AT WHAT HEIGHTS ARE SPECTRAL LINES FORMED IN SOLAR MAGNETIC FLUX TUBES?

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ABSTRACT

Illustrative examples, taken from a study of the formation of magnetically split lines in solar magnetic flux tubes, are presented. In particular, we are interested in how the heights of formation depend on different flux tube parameters, like the magnetic field strength, the temperature and temperature gradient, as well as on line parameters, such as line strength, excitation potential and ionization stage. The result should help to improve the construction of empirical models of magnetic features and provide a new understanding of the spectral diagnostics used in the study of the solar magnetic field.

INTRODUCTION

Depth-dependent parameters in the solar photosphere, such as temperature, magnetic field and velocity are generally studied by observing spectral lines. For the interpretation of the 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, but little work has been done in the case of magnetically split lines. We have therefore made a systematic study of how the HOFs of magnetically split lines depend on atmospheric and atomic parameters. A detailed description of the method used is given by Grossmann-Doerth, Larsson, Solanki (1988, hereafter called GLS). We take the contribution function to the relative "line depression" Stokes vector, $R\dagger = (1 - I/I_c, -Q/I_c, -U/I_c, -V/I_c)$, to represent the heights of formation of the lines. As has been pointed out by GLS this is a more useful diagnostic tool than the contribution function of the emission Stokes vector. For example, it is much more sensitive to changes in the magnetic field and its dependence on B can be readily interpreted.

SPECTRAL LINES AND ATMOSPHERE MODELS

In our study of the 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.

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In order to save computing time all calculations have been made assuming LTE. The lines were chosen to form a representative sample of the Fe I and Fe II lines in the visible solar spectrum. This sample consists of 9 hypothetical and 11 real lines. The hypothetical lines include 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 strong line. The group of real lines also consists of Fe I and Fe II lines with different line strengths, excitation potentials and Landé factors.

The flux tube models have been chosen to test the dependence of the HOF on the magnetic field, the temperature and the temperature gradient. We have, in addition, used two empirical flux tube models, one for network and one for plage regions (Solanki, 1986). From these we hope to obtain estimates of the true formation heights for the selected lines in small scale solar magnetic features.

GENERAL BEHAVIOUR OF THE CONTRIBUTION FUNCTIONS

Due to the different physical meanings of Stokes I, Q, U and V, the shapes of their CFs are quite different. The CFs of Q, U and V generally have both a positiv and a negative component due to the fact that these three parameters measure intensity differences between two orthogonal modes of polarization. Since, at a given wavelength, the opacity of the two modes is in general different they will be formed at different heights in the atmosphere. Magnetooptical effects also 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 cores of strong lines, as discussed by Rees et al. (1989). Our calculations confirm the presence of these oscillations (Fig. 1). Although the shapes of the CFs get more complicated due to these effects, we find that the average heights of formation are only slightly affected.

At disc center we find for Stokes I (unpolarized light) line cores HOF values, in terms of continuum optical depth, to be in the range $-4.4 \leq \log \tau_{5000} \leq -0.6$. For Stokes V (circularly polarized light) maxima the corresponding values are -3.0 and -0.6. The exact value of the HOFs is found to depend on a number of factors, of which temperature and temperature gradient will be discussed in this paper. Even though we sometimes discuss the average height of formation of a line one has to be aware of the fact that each line and even each wavelength of a line is formed over a rather extended region in the atmosphere.

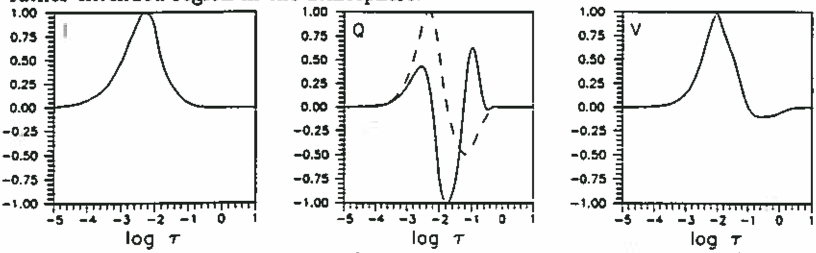

Fig. 1. Contribution Functions for Stokes I and Q at line center and for V at the wavelength at which the V profile has its maximum. The line is FeI 5414.1 A calculated is a network model. We assume a near vertical fluxtube with azimuth angle 30°. Solid line models include magnetooptical effects while the dashed do not.

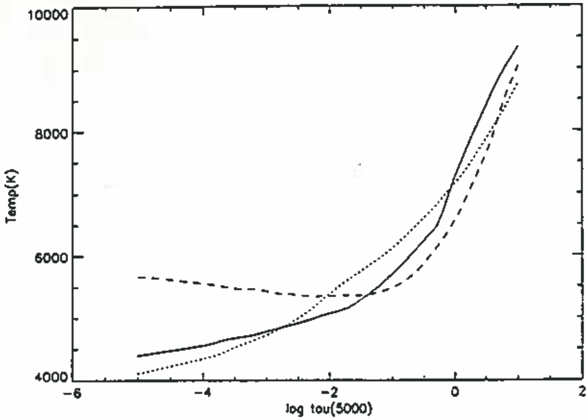

Fig. 2. Temperature as a function of log τ_{5000} for three different fluxtube models. Solid line is Temp1, which has a gradient very similar to the HSRA model. Dashed line is Temp4 and dotted line Temp5. These models are used to demonstate how the heights of formation of Stokes profiles depend on the temperature gradient in the fluxtube.

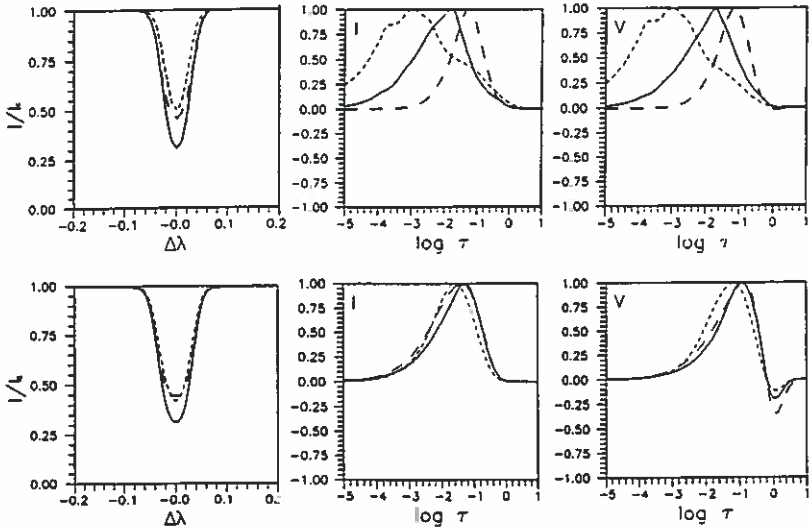

Fig. 3. Stokes I profiles and contribution functions of a low excitation FeI line (upper 3 diagrams) and an FeII line (lower 3 diagrams) showing the dependence on temperature gradient. Atmosphere and symbols as in Fig. 2. Again the CF to I is for line center and the CF to V is for the wavelength where the profile has its maximum.

TEMPERATURE DEPENDENCE

The heights of formation of Stokes profiles depend in a complex way on the temperature and on the temperature gradient. This dependence also varies with ionization stage and excitation potential.

The low excitation Fe I lines are greatly weakened as the temperature is increased, and the lines are therefore formed deeper in the atmosphere. The decrease in the HOF is larger for the line centers than for the wings. For a temperature increase of 1200K the decrease in HOF is approximately 1.6 in units of $\log \tau_{5000}$ for the line center and 0.5 for the wing. Although the high excitation Fe I line undergoes a similar line weakening the effect is much smaller, 0.8 for the line center while the HOF of the wings is unaffected. The Fe II line shows a completely different behavior. The temperature hardly affects the line strength at all, but the line (center as well as wings) is formed higher up in the atmosphere as the temperature increases. $\delta \log \tau(\mathrm{HOF}) = -0.5$ for a $\delta T = 1200\mathrm{K}$.

These results influence the interpretation of the thermal line ratio (lowχ_e/highχ_e or Fe I/Fe II lines, e.g. Landi Degl'Innocenti and Landolfi, 1982), which is often used to determine the temperature in the magnetic atmosphere. If the HOFs of two lines have different temperature dependences, their relative heights of origin in the atmosphere will change with temperature, making the interpretation of such line ratios in general somewhat complicated. However, the often used line ratio between Fe I 5247.1Å and 5250.6Å should be easily interpretable, since the V maxima of these lines are formed at almost the same heights in all models.

The atmospheric parameter which influences the HOFs the most is the temperature gradient. Not only does the average HOF change between models with different temperature gradients but also the width of the CFs are affected. The three models used for testing the dependence on temperature gradient are shown in Fig. 2 (TEMP1 has a gradient much like that of the HSRA, Gingerich et al. 1971). As shown in Fig. 3, the low excitation Fe I line is also more sensitive to changes in the temperature gradient than are the Fe II line. Unlike the absolute value of the temperature the gradient does not have a large influence on the line strength and it does not change the difference in HOF between the wing and the line center.

In a model like TEMP5, with a steeper temperature gradient in the line forming layers than 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, near this minimum temperature.

REFERENCES

Gingerich, O., Noyes, R.W., Kalkofen, W., Cuny, Y., (1971) Solar Phys. 18, 347

Grossmann-Doerth, U., Larsson, B., Solanki, S.K., (1988) *Astron. Astrophys.* **204**, 266-274

Landi Degl'Innocenti, E., Landolfi, M., (1982) *Solar Phys.* **77**, 13

Magain, P., (1986) *Astron. Astrophys.* **163**, 135

Rees, D.E., Murphy, G.A., Durrant, C.J., (1989) *Astrophys. J.* **339**, 1093

Solanki, S.K., (1986) *Astron. Astrophys.* **168**, 311