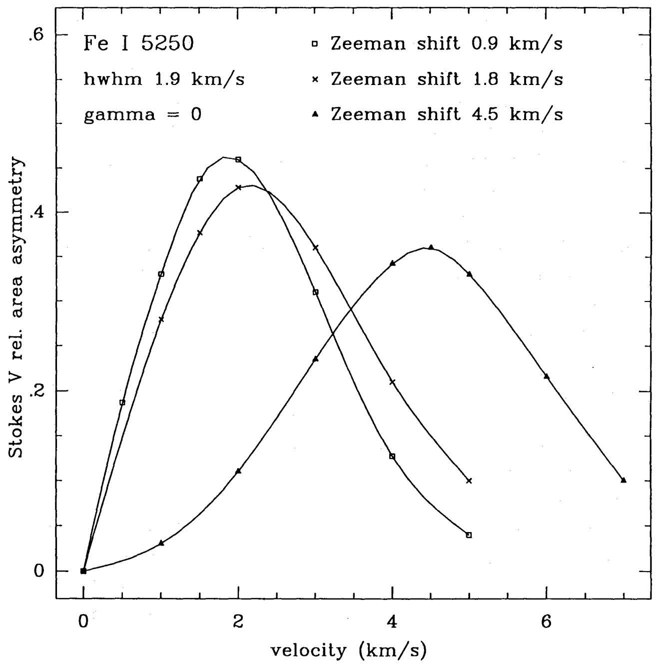

Fig. 2. Stokes V relative area asymmetry of the FeI $\lambda 5250.2$ line ($\Delta\lambda_L$ = 1.9 km/s) for three Zeeman shift values: Smaller (0.9 km/s), equal to (1.8 km/s) and larger than (4.5 km/s) the half width $\Delta\lambda_L$ of the line (1.9 km/s). δA reaches its maximum at $\Delta\lambda_D$ equal to the larger of $\Delta\lambda_L$ and $\Delta\lambda_H$ if $\Delta\lambda_L \neq \Delta\lambda_H$ and at $\Delta\lambda_L$ if $\Delta\lambda_L \approx \Delta\lambda_H$. Atmospheric model same as in Fig. 1.

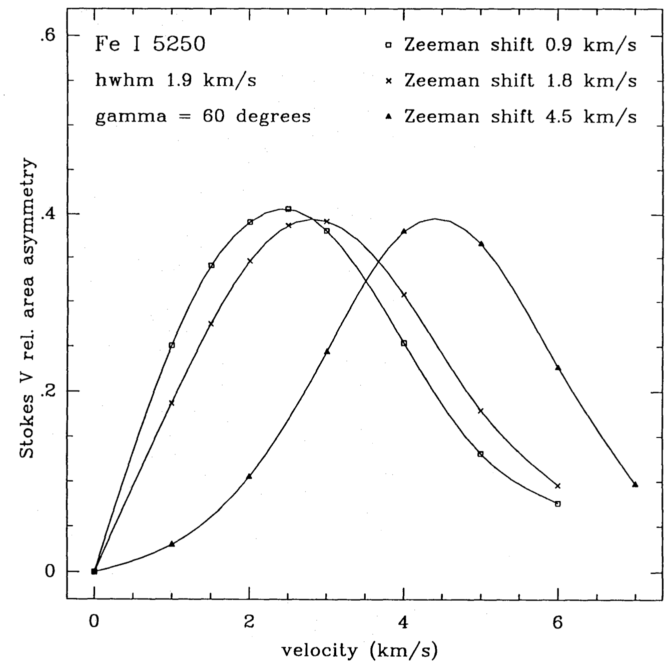

Fig. 3. Same as Fig. 2 except that here the angle between magnetic field and line-of-sight has been 60°.

$\Delta\lambda_H$. In Fig. 2 δA is shown for the FeI $\lambda 5250.2$ line ($\Delta\lambda_L = 1.9$ km/s) for three values of the Zeeman shift: Note that for $\Delta\lambda_H$ = 0.9 km/s (corresponding to 400 Gauss) which is much smaller than $\Delta\lambda_L$ δA has its maximum at $\Delta\lambda_D \approx \Delta\lambda_L$. If $\Delta\lambda_H \approx \Delta\lambda_L$ δA has its maximum at the same value of $\Delta\lambda_D$. Finally, for $\Delta\lambda_H$ = 4.5 km/s (corresponding to 2000 Gauss) which is much *larger* than $\Delta\lambda_L$ δA reaches its maximum at $\Delta\lambda_D \approx \Delta\lambda_H$.

In both Fig. 1 and Fig. 2 the area asymmetries are shown for a magnetic field *parallel* to the line-of-sight. In Fig. 3 δA is plotted again as function of velocity and for the same Zeeman shifts as in Fig. 2 but here the angle between the field and the line-of-sight has been 60°. Note that there is hardly any difference between these curves and the corresponding ones of Fig. 2. Thus it appears that - at least for the FeI $\lambda 5250.2$ line - the cross-talk between the various Stokes parameters which is caused by the magneto-optical effects in a non-parallel configuration has only little influence on the area asymmetry. Finally, in Fig. 4 the *amplitude* asymmetries are plotted for the same conditions and parameter values as for the *area* asymmetry in Fig. 2. Comparing Fig. 2 with Fig. 4 we see that there is no difference in the behaviour of both types of asymmetry. Consequently, our exploratory calculations fully confirm the heuristic considerations described above: The Stokes V asymmetries reach a maximum if the change of Doppler shift is equal to the larger of the change of Zeeman shift and line half-width. The results of Solanki (1989) who used more realistic 2D models comparing them with observed Stokes V-profiles can be understood on the basis of this concept.

The heuristic rule confirmed above is also basic for our understanding of the dependence of δA on *line strength*. Since the area asymmetry is a result of line saturation we would expect δA to vanish with decreasing line strength (Solanki and Pahlke, 1988). For relatively weak lines δA increases rapidly with line strength due to the increase of saturation of the line flanks where Stokes V is large. Strong lines, on the other hand, become very broad since the line core is completely saturated and the width is determined primarily by saturation and the increasingly prominent damping wings while thermal broadening of the absorption coefficients and Zeeman splitting contribute only little to the line width. Consequently, as $\Delta\lambda_D$ must be comparable to

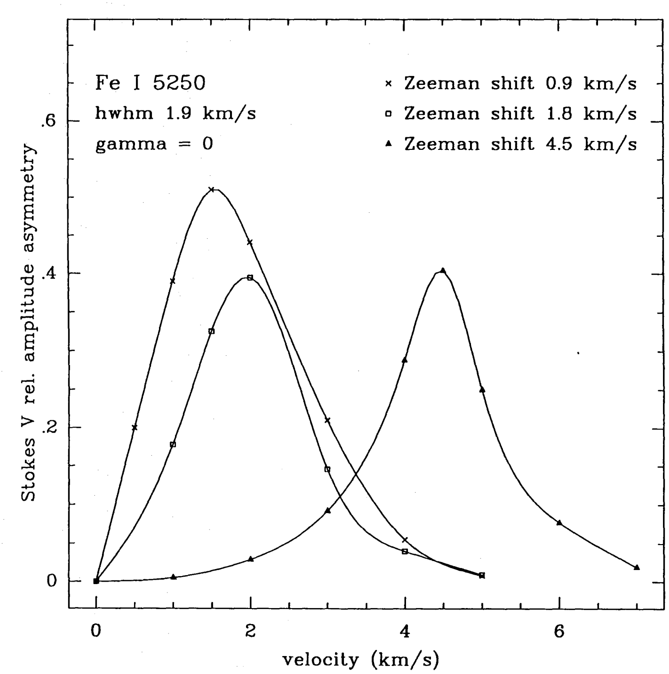

Fig. 4. Same as Fig. 2 except that here the *amplitude* asymmetry is plotted.

the larger of line half-width and Zeeman shift for maximum area asymmetry, the mechanism which creates the area asymmetry requires progressively larger velocities to be equally effective. Since for very strong lines the saturation of the line flanks does not change significantly with line strength it is no longer capable to compensate the decrease in efficiency of the basic mechanism as it would for weak lines. The result is a decrease in δA as the line strength increases beyond a certain value. In fact, it has been shown by Sanchez Almeida et al. (1989) that both observed and calculated V-profiles exhibit the dependence on line strength proposed above: δA first increases with increasing line strength (equivalent width) up to a maximum and then decreases again for very strong lines. The present concept is also supported by the fact that an increase of the damping constant (i.e. increase of the line wings leads to a stronger decrease of the absolute area asymmetry with equivalent width. The behaviour of the *amplitude* asymmetry fits in our picture as far as its increase with line strength for weak and moderately strong lines is concerned. However, δa does not decrease with line strength for very strong lines which is due to other effects which appear to become dominant in that regime (Solanki 1989).

4. Conclusion

The lack of a significant zero-crossing shift of observed Stokes V profiles together with a strong asymmetry can be understood in a natural way in terms of a magnetic flux concentration expanding with height and surrounded by downflowing material. We have given a *general* proof that the zero crossing of Stokes V is unshifted if magnetic field and flow are spatially separated. The dependence of the asymmetry on the relative magnitudes of Zeeman splitting, Doppler shift, line width and line strength has been predicted using heuristic arguments which have been fully confirmed by the exploratory calculations presented here. Similar results have been obtained by Sanchez Almeida et al. (1989) and also by Solanki (1989) who showed that this model, supplemented by an oscillatory motion within the flux concentration for producing the large observed values of the amplitude asymmetry, can quantitatively reproduce the observations.

The explanation of the major observed features of Stokes V by the geometric separation of magnetic and velocity fields finds independent support in numerical 2D simulations of the dynamics of flux concentrations (Knölker et al.,1988; Grossmann-Doerth et al., 1989) since the emerging models exhibit in their outer parts the same property: Magnetic field without velocity in the upper parts and field-free downflow below the fluxtube boundary. We plan to present in the near future Stokes profiles emerging from these models which permit a quantitative comparison with observations. This approach will open fascinating possibilities for the diagnostics of magnetic structures in the solar and stellar photospheres.

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