STOKES PROFILE FORMATION HEIGHTS IN SOLAR MAGNETIC FLUX TUBES

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Abstract: The formation heights of magnetically split lines in small solar magnetic flux tubes are investigated. In particular, we are interested in how the heights of formation depend on different flux tube parameters, like magnetic field strength, temperature and temperature gradient, as well as on line parameters, such as line strength, excitation potential and ionisation stage. The results should help to improve the construction of empirical models of magnetic features and improve our understanding of the spectral diagnostics used in the study of the solar magnetic field.

1. Introduction

Depth-dependent parameters of the solar photosphere, such as temperature, magnetic field and velocity are generally studied by observing spectral lines. For the interpretation of observational data it is important to know at which height a given wavelength in a spectral line is formed. Heights of formation (HOFs) of lines in the non-magnetic atmosphere have been relatively well studied, through both their contribution and their response functions. The situation for magnetically split lines is much less satisfactory. Although the problem has been addressed by a number of investigations (e.g. Wittman 1973, 1974, Landi Degl'Innocenti and Landi Degl'Innocenti 1977, Van Ballegooijen 1985, Grossmann-Doerth et al. 1988a, Rees et al. 1989, Murphy 1990) there does not, to our knowledge, exist any systematic study of how the heights of formation of magnetically split lines depend on different atmospheric and atomic parameters. In this paper we present such a study. In a sense the present investigation is complementary to that of Bruls et al. (1990). Their calculations are in NLTE and cover 4 models ranging from a sunspot umbra to an average 1-component network model. We restrict ourselves to LTE and small-scale magnetic structures, but consider in detail the effects of varying atmospheric and atomic parameters, besides listing the heights of formation of a number of lines in empirical flux tube models of magnetic elements. Since small-scale magnetic features may cover a wide range of properties (e.g. in temperature, cf. Solanki and Stenflo 1984, Zayer et al. 1990), it is not sufficient, although useful, to simply list the HOFs in one or two models of magnetic elements. A systematic study of the type reported on here is necessary to obtain an idea of the range of variation of the formation heights for different possible models and lines and thus to help improve diagnostics of the internal structure of magnetic features.

Grossmann-Doerth et al. (1988a, hereafter refered to as paper I) discussed the general problem of determining the heights of formation of magnetically split lines. Combining the approaches of Van Ballegooijen (1985a) and of Magain (1986) they derived the contribution function of the relative "line depression" Stokes vector, $R^{\dagger} = (1 - I/I_c, -Q/I_c, -U/I_c, -V/I_c)$, for magnetically split lines. They also demonstrated that this is a more useful diagnostic tool than the contribution function to the intensity. For example, the line depression contribution function is much more sensitive to changes in the magnetic field and its dependence on B can be interpreted in a straight forward manner. Therefore, in the present paper we exclusively discuss the line depression contribution functions calculated using the FORTRAN code presented in paper I for the numerical solution of the Unno-Rachkovsky equations based on Jones calculus, as proposed by Van Ballegooijen (1985a). The CFs are expressed per unit length and represented in a normalised form (i.e. divided by their peak value).

2. Spectral Lines and Flux Tube Models

In the present study of the heights of formation (HOF) of magnetically split lines we have calculated contribution functions (CFs) of a set of 20 Fe I and Fe II lines in 11 different flux tube models each. With few exceptions all the calculations presented here have been made assuming LTE, plane parallel atmospheres and vertical incidence. Except for some illustrative examples we only consider the central ray corresponding to the axis of symmetry of a cylindrically symmetric flux tube, since for vertical incidence the largest fraction of the Stokes V signal arises from the central part of the flux tube. The lines have been chosen to form a representative sample of the Fe I and Fe II lines in the visible solar spectrum. Fe I and Fe II lines lie at the heart of most empirical models and of most diagnostic techniques of small-scale magnetic features (e.g. Harvey and Livingston 1969, Stenflo 1973, Chapman 1977, Stellmacher and Wiehr 1979, Solanki and Stenflo 1984, 1985, Solanki 1986, Keller et al. 1990a, Zayer et al. 1989). The chosen lines are listed in Table 1. They can be divided into two groups, one consisting of 9 hypothetical lines, the other of 11 real lines. Among the hypothetical lines there are 3 Fe I lines with low excitation potential, 3 with high excitation potential and 3 Fe II lines. Each of these subgroups is composed of a weak, a medium strong and a relatively strong line. The group of real lines also consists of Fe I and Fe II lines with different line strength, excitation potentials and Landé factors. Most of the real lines correspond to the ones chosen by Solanki (1986) and Keller et al. (1990a) to construct empirical models of the atmosphere in magnetic elements.

The flux tube models used here have been chosen to test the dependence of the HOF on magnetic field strength, temperature and temperature gradient. In addition, we have used two empirical flux tube models, one for network and one for plage regions (Solanki 1986). From these we hope to obtain an idea of the typical formation heights of the chosen lines in small scale solar magnetic features. Finally, as a reference, CFs have also been calculated for the quiet sun model, the HSRA (Gingerich et al. 1971).

In addition to the CFs we have calculated an average HOF at each wavelength of interest of each line in the different models. It is not obvious how to define such an average, in particular for the CFs of Stokes Q, U and

Table 1: List of Fe lines

Ion	λ(Å)	χ_e(eV)	g_{eff}ls	g_{eff}emp	loggf
Fe I	5048.44	3.96	1.500	1.431	-1.02
Fe I	5083.34	0.96	1.250	1.250	-3.10
Fe I	5127.68	0.91	1.500	1.497	-3.03
Fe II	5197.57	3.23	0.700	0.671	-2.31
Fe I	5247.06	0.09	2.000	1.992	-4.95
Fe I	5250.22	0.12	3.000	2.999	-4.94
Fe I	5250.65	2.20	1.500	1.502	-2.12
Fe I	5293.96	4.14	1.000	0.976	-1.63
Fe I	5383.38	4.31	1.083	1.123	0.32
Fe II	5414.07	3.22	1.206	1.190	-3.23
Fe I	5445.05	4.39	1.200	1.248	-0.06
Fe I	5000.00	0.0	0.500		-6.50
Fe I	5000.00	0.0	0.500		-4.93
Fe I	5000.00	0.0	0.500		-3.07
Fe I	5000.00	4.0	0.500		-2.65
Fe I	5000.00	4.0	0.500		-1.20
Fe I	5000.00	4.0	0.500		-0.10
Fe II	5000.00	3.0	0.500		-4.65
Fe II	5000.00	3.0	0.500		-3.30
Fe II	5000.00	3.0	0.500		-2.00

The abundance used is 7.56 relative to log(A(H))=12

V, which can and generally do have different signs at different heights due to the fact that these Stokes parameters measure intensity *differences* between two orthogonal modes of polarization. Since, at a given wavelength, the opacity for the two modes is in general different they will be formed at different heights in the atmosphere. We have taken the centre-of-gravity of the contribution function to represent the average height at which the line is formed, although we also tabulate the centre-of-gravity of the absolute value of the contribution function. In the following the expressions 'height of formation" and HOF refer to the centre-of-gravity of the CF. However, we wish to stress that each line, and even each individual wavelength of a line, is formed over a rather extended region in the atmosphere and such average HOF values determined here only give a very rough indication of the layers over which the lines are formed.

3. General Properties of the Contribution Function

Magnetooptical effects influence the shapes of the CFs of Stokes Q and U, which may exhibit strong oscillations as a function of optical depth τ in the flanks of sufficiently strong lines, where the imaginary part of the eigenvalue of the absorption matrix becomes larger than its real part. For more details we refer to Rees et al. (1989), who discovered and first explained this phenomenon. Our calculations confirm the presence of these oscillations for our stronger lines. Although the shapes of the CFs gets more complicated due to the oscillations, we find that the average height of formation is, at the most, only slightly shifted.

In the following we concentrate on Stokes I and V, since most Stokes diagnostics so far applied to small-scale magnetic features depend on only these two Stokes parameters. We are more interested in basic effects than in the detailed CFs at many wavelengths of each individual line. For this reason and in order to maintain clarity we have decided to present and discuss the CFs only at line centre of Stokes I and at the wavelength of the Stokes V wing maximum, $\lambda(V_{max})$. Since often the CF(I) at $\lambda(V_{max})$, as well as CF(Q) and CF(U) at the wavelength of Q_{max} and U_{max} are rather similar to CF(V), it may in many cases be taken as an approximation for the other CFs in the line flanks. Of course, there are situations when this approximation does not hold. For example CF(I) differs considerably from the rest if only a part of the atmosphere along the line of sight is magnetic.

The HOF can depend considerably on the model atmosphere and the line parameters. At disk centre we find for the Stokes I core average heights of formation in the range $-4.4 \leq \log\tau \leq -0.6$. For the Stokes V peaks the corresponding values are -3.0 and -0.6. The somewhat lower Stokes V HOFs basically reflect the fact that the Stokes V CF refers to the line flank. Some of the factors determining the HOFs are discussed in the following sections.

One of the questions we have addressed is what does the CF look like when the magnetic field fills only a part of the atmosphere and a particular ray passes through both the magnetic and the non-magnetic parts. This situation is pertinent to small-scale solar magnetic features (e.g., Rees and Semel 1980, Van Ballegooijen 1985a,b) and has important consequences for observed Stokes profiles, e.g. the Stokes V asymmetry (Grossmann-Doerth et al. 1988b, 1989, Solanki 1989). To address this question we have considered two simple cases. In the first case the atmosphere is field free above $\log\tau = -1.5$. At this height there is a sharp transition to a field of 1000G that stays constant to the bottom of the tabulated atmosphere. In the second case the field is 1000G above $\log\tau = -1.5$, and 0 below that level. Fig. 1 illustrates the contribution functions resulting from the two cases. Interestingly, in the first case the CFs of Q, U and V disappear whenever $B = 0$, but in the second case they can be non-zero in the non-magnetic part of the atmosphere. Therefore, under certain circumstances, Stokes V, Q and U can obtain a contribution from the non-magnetic part of the atmosphere.

The apparent inconsistency between the two cases can be explained by considering the way in which the CF is calculated. We briefly illustrate this for the density matrix notation of the transfer equation (Van Ballegooijen 1985a). For the Müller matrix formalism the arguments are analogous to those outlined here. They are also independent of the numerical method of solution of the equation and in particular are also valid for the Feautrier and DELO techniques (Rees et al. 1989). If $\mathbf{C}$ is the 2×2 complex contribution matrix (cf. Van Ballegooijen 1985a or Paper I) then

$$\mathbf{C} = (\mathbf{T})^{-1}\mathbf{F}(\mathbf{T}^{*})^{-1},$$

where $\mathbf{F}$ is the Source function matrix and $\mathbf{T}$ is the density matrix analogue to the matrix attenuation operator

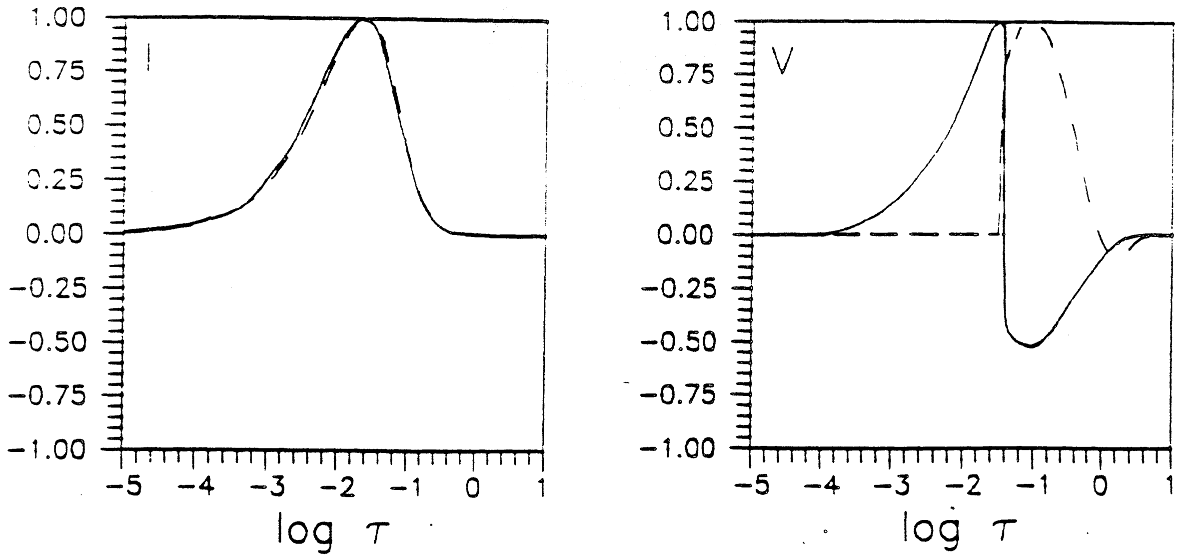

Fig. 1 The Stokes I contribution function (CF) at line center and the Stokes V CF at the wavelength of the V peaks of a high excitation Fe I line plotted vs. the continuum optical depth $\log\tau$ for two test atmospheres. Case 1 (dashed curve): The upper part of the atmosphere, above $\log\tau_{\rm crit} = -1.5$, is field free, while below this height a constant vertical field of strength 1000G is present. Note, that the CF is zero wherever there is no field. Case 2 (solid curve): A constant field of 1000G is now present above $\log\tau_{\rm crit} = -1.5$, while the atmosphere below that height is field free. The CF of Stokes V is now non-zero also in the field free part of the atmosphere.

(e.g. Landi Degl'Innocenti and Landi Degl'Innocenti 1985). $\mathbf{T}$ is found by integrating a set of 4 complex ordinary differential equations,

$$d\mathbf{T}/d\tau = \mathbf{A}\mathbf{T}, \qquad \text{with} \quad \mathbf{T}(\tau = 0) = \mathbf{1},$$

downwards from $\tau = 0$. This implies that in the first case (i.e. $B = 0$ for $\tau \leq \tau_{\rm crit}$) in the field free part of the atmosphere $\mathbf{T}(\tau \leq \tau_{\rm crit})$ is diagonal since $\mathbf{A}(\tau \leq \tau_{\rm crit})$ is diagonal (both $\mathbf{T}$ and $\mathbf{A}$ are proportional to the unity matrix there). $\mathbf{F}(\tau \leq \tau_{\rm crit})$ is also proportional to the unity matrix, so that $C_Q = C_U = C_V = 0$ for $\tau < \tau_{\rm crit}$ in this case. For the second case (i.e. $B = 0$ for $\tau > \tau_{\rm crit}$) $\mathbf{T}(\tau > \tau_{\rm crit})$ is not diagonal, although $\mathbf{A}(\tau > \tau_{\rm crit})$ and $\mathbf{F}(\tau > \tau_{\rm crit})$ are, since $\mathbf{A}(\tau < \tau_{\rm crit})$ also influences $\mathbf{T}(\tau > \tau_{\rm crit})$. Therefore, C_Q, C_U and C_V do not necessarily disappear in the part of the atmosphere where there is no field.

This behaviour warns us to bear the exact meaning of contribution functions in mind whenever discussing them or formation heights derived from them: The intensity CF tells us how much light of a given frequency is emitted at a given depth τ and escapes at the upper boundary of the atmosphere. This definition of the CF shows that the CF depends only on the properties of the atmosphere above the depth in question. Similarly, the line depression CF tells us how strongly the light intensity at a given wavelength is suppressed at a given depth and is not reemitted at that wavelength until the upper boundary of the atmosphere is reached. Basically, the current tests imply that the CF is sensitive to the atmosphere above the height of interest, but not below it.

4. Temperature Dependence

Like the Stokes profiles themselves their heights of formation depend in a complex manner on the temperature stratification. This dependence is itself a function of ionisation stage and excitation potential. In order to examine the dependence on the absolute value of temperature we have used four models (HSRA, TEMP1, TEMP2 and TEMP3). Each of the latter 3 models is about 400K hotter than the preceding one. Our computational results may be summarized as follows: A low excitation Fe I line is greatly weakened when the temperature is increased, and hence its HOF is shifted downwards. The shift is much larger for the line core than for the flanks. For a temperature increase of 1200K the decrease in its HOF is approximately 1.6 in units of $\log\tau$ for the line centre and 0.5 for the flanks. For the high excitation Fe I line both the line weakening and the shift of the HOF due to the temperature increase are much smaller. The HOF of the line core is shifted downwards by 0.8 in $\log\tau$, while the HOF of the flanks is almost unaffected. The Fe II line shows a completely different behaviour. The temperature hardly affects the line strength at all and the HOF actually increases with temperature instead of decreasing. The amount of increase is similar for both the line flank and core, $\delta\log\tau = 0.5$ for a temperature difference of 1200K.

To reliably determine the temperature in unresolved magnetic features we have to use Stokes V, Q, or U profiles, since Stokes I is in general contaminated by light from the non-magnetic atmosphere. Due to the rough proportionality of Stokes V, Q, and U to the magnetic flux, ratios between the V, Q, or U profiles of two or more lines that differ strongly in their temperature sensitivities must be considered (e.g. Stenflo 1975, Landi Degl'Innocenti and Landolfi 1982), although diagnostics of the temperature that rely on the line profile shape do exist (e.g. Solanki et al. 1987, Lites et al. 1987). If the HOFs of the two lines have different temperature dependences, their relative heights of origin in the atmosphere will change with temperature, complicating the interpretation of such line ratios. As can be seen from the last paragraph, this is generally the case if the ratio is formed between two lines with strongly different excitation potentials or belonging to different ions. Exactly such line ratios (often termed "thermal line ratios") have been proposed and used to construct empirical models of magnetic elements (Landi Degl'Innocenti and Landolfi 1982, Zayer et al. 1990). Note, that for weak Zeeman splitting the situation is worse at line centre than in the flanks. Therefore, Stokes V line ratios and ratios involving only Q and U σ components should be less affected. Unfortunately, the line-centre line ratios (between the π-components of Stokes Q and or U profiles) show the best promise of providing diagnostics of the temperature in the higher layers of flux tubes.

Note that the σ-components are simpler to interpret only if the Zeeman splitting is small compared to the Doppler width, since otherwise the peaks of the σ-components also correspond to the line core and are affected in a similar manner as the core of the π component. However, this should not be a major problem for lines in the visible. The most strongly split lines in the near infrared are all high excitation Fe I lines ($5\text{eV} \lesssim \chi_e \lesssim 6.5\text{eV}$), which are of only limited use for the determination of the temperature in small magnetic features (Muglach and Solanki 1990).

The parameter which influences the HOFs the most is the temperature gradient. Not only does the average HOF change dramatically between models with different temperature gradients, but so does the width of the contribution functions. The $T(\tau)$ structure of the three models used to test the dependence on temperature gradient is shown in Fig. 2. The models have been chosen such that the lines formed in all three of them have roughly similar equivalent widths, although certain differences in equivalent width and profile shape are unavoidable. In particular, the equivalent widths of the Fe I lines for the three models are considerably closer together than for the TEMP1,2 and 3 models. In this manner we ensure that differences between the HOFs resulting from different models are not mainly due to changes in the equivalent widths of the lines. As pointed out earlier TEMP1 has a gradient much like that of the HSRA. TEMP4 has a very flat temperature profile above $\log\tau \approx -1$, with the temperature actually increasing again outwards above $\log\tau \approx -2.5$. This model is roughly similar to the empirical flux tube models of Stenflo (1975) and Chapman (1977, 1979). TEMP5 is in many ways the opposite to TEMP4, since it has an almost constant gradient throughout the photosphere, whereas $dT/d\tau$ of TEMP4 changes dramatically around $\log\tau = 1$.

Examples of profiles and their line core CFs resulting from these 3 models are shown in Fig. 3. The CFs of the low excitation Fe I line are again more sensitive to changes in the temperature structure than the CFs of the high excitation Fe I and the Fe II line. In a model like TEMP5, with a steeper temperature gradient in the line forming layers than both the HSRA, the low excitation Fe I line are formed much higher in the atmosphere than the high excitation Fe I line and the Fe II line, while in a model with a temperature minimum deep in the photosphere (TEMP4) all the lines are formed at almost the same height. The temperature gradient does not change the difference in HOF between the line flank and the core. This implies that the large variations of the line core CFs seen in Fig. 3 are mirrored by the CFs at, say, the Stokes V peaks or the Q or U σ-component peaks. The strong influence of the temperature gradient on the HOFs again has serious consequences for the interpretation of thermal line ratios. Now, since the Stokes V peak CFs are affected in a similar manner as the line core CFs the Stokes V line ratios become as complex to interpret as those of the Stokes Q and U π-components.

As a concrete example we have considered the often used Stokes V line ratio between Fe I 5247.1Å and 5250.6Å (Stenflo et al. 1987, Keller et al. 1990a, Zayer et al. 1990). According to our calculations it should be easily

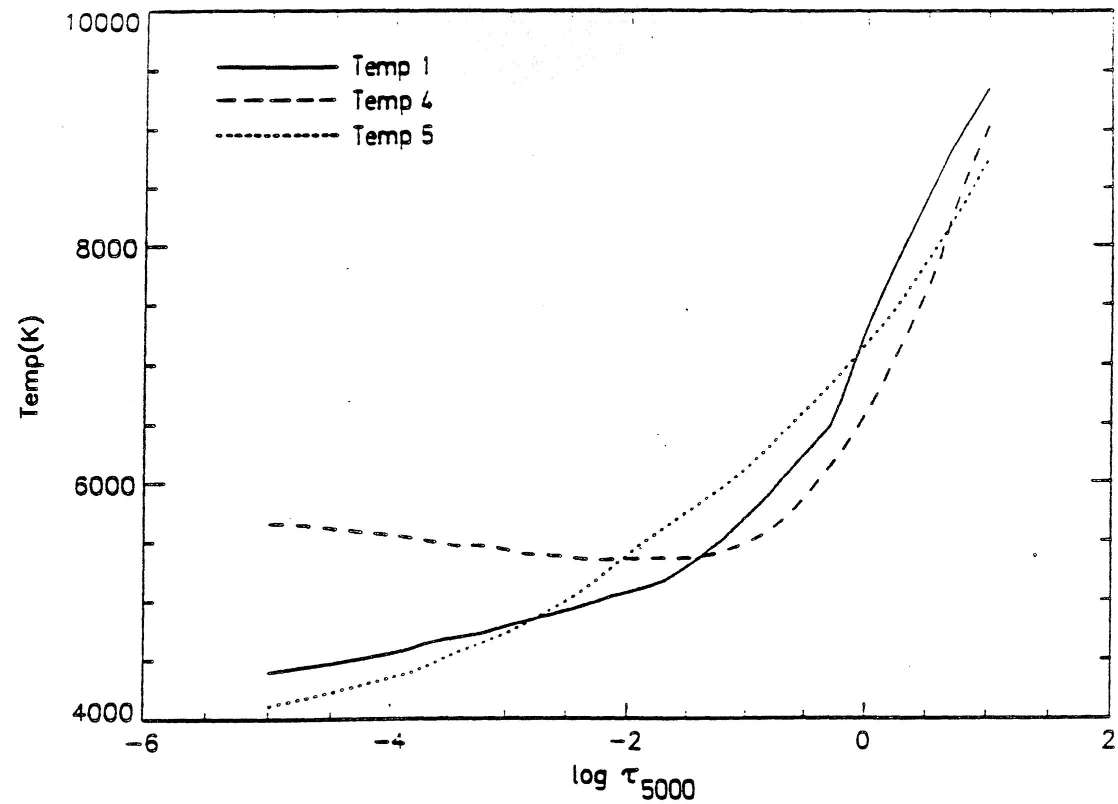

Fig. 2 Temperature as a function of log τ for three flux tube models. The solid curve represents TEMP1, which has a temperature gradient very similar to the quiet sun HSRA model. The dashed curve represents the TEMP4 model and the dotted curve the TEMP5 model.

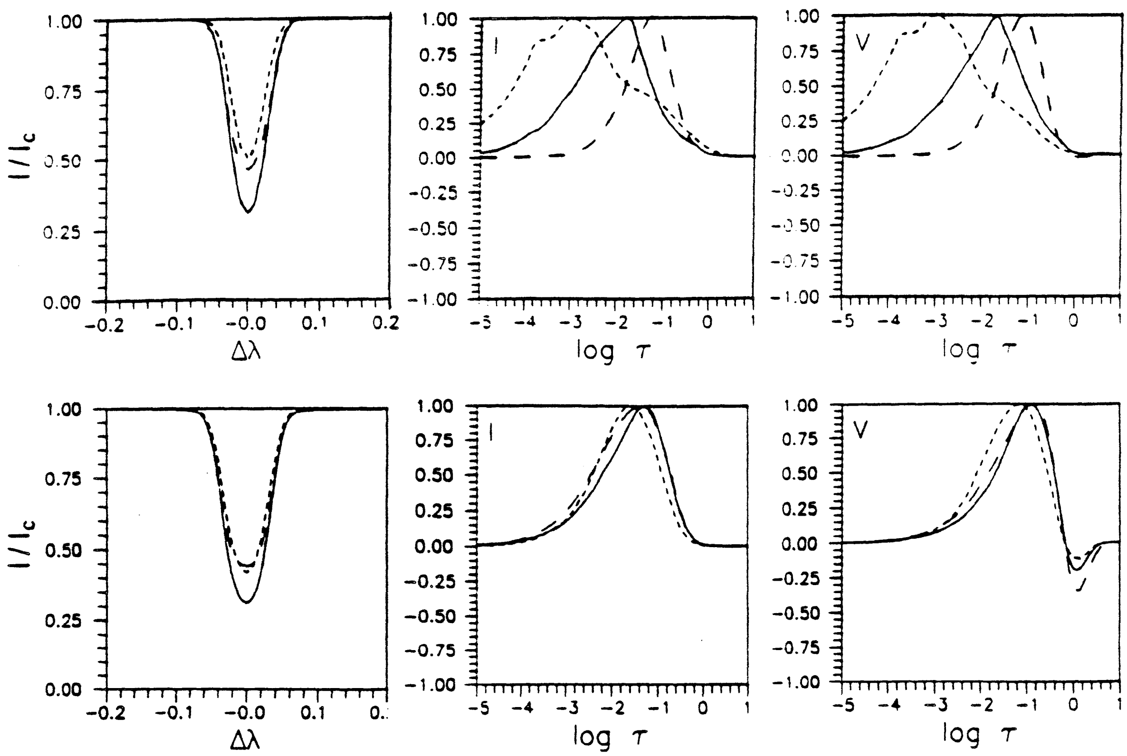

Fig. 3 Stokes I line profiles (left panels) and Stokes I (middle panels) and Stokes V (right panels) contribution functions of a low excitation Fe I line (upper three panels), and an Fe II line (lower three panels) showing the dependence on temperature gradient. The symbols refer to the same atmospheres as in Fig. 2. The CF to Stokes I is for the line centre, while the CF to Stokes V is for the wavelength at which Stokes V has its maximum.

interpretable, since the V maxima of these lines are formed at almost the same heights in all models. (However, the cores of these two lines are often formed at rather different heights.)

5. Dependence on Magnetic Field Strength

In general for Zeeman splittings larger than the line width the HOFs depend strongly on field strenght. Starting from an unsplit line, an increase in the splitting due to a longitudinal field causes the line centre to be formed deeper and deeper in the atmosphere and the HOF of the line flanks, particularly at the wavelength where Stokes V has its maximum, to increase. This increase continues until the line is fully split. Let us now consider the specific case of the two Fe I lines 5250.2Å ($g_{\rm eff} = 3$) and 5247.1Å ($g_{\rm eff} = 2$). We have calculated the HOFs of these two lines in a standard atmosphere, the HSRA, assuming constant magnetic fields of different strengths. The CFs for 3 cases 100G, 1000G and 3000G are illustrated in Fig. 4. As can be seen from the figure the lines are formed at the same

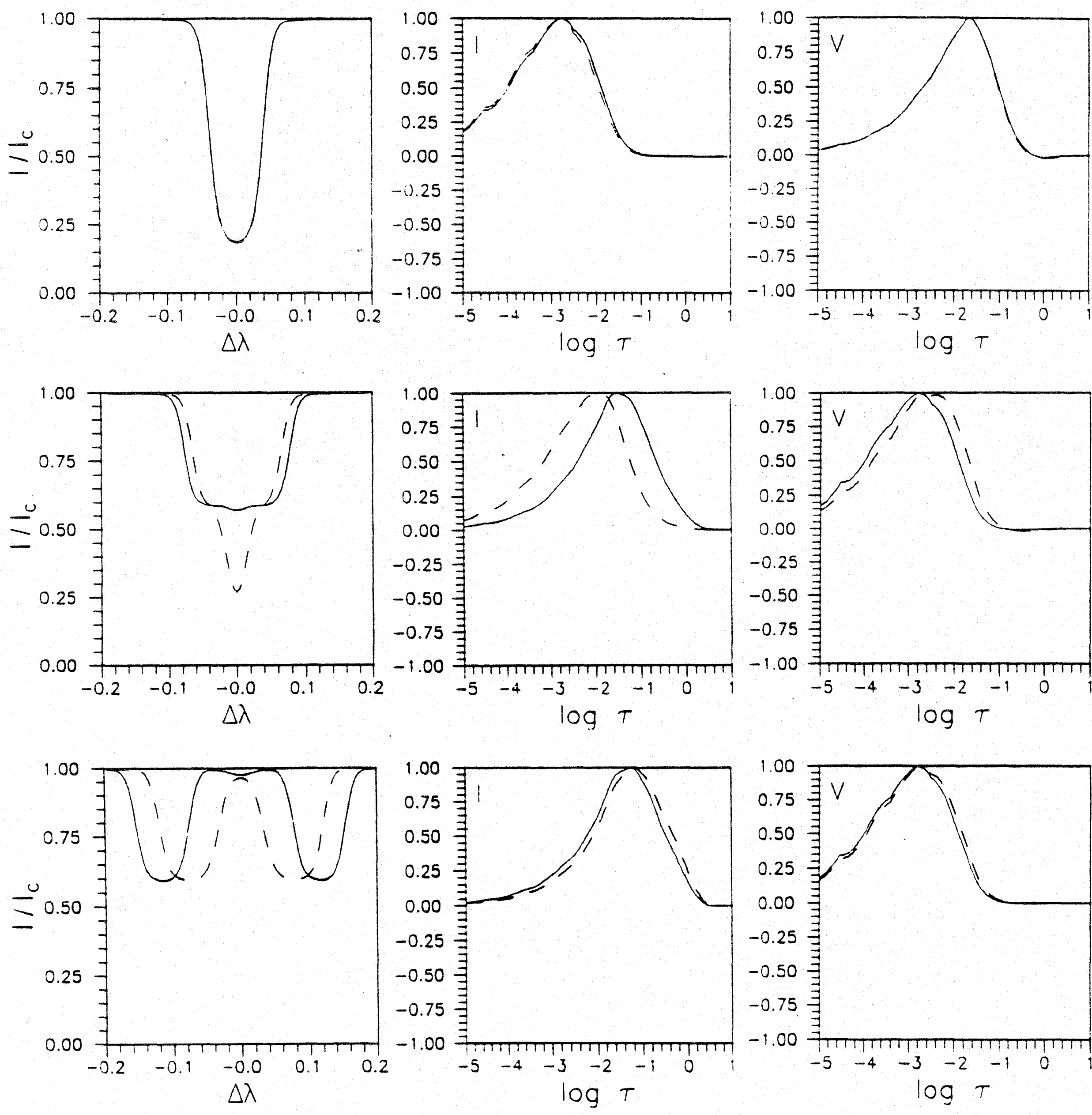

Fig. 4 Stokes I profiles of Fe I 5250.2Å and 5247.1Å (left) and their Stokes I (center) and Stokes V (right) contribution function for 100G (upper three panels), 1000G (middle panels) and 3000G (lower panel). The solid curve is for 5250.2 Åand the dashed curve for 5247.1 Å.

height for both weak and strong fields, when either both lines show no effect on their line profile shapes due to the magnetic field, or both are completely split. However, there is an intermediate field strength range for which the cores of the 2 lines are not formed at the same height. Fortunately, the difference in HOF is relatively small at $\lambda(V_{max})$, so that that the ratio between the V_{max} of these two lines is always sensitive to the field strength at a given height and the field strength gradient does not *directly* affect the line ratio. However, the gradient can have a substantial indirect effect on the line ratio, via the temperature. Recall that both lines have low excitation potentials and are thus extremely temperature sensitive. Fig. 3 shows the spread of the CFs of similar lines, due to variations of the temperature stratification of the magnetic features. Thus, due to its strong dependence on height, the magnetic field strength at the HOF can be quite different from model to model, although as a function of geometrical height it may be relatively unaffected by the temperature (cf. Zayer et al. 1990, Grossmann-Doerth and Solanki 1990).

Note, that it is better to use the V_{max} values, instead of the ratio between the V profiles at some fixed wavelength (as is the case for magnetograms, Stenflo 1973, Frazier and Stenflo, Wiehr 1978, and filtergrams, Keller et al. 1990b), since the differences in HOF between the two lines can be considerably larger at a fixed wavelength than if the HOFs at the two $\lambda(V_{max})$ are compared.

The behaviour described here is only true as long as B is almost parallel to the LOS. When observing the field at an angle at which the π-component is equally strong as the σ-components the decrease of the HOF at line centre with increasing B is negligible. This is encouraging for the line ratio between the π-components of 5250.2Å and 5247.1Å (in particular of their Q and U profiles), which could provide a diagnostic of the magnetic field strength in higher layers of the atmosphere.

6. Estimated Formation Heights in Solar Magnetic Elements

In Table 2 we present average values of HOFs of Stokes I and V for the 11 selected lines actually present in the solar spectrum, calculated in the empirical network flux tube model of Solanki (1986). The corresponding model of Keller et al. (1990) give relatively similar results. Therefore we consider the values listed in Table 2 to represent the current best estimate of the formation heights of these typical iron lines in small-scale magnetic features.

7. Conclusions

We have calculated the Stokes contribution functions of a variety of magnetically split Fe I and II lines in a number of atmospheres. Thereby we have been able to obtain a better understanding of some of the diagnostics of the temperature and magnetic field within small-scale magnetic features. We find that among the atmospheric parameters the temperature gradient plays the dominant role in determining the heights of formation of temperature sensitive lines. The interpretation of many diagnostics cannot be assumed to be so straightforward as has been thought in the past. In particular, diagnostics based on multiple lines can become rather complex to interpret, since the differences between the heights of formation of the different lines changes with the assumed temperature structure. However, other diagnostics turn out to be relatively unaffected, a prime example being the magnetic line ratio between Fe I 5250.2Å and Fe I 5247.1Å of Stenflo (1973).

We have also presented estimates of the heights of formation in small-scale solar magnetic elements of 11 typical Fe I and II lines. One of the conclusions which can be drawn from this tabulation is that the Stokes V maxima of all these lines are formed at not too different heights. This implies that current Stokes V based empirical models of magnetic elements are only reliable over a rather limited range of the atmosphere (approximately $-3 \lesssim \log\tau \lesssim -1$). To increase this height range upwards either the line profile shapes of Stokes V near the line cores will have to be employed, or the π-components of Stokes Q and U.

Table 2: Height of Formation of Fe lines in an empirical network fluxtube model

Ion	λ (Å)	HOF I (log τ)	HOF V (log τ)	HOF V* (log τ)
Fe I	5048.44	-1.7	-2.0	-1.9
Fe I	5083.34	-2.9	-2.9	-2.6
Fe I	5127.68	-3.0	-2.5	-2.4
Fe II	5197.57	-2.7	-2.0	-1.6
Fe I	5247.06	-2.0	-2.2	-2.2
Fe I	5250.22	-1.8	-2.2	-2.2
Fe I	5250.65	-2.5	-2.6	-2.4
Fe I	5293.96	-1.3	-1.3	-1.3
Fe I	5383.38	-2.9	-3.1	-2.0
Fe II	5414.07	-1.5	-1.6	-1.5
Fe I	5445.05	-2.4	-2.2	-1.8

HOF V is the center-of-gravity of the contribution function. HOF V* is the center-of-gravity of the absolute value of the contribution function.

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