EMPIRICAL PHOTOSPHERIC FLUXTUBE MODELS FROM INVERSION OF STOKES V DATA

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ABSTRACT. We present results of an inversion procedure that derives the turbulent velocity, the magnetic field strength, and the temperature stratification of the photospheric layers of solar magnetic fluxtubes from 10 FeI and FeII Stokes V line profiles around 5250 Å and from the continuum contrast. The free parameters of two-dimensional magnetohydrostatic fluxtube models are determined by minimizing the difference between observed and calculated Stokes V parameters in an iterative manner. Results of this inversion procedure applied to observations of a plage and a network region at disk center indicate a temperature deficit (at equal geometrical height) of the fluxtubes at the level of continuum formation and a temperature excess at the highest levels of line formation in general agreement with the latest theoretical fluxtube models.

1. Introduction

Most existing empirical models of solar magnetic fluxtubes have been obtained by fitting synthetic spectra from simple fluxtube models to observed Stokes I profiles or synthetic continuum intensities to the observed center-to-limb variation of the facular continuum contrast. A few one-dimensional models have been derived from Stokes V observations (see the references in Solanki, this volume). Only in the latter case the analysis can be performed independently of the spatial resolution and the filling factor. In this work we present empirical, two-dimensional, self-consistent fluxtube models obtained by an inversion of Stokes V line profiles. These models take into account the spreading of the fluxtube with increasing height, the current sheet, and tension forces, in contrast to earlier models. A more precise description of the inversion procedure and its application to observations can be found in Keller et al. (1989).

2. Inversion of Stokes V Profiles

The inversion of Stokes V profiles is based on the determination of a few model fluxtube parameters by the iterative least-squares fitting algorithm of Marquardt (1963). The free parameters of the axisymmetric, magnetohydrostatic fluxtube models of Steiner et al. (1986) are the magnetic field strength at optical depth unity inside the fluxtube $B(\tau_i = 1)$, the macroturbulence velocity as a function of the strength and the excitation potential of

J. O. Stenflo (ed.), Solar Photosphere: Structure, Convection, and Magnetic Fields, 121–124.

https://doi.org/10.1017/S0074180900044053 Published online by Cambridge University Press

the spectral lines, and the temperature difference between the fluxtube interior and the quiet photosphere at equal geometrical height at five grid points. The zero level of the geometrical height scale is defined at optical depth unity of the quiet photosphere at 5000 Å ($\tau_e = 1$). The horizontal temperature distribution inside the fluxtube is homogenous, the microturbulence velocity has a value of $0.6\,\mathrm{km\,s^{-1}}$ independent of the height, and the radius of the fluxtube at $\tau_e = 1$ is 100 km. These models are used to calculate synthetic Stokes V profiles which are parameterized such that the chosen parameters vary dominantly with one model fluxtube parameter. The minimization of the difference between observed and synthetic Stokes V parameters leads to a determination of the free model fluxtube parameters.

We have selected 8 FeI and 2 FeII lines around 5250 Å for this inversion procedure. The observed Stokes V profiles have been symmetrized around their zero-crossings to avoid complicate fluxtube models that can explain the observed Stokes V asymmetry (Grossmann-Doerth et al., 1988b). The following Stokes V parameters have been used: The magnetic line ratio (Stenflo, 1973), formed between the FeI 5247.1 Å and the FeI 5250.2 Å Stokes V amplitudes, is insensitive to all fluxtube parameters except the magnetic field strength and the macroturbulence velocity (Solanki et al., 1987). A 'thermal' line ratio is formed between the FeI 5247.1 Å and FeI 5250.6 Å lines (Stenflo et al., 1987). The difference in the excitation potential of these two lines is the reason for the sensitivity of this ratio to the temperature. The ratios of the areas of the Stokes V wings between the FeI lines and the FeII 5197 Å line depend strongly on the temperature because FeII lines are rather insensitive to the temperature compared to FeI. These FeI to FeII Stokes V ratios with lines of different strength and excitation potential are the main diagnostics for the temperature stratification. Note that the Stokes V signal is proportional to the filling factor. Thus, ratios of Stokes V amplitudes or areas are independent of the filling factor. When deriving the temperature structure of fluxtubes it is essential to include the broadening of spectral lines by turbulent velocities (Solanki, 1986). We, therefore, fit the FWHM of the Stokes V wings and the distance between the two Stokes V extrema. It was necessary to include an estimated continuum contrast of magnetic fluxtubes (1.8; Koutchmy, 1977 even states a lower limit of 2) to stabilize the inversion code. The influence of the estimated continuum contrast on the resulting model, however, is negligible at the levels of line formation.

3. Results

In this chapter we present two-dimensional fluxtube models obtained by applying the inversion procedure to high spectral resolution Fourier Transform Spectrometer observations of a plage and a network region at disk center (Stenflo et al., 1984). When starting the inversion procedure from different initial values we obtain nearly the same models; this shows that the inversion applied to this specific data set gives unique solutions. Figure 1 shows the temperature on the axis of the fluxtube model as a function of the optical depth and as a function of the geometrical height. The magnetic field strength at $\tau_i = 1$ is 2400 G for the plage and 2160 G for the network fluxtubes. The macroturbulence velocities of weak lines are comparable to the values measured from Stokes I profiles in the quiet photosphere; however, strong lines show macroturbulence velocities which exceed the values found in the quiet photosphere by roughly $2\,\mathrm{km\,s^{-1}}$. This is in agreement with earlier models derived from the same data with a different technique (Solanki, 1986). The estimated accuracy of the results is 100 K for the temperature, $0.2\,\mathrm{km\,s^{-1}}$ for the turbulent velocity, and 100 G for the magnetic field strength.

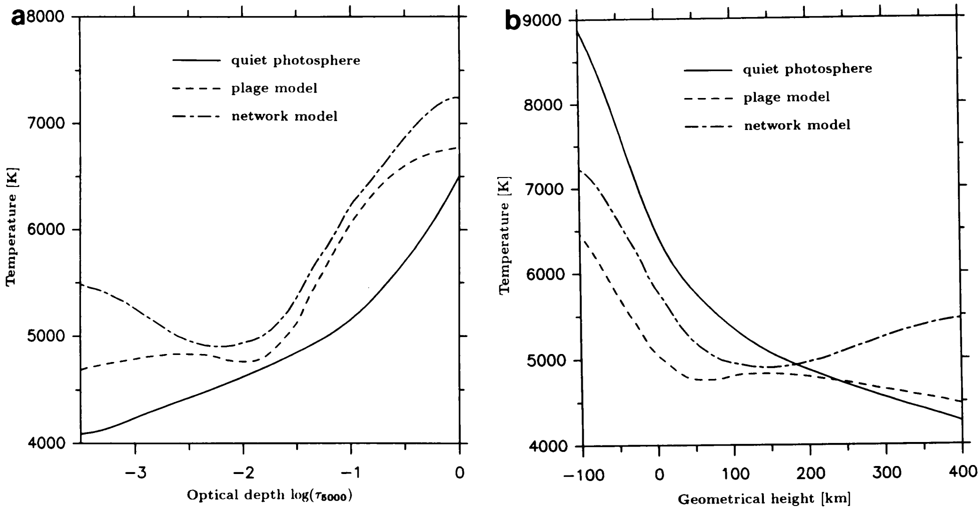

Figure 1. The plage and network models compared with the quiet solar photosphere at (a) equal optical depth and (b) equal geometrical height.

The influence of different microturbulence velocities, radii of the fluxtubes, errors in the determination of the oscillator strengths of the spectral lines, and different grid point locations on the resulting temperature stratification have been investigated and found to have no significance. Due to NLTE effects the fluxtube temperature in the upper photospheric layers is only a lower limit.

4. Discussion

Most empirical temperature stratifications of fluxtubes have been obtained as a function of the optical depth; no geometrical height scale is associated with these models. However, the temperature stratifications of the models presented in this work have been obtained as a function of the geometrical height scale. This is a large advantage for the interpretation of the results and the comparison with theoretical models. The optical depth scale can easily be computed from the temperature and the pressure startifications. Our fluxtube models show a temperature deficit compared to the quiet photosphere below $z = 0$ km. The partial inhibition of convective motion inside magnetic elements seems to be the source of this temperature deficit. Deinzer et al. (1984) even found a temperature deficit of up to 3000 K at $z = -125$ km in their theoretical models. The temperature excess in the higher layers have recently been explained by radiative transfer effects (see Fig. 2b). The hot bottom illuminates and heats the higher levels of the fluxtubes (Kalkofen et al., 1988; Grossmann-Doerth et al., 1988a). Our temperature startifications are in good agreement with earlier models (see Fig. 2a) derived from the same Stokes V data (Solanki, 1986). We confirm that the fluxtubes in the network region are hotter than those in the plage region at equal optical depth and find the same behavior at equal geometrical height. Although there is now a general agreement between theoretical and empirical models we want to emphasize that existing theoretical models cannot explain the low temperature occuring around $\tau_i = -2$.

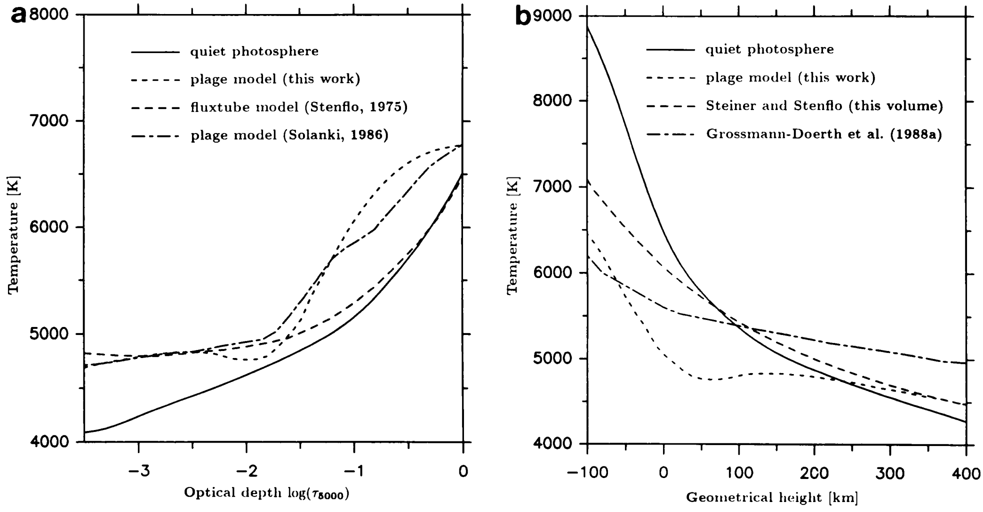

Figure 2. The plage model compared with empirical (a) and theoretical models (b) from the literature.

ACKNOWLEDGEMENTS. It is a great pleasure for me to thank S.K. Solanki, O. Steiner, and J.O. Stenflo for many fruitful discussions. The Swiss Society for Astrophysics and Astronomy provided a travel grant which is thankfully acknowledged. Part of this work was supported by the Swiss National Science Foundation under grant No. 2000-5.229.

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