1991A&A...249..239G

Astron. Astrophys. 249, 239–242 (1991)

ASTRONOMY
AND
ASTROPHYSICS

The effect of non-linear oscillations in magnetic flux tubes on Stokes *V* asymmetry*

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Received January 4, accepted April 19, 1991

Abstract. The present knowledge on, and interpretation of, the asymmetry of Stokes V of spectral lines thought to be formed in and around magnetic flux tubes is reviewed. Crude models of non-linear oscillations in the flux tube were investigated in order to explain the observed values of Stokes V amplitude and area asymmetry. It was found that flux tube models with quasi-oscillatory motions, consisting of a slow upflow and a rapid downflow in the magnetic region, as well as a downflow in the non-magnetic surroundings, may reproduce the observations, both asymmetries and zero-crossing shift of Stokes V .

Key words: solar magnetic fields – flux tubes – Stokes parameters

1. Introduction

The asymmetry between the blue and red wings of Stokes V profiles in facular and network regions is now observationally well established (e.g. Stenflo et al., 1984; Solanki and Stenflo, 1984; 1985; Wiehr, 1985). The asymmetry is defined as the relative difference between the blue (a_b) and the red (a_r) Stokes V *peaks*, $\delta a = (a_b - a_r)/(a_b + a_r)$, and between the blue ($A_b$) and red ($A_r$) Stokes V *wing areas*, $\delta A = (A_b - A_r)/(A_b + A_r)$. Another well established observational finding is that the zero-crossing wavelengths λ_V of Stokes V profiles differ from the rest wavelengths of the lines by an amount corresponding to a Doppler velocity of less than $\pm 0.25\ \mathrm{km\,s^{-1}}$ (Stenflo and Harvey, 1985; Solanki 1986; Wiehr 1987). It has recently been shown (Grossmann-Doerth et al., 1988; 1989) that significant asymmetries together with an unshifted λ_V can be produced by flows *outside* the magnetic features ("Canopy mechanism"). This model is quite attractive because it can explain the asymmetry without any shift of the zero-crossing wavelength as a natural consequence of the geometrical structure of a static magnetic flux tube embedded in the granular velocity field. The model is also capable of reproducing quantitatively the observed δA and λ_V values of a set of spectral lines at disk centre (Solanki, 1989) and the centre-to-limb variation of these parameters for Fe I 5250.2Å (Bünte et al., 1991; Knölker et al.,1991).

However, the "Canopy Mechanism" fails to reproduce the observed asymmetry ratio $R_a = \delta a/\delta A$ which lies in the range two to eight. Since the mechanism leaves the *shape* of the wings of Stokes V virtually intact it produces values of R_a near unity. In addition, the calculated Stokes V widths are too small.

To resolve this problem Solanki (1989) invoked a non-stationary velocity within the magnetic features, in addition to the external flow. By assuming that the velocities during the up- and the downflowing phases have the same amplitude and by further giving the line profiles different weights in the two phases he was able to roughly reproduce the observed values of δa, δA and line width. However, the model proved to have unrealistic properties, in particular the relative behaviour of non-ionized and ionized Fe lines does not agree with observations. Moreover, the weight parameter has little physical meaning if both velocity phases have the same amplitude, simulating a linear oscillation.

A more realistic approach was taken by Solanki and Roberts (1990) who investigated linear longitudinal waves in thin magnetic flux tubes surrounded by granular downflow. Three main results emerge from their computations:

1. The asymmetry is quite sensitive to temperature, velocity correlation and velocity gradient, at the level of formation of the spectral lines. Changes in continuum intensity produced by these waves are too small to have a substantial effect.
2. Due to the phase shift between temperature and velocity only downwards propagating linear waves produce the correct sign of the asymmetry.
3. Since Fe II lines are less sensitive to the local temperature than low excitation Fe I lines, the asymmetry of the Fe II lines is less affected by a linear wave than that of Fe I lines. In particular the enhancement of the amplitude asymmetry is smaller. The difference between the asymmetry of Fe I and Fe II lines increases with the ratio of wave amplitude to external downflow velocity.

Observations show that Fe II lines have δa values similar to, and possibly even larger than, Fe I lines (Solanki and Stenflo, 1985) in contradiction to item 3 above. Hence the applicability of mechanisms based on temperature-velocity correlations to enhance δa appears doubtful (Solanki and Roberts, 1990). Also, it seems unlikely that more downwards propagating waves are present in flux tubes than upwards propagating ones, as required by item 2, particularly since magnetic fields are well correlated with areas of strong chromospheric heating (Skumanich et al., 1975; Schrijver et al., 1989).

We are thus facing the following situation: The "Canopy Mechanism" explains the observed area asymmetry together with the absence of a significant shift of the zero-crossing wavelength.

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* Mitteilungen aus dem Kiepenheuer Institut Nr. 351
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However it cannot explain the observed asymmetry ratio. We know that appreciable *stationary* flows cannot be present within the fluxtube (Solanki and Pahlke, 1988). As noted above *oscillatory* motions within the flux tubes with equal amplitudes of up- and downflow are unable to reproduce the observations. Furthermore, several processes *not* invoking internal mass flows were investigated by Solanki (1989) and found to be equally unable to simulate the observations.

One of the last ideas which comes to mind to resolve the problem are *non* -linear oscillations, i.e. the superposition of up- and downflows with different amplitudes and different durations. The present study investigates this possibility by means of simple numerical experiments.

2. Spectral lines

We have computed Stokes profiles of several spectral lines under varying physical conditions. As a guide the observed values of Stokes V profile asymmetries of the 5 spectral lines shown in Table 1 were used. These data were obtained from FTS observations of a network region (cf. Stenflo et al., 1984; 1987). The errors given in Table 1 are the statistical errors due to noise in the data, they do not include errors due to weak blends.

Table 1. Observational data

Spectral line	δa %	δA %
Fe I 5250.2	20 ± 4	8 ± 2
Fe I 5083.3	25 ± 8	7 ± 2
Fe I 15648.5	-3 ± 10	-1 ± 2
Fe I 16468.7	10 ± 2	4 ± 1
Fe II 5197.6	30 ± 10	4 ± 3

The aim of these numerical experiments was to determine the range of physical conditions under which Stokes V profiles of the listed lines that were generated by the superposition of two sets of profiles, one from an upflow and the other from a downflow phase, would roughly agree with the data in Table 1 and would not exhibit a zero-crossing shift of more than about 0.3 km s^{-1} .

3. Models

Three models were used. In all of them the final Stokes V profiles were obtained by a weighted superposition of the Stokes V profiles formed along two rays (or, in case of model-3, two sets of rays), one with a positive, the other with a negative velocity in the magnetic region. The three models are specified as follows:

Model-1 : Core oscillation

The velocities of the up- and down-flows are kept uniform throughout the atmosphere, simulating crudely the effect of an oscillation in the central part of a flux tube.

The model has three free parameters: v_u upward velocity, v_d downward velocity and w, the statistical weight of v_u versus v_d.

Two atmospheric models were used: VAL (Vernazza et al., 1981) with a uniform vertical magnetic field of 1200 G and the network flux tube model of Solanki (1986) whose magnetic field strength is height dependent.

Model-2 : Canopy oscillation

In this model the atmosphere is divided vertically into two parts. In the upper part there is a uniform vertical magnetic field and a uniform positive or negative velocity. In the lower part there is no magnetic field and a uniform downward velocity in the range 0.5 to 2 km s^{-1} which is equal for both rays.

The model is thought to simulate oscillations in the outer ("Canopy") part of a flux tube.

This model has four free parameters: v_u, upward velocity, v_d, downward velocity , w, statistical weight of v_u versus v_d and v_l, the velocity in the lower part of the atmosphere. Additional free parameters which, however, have not been varied much in the present investigation are the magnetic field strength (normally 1200 G) and the optical depth of the transition layer between the magnetic and the non-magnetic part of the atmosphere ($\tau_{5000} = 0.1$ in most cases).

Only a single atmospheric model, the VAL, has been used.

Model-3 : Complete Flux-Tube Oscillation

This is a 2D Thin Flux Tube Model with a downflow in the exterior field-free region. Two versions of this model were used, one with slab, the other with cylindrical geometry.

The velocities in the fluxtube were either uniform or linearly increasing with height. Thus the model actually consists of four sub-models.

Model-3 has four free parameters: v_u upward velocity, v_d downward velocity , w statistical weight of v_u versus v_d and v_e velocity in the exterior. In case of a non-uniform internal velocity v_u and v_d denote the maximum value which is reached at the top of the fluxtube; the velocity decreases linearly to zero at the bottom.

4. Results

Models 1 and 2 are very crude. We used them for exploratory purposes, i.e. to test our concept qualitatively. Computations with these models showed that Stokes V profiles with the desired properties could be obtained provided the upwards directed flow is slower and lasts longer than the opposite flow. In model-1 the parameter values of models with required properties of Stokes V of the Fe I 5250 line were different from those of the Fe I 5083 line. However, for model-2 we found a small parameter range in which the Stokes V profile of three diverse lines had the observed properties (cf. Table 2) - although the shapes of the line profiles were quite different from the observed shapes, e.g. some of the profiles were double-humped.

Table 2. Parameter ranges of "good" specimens of model-2 (velocities in km s^{-1}). Notation as in Sect. 3.

Spectral line :	Fe I 5250	Fe I 5083	Fe II 5197
v_u	0.5 ... 1.0	0.5 ... 1.0	0.3 ... 0.5
v_d	2.5 ... 3.5	2.5 ... 4.0	2 ... 3
$v_u + v_d$	≈ 4	≈ 4	≈ 4
w	≈ 3	≈ 3	≈ 3
v_l	1 ... 2	1 ... 2	1 ... 2

Encouraged by these results we proceeded to the more realistic model-3. Altogether nearly hundred composite Stokes profiles were computed for the spectral lines of Table 1. The flux tube was covered with normally 10 rays placed equidistantly from center out to a radius where the contribution to Stokes V became insignificant. All properties of the Stokes V profile except its absolute amplitude are thus uniquely determined. Normal incidence of the rays was always assumed. Because a composite profile in this model needs 20 individual profiles instead of two and for most "cases", i.e. definite sets of model parameters, five spectral lines had to be computed, the number of cases investigated was much smaller than for the other models, about four for each submodel. Guided by the experience gained during the explorations of the previous simpler models we attempted to find a parameter set which produced Stokes V profiles of the six spectral lines whose properties were within the observational bounds. This goal we did not achieve. However we found cases where most of the properties of the six lines met the requirement. In the following the best case for each submodel is listed.

Table 3.1. Slab with uniform velocity. $v_u = 1.0$, $v_d = 3.0$, $v_e = 1.5$, $w = 1.8$

Spectral line	δa %	δA %	v_s km s^{-1}
Fe I 5250	24	5	0.4
Fe I 5083	30	4	0.4
Fe I 15648	−1	2	1.0
Fe I 16468	9	0	0
Fe II 5197	28	4	0

Table 3.2. Slab with linearly varying velocity. $v_u = 1.0$, $v_d = 4.0$, $v_e = 2.0$, $w = 1.7$

Spectral line	δa %	δA %	v_s km s^{-1}
Fe I 5250	19	5	0
Fe I 5083	13	1	0.6
Fe I 15648	−3	0	0.7
Fe I 16468	7	4	0.2
Fe II 5197	29	7	0.3

Table 3.3. Cylinder with uniform velocity. $v_u = 0.5$, $v_d = 2.0$, $v_e = 2.0$, $w = 2.0$

Spectral line	δa %	δA %	v_s km s^{-1}
Fe I 5250	38	6	−0.2
Fe I 5083	16	16	0.6
Fe I 15648	2	3	0.6
Fe I 16468	19	6	0.2
Fe II 5197	15	8	0.5

Table 3.4. Cylinder with linearly varying velocity. $v_u = 0.5$, $v_d = 2.5$, $v_e = 2.0$, $w = 2.0$

Spectral line	δa %	δA %	v_s km s^{-1}
Fe I 5250	16	8	0.1
Fe I 5083	27	10	0.4
Fe I 15648	4	3	0.2
Fe I 16468	10	5	0.2
Fe II 5197	17	8	0.2

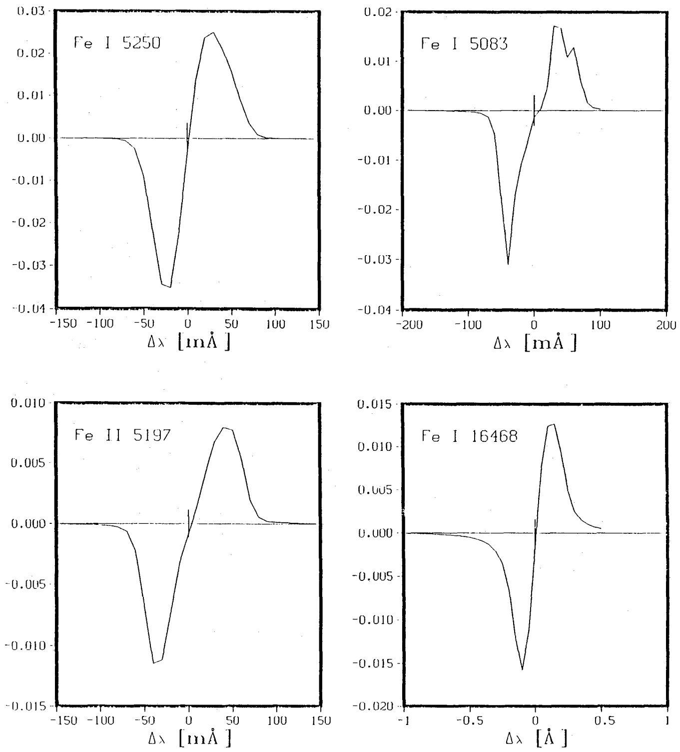

Fig. 1. Composite Stokes V profiles of the four lines which show significant asymmetry, emerging from a (cylindrical) thin flux tube with up- and down velocities as described in the text as case 4.

Figure 1 shows the Stokes V profiles of case 4 which come closest to the observational data (the line Fe I 15648 which has almost no asymmetry because of its very large Zeeman splitting has been omitted).

These data illustrate our main result: Velocity fields may be found which generate Stokes V profiles whose properties match nearly all the observed properties of the five lines. A set of parameter values may exist which would lead to a complete agreement with the observations, but we feel that this is not very likely. The failure to find a complete agreement may be attributed to the crudeness of our oscillation model and to the scatter of individual observational data that is larger than indicated by the statistical deviation values in Table 1.

5. Conclusions

Our computations show that in principle non-linear oscillations in the fluxtube could be the reason for the observed large amplitude asymmetry of Stokes V . They also show that in this case, in order to produce the right sign of the asymmetry, such oscillations must have a smaller and longer lasting upward than downward velocity amplitude. In order to produce the right magnitude of both asymmetry and zero crossing shift the velocity amplitudes must be about 0.5 km s^{-1} upward and about 2 km s^{-1} downward and the upward phase must last about twice as long as the downward phase. However there is no compelling evidence that this mechanism is actually at work in the photopheric flux tubes. Unlike the "Canopy Mechanism" which explains area asymmetry *and* absence of zero-crossing shift in a natural way, the superposition scheme would require the relevant physical parameters to assume values which lie within narrow limits. Although it might be argued that these values are specific properties of the magnetic fluxtubes we feel that before a reliable self-consistent simulation of non-linear flux tube oscillations is available the superposition mechanism ought to be considered with caution.

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