Astron. Astrophys. 332, 1064–1068 (1998)

ASTRONOMY AND ASTROPHYSICS

Spectral line radiation from solar small-scale flux tubes. II

S.S. Hasan[1,2], **F. Kneer**[3], **and W. Kalkofen**[1]

[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
[2] Indian Institute for Astrophysics, Sarjapur Road, Bangalore 560034, India
[3] Universitäts-Sternwarte, Geismarlandstr. 11, D-37083 Göttingen, Germany

Received 29 September 1997 / Accepted 28 November 1997

Abstract. We examine spectral line radiation from small-scale magnetic flux tubes in the solar atmosphere. This is a continuation of work by Kneer et al. (1996). The main difference with the previous investigation is in the choice of the external atmosphere. Earlier we adopted an atmosphere resembling the empirical quiet Sun model for the ambient medium. In the present study, we iteratively adjust the temperature structure of the external atmosphere to fit the Stokes I and V profiles and the average continuum intensities with those obtained from observations. Our models are hotter in the uppermost photospheric layers and cooler in the deeper layers than the quiet Sun model and agree well with semi-empirical flux tube models.

Key words: Sun: magnetic fields – Sun: photosphere

1. Introduction

Small-scale magnetic flux tubes are central to investigations of the structure and dynamics of the solar atmosphere as well as of stellar atmospheres in general. In both the quiet and the active Sun, flux tubes are commonly accepted to play an essential role in the heating processes of the chromosphere and the corona (see Narain & Ulmschneider 1996).

In the present investigation we model the thermal structure of small-scale flux tubes in solar plages using observations with high spatial resolution. This is a continuation of earlier work (Hasan & Kalkofen 1994, hereafter HK, and Kneer et al. 1996, hereafter Paper I) in which flux tube models were constructed in the thin-tube approximation with radiative and convective energy transport. For reasons of consistency, a model atmosphere for the external medium was first determined to match the combined VAL-C (Vernazza et al. 1981) and Spruit (1977) models, henceforth labeled VALC-SP. Flux tube models were then determined by solving the magnetostatic equations for a thin tube along with the radiative transfer equation (for a grey atmosphere with 4 angles). The magnetic topology was specified in terms of β, the ratio of gas to magnetic pressure at a reference level. Further details can be found in HK. The spectral line radiation from the above models was determined in Paper I. It was found that the observed continuum intensities or the Stokes I and V profiles did not match well the observations. We attributed the discrepancies to our choice of the model of the ambient atmosphere. Below, we demonstrate that a modification of the external model yields much better agreement between observations and the predictions of the radiation field from the theoretical models of small-scale flux tubes.

Send offprint requests to: F. Kneer

2. Observational constraints

We use observations of Stokes I and V profiles of the Fe II 6149 Å, Fe I 6151 Å and Fe I 6173 Å lines of small-scale flux tubes in solar plages, including their surrounding atmosphere, as in Paper I. These lines differ in their Landé g factors and temperature dependence (for the line parameters, see the above paper). In spite of the high spatial resolution of $0\farcs6 - 1\farcs0$, the observed continuum intensity is averaged over the flux tube and the ambient medium. One observes that near disk center of the Sun this average intensity is by no means conspicuous, in the sense that magnetic features appear either substantially brighter or darker than the average quiet Sun (del Toro Iniesta et al. 1990, Kneer & von Uexküll 1991, Stolpe & Kneer 1997, and references therein). Instead, one sees abnormal granulation (e.g. de Boer & Kneer 1992, and references therein), a sort of disturbed, sub-arcsec pattern, but on average no intensity change. Consequently, our endeavour will be to obtain from the models an average continuum intensity close to the quiet Sun value (see also the study by Title & Berger 1996).

3. Modeling

One method of determining the physical parameters that reproduce the observations is to apply inversion techniques, i.e., to find a set of parameters of a model atmosphere such that the calculated intensities match, in the sense of least squares, the observations. Recent developments of the inversion method are described in del Toro Iniesta & Ruiz Cobo (1996). In the present investigation we prescribe a model for the temperature as a function of height in the external atmosphere, and calculate flux tube models as described in our earlier work (HK). The external temperature is iteratively adjusted to provide a fit between

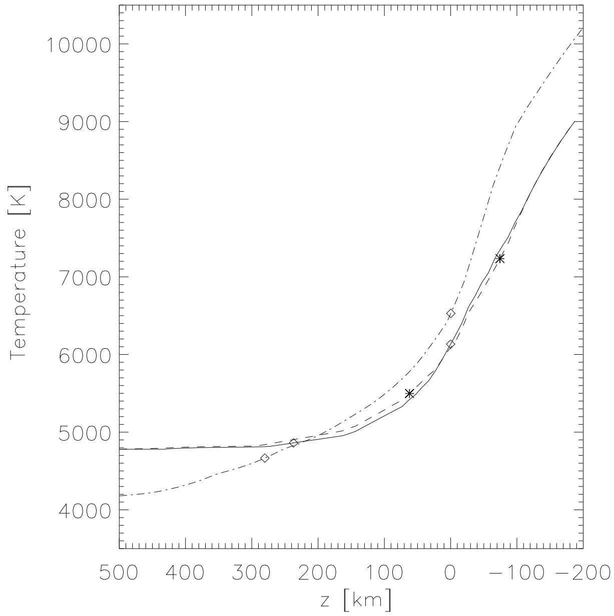

Fig. 1. Temperature versus geometric height for various models. Solid: temperature model of the atmosphere surrounding the flux tube; dashed: temperature in the flux tube; dash-dotted: VALC model (Vernazza et al., 1981) extended to deeper layers using the subphotospheric model of Spruit (1977). The asterisks and diamonds are at the position where the continuum optical depth (at 500 nm) $\tau_{\rm cont} = 1$ (lower positions) and the line centre optical depth of the Fe I 6173 line is at $\tau_{\rm lc,6173} = 1$. Diamonds refer to nonmagnetic atmospheres, asterisks to flux tubes.

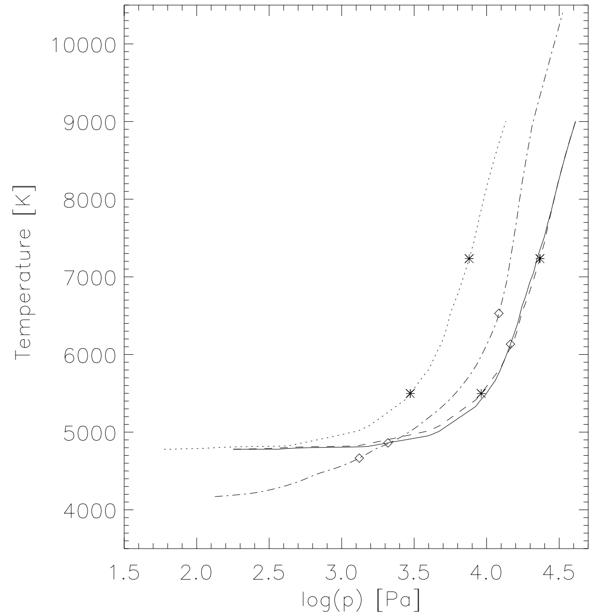

Fig. 2. Temperature versus pressure for various models. Solid: temperature of the atmosphere surrounding the flux tube; dashed: temperature in the flux tube, where the pressure is the total pressure, i.e., the sum of the gas and magnetic pressure; dotted: temperature versus gas pressure in the flux tube; dash-dotted: VALC model extended to deeper layers by model of Spruit. The asterisks and diamonds have the same meaning as in Fig. 1.

the observed and calculated Stokes profiles and continuum intensities.

We assume a slender, vertical magnetic tube with given plasma β_0 (the index '0' refers to the level $\tau_{\rm cont} = 1$ and $z = 0$ in the ambient medium), tube radius R_0, and convective efficiency parameter α. Our choice for these parameters is: $\beta_0 = 0.5$, $R_0 = 100$ km, and $\alpha = 0.2$, which are kept fixed. We find that the temperature structure of flux tube models is most sensitive to β_0, while the specific values of R_0 and α are unimportant so long as the tube is thin enough to allow for efficient radiative coupling with the ambient medium (cf., Hasan & Kalkofen 1994). Regarding the choice of β, Solanki (1995) reports on values of $\beta \leq 0.5$ using measurements of intense magnetic flux tubes in the infrared.

The spectral line radiation from the tubes is determined using the procedure adopted in Paper I. Emergent intensities, including Stokes profiles, are calculated from rays parallel to the tube axis. They are averaged over area corresponding to various filling factors at $z_0 = 0$. The Stokes profiles are then convolved with a Gaussian profile corresponding to a broadening macroturbulent velocity of 2.0 km s^{-1}. Although such velocities are usually required to match the widths of the observed profiles (e.g., Rüedi et al. 1992, Grossmann-Doerth et al. 1994, Bellot Rubio et al. 1997), we caution against too literal an interpretation of this broadening mechanism. The problem arises from the need for high velocities, of about 40% of the tube speed, in atmospheres assumed to be static (cf., Kneer & Stolpe 1996). Models incorporating *a priori* dynamic behaviour avoid this inconsistency. They have been proposed by Steiner et al. (1996, 1997) based on numerical, time-dependent MHD simulations, and by Sánchez Almeida & Landi Degl'Innocenti (1996), on micro-structured magnetic atmospheres, who included at the outset stochastic structuring and dynamics.

4. Results

Fig. 1 depicts the variation with height z of the temperature in the flux tube and external atmosphere based on a model in which the Stokes profiles match those of observations. For comparison, this figure also contains the temperature profile in the quiet Sun (VALC-SP, dash-dotted). With the observations used here, the temperatures above $z = 400$ km and below $z = -100$ km cannot be determined since the observations are insensitive to these regions of the atmosphere.

One notices in Fig. 1 that, contrary to what had been adopted in our earlier work (Paper I), the temperatures of both the flux tube and the surrounding atmosphere must be lower than the VALC-SP model at low photospheric and sub-photospheric levels, while at high levels they come close to this model or are hotter. The "hot cloud" in high layers above faculae has been repeatedly found in multi-dimensional modeling of flux tubes (cf. Fabiani Bendicho et al. 1992 and references therein). The result of lowering the (modulus of the) temperature gradient comes from the need to reduce both the continuum intensity and the

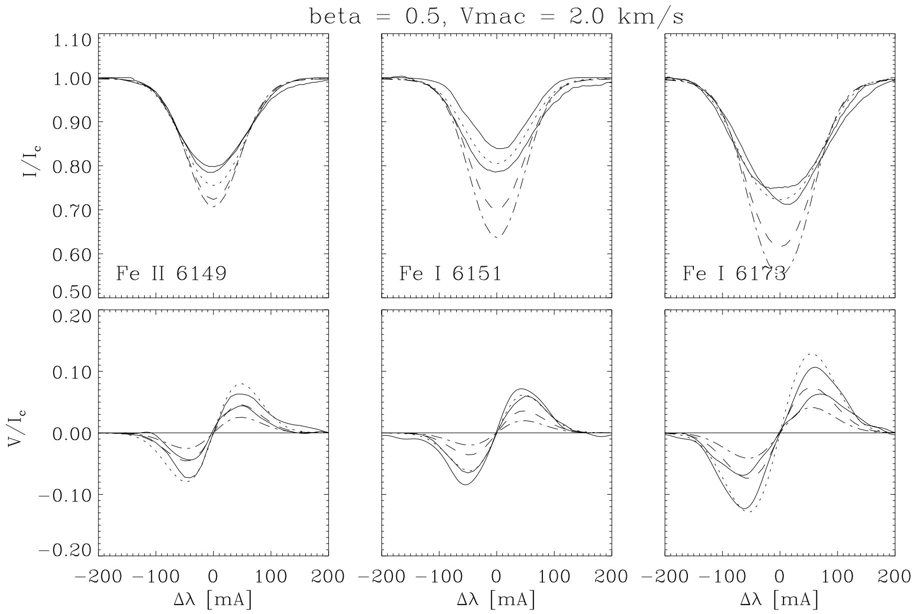

Fig. 3. Stokes I and V profiles calculated with the tube model and the non-magnetic ambient atmosphere (see text) compared with observations. Solid: observed profiles from different locations in solar plages; dotted, dashed, and dash-dotted: calculated profiles with filling factor (at $\tau_{\rm cont} = 1$ in the ambient atmosphere) of 0.46, 0.23, and 0.115, respectively. The calculated profiles are convolved with a Gaussian corresponding to a macroturbulence parameter of 2.0 km s^{-1}.

Table 1. Continuum intensities at 617 nm in units of 10^{-5} erg cm^{-2} s^{-1} cm^{-1} ster^{-1}, QS: quiet Sun (VALC-SP), FT: flux tube alone, AA: ambient atmosphere alone, FA/xx.x: average from flux tube and ambient medium with filling factor of the flux tube at $z_0 = 0$ of xx.x%

QS	FT	AA	$FA/46.0$	$FA/23.0$	$FA/11.5$
4.10	5.67	3.31	4.60	3.91	3.62

line strength from the tube and the ambient atmosphere. Such behaviour was also conjectured in our earlier work (Paper I). Because of the magnetic field, the gas pressure inside the tube is reduced, due to which both the line centre optical depth and the continuum optical depth are moved to lower z values and to higher temperatures, which again reduces the strength of the Fe I lines because of higher ionization of iron.

Table 1 gives the continuum intensities at 617 nm as calculated for various models and mixtures of flux tube and ambient atmosphere. From the values there one could adopt a filling factor of 25%–40%. This would match the observed value (QS) of the average continuum intensity. The intensity from the flux tube alone appears only about 40% brighter than the average quiet Sun (at 6170 Å).

Fig. 2 shows the run of temperature versus gas pressure. For the flux tube model we have included the structure both with magnetic pressure (dashed curve) and without (dotted). Comparing the model structures with increasingly higher temperatures, i.e. atmosphere surrounding the flux tube, quiet Sun (VALC-SP), and the flux tube alone, one notices that the depth where $\tau_{\rm cont} = 1$ occurs at decreasing gas pressure, because of the higher H$^-$ opacity (from the higher electron density).

Fig. 3 shows the Stokes I and V profiles: The solid profiles are observations from various locations in plages close to disc centre. The dotted, dashed, and dash-dotted profiles are calculated with the above model and with filling factors (at $z = 0$) of 46%, 23%, and 11.5%, respectively. Again, as for the continuum intensities, filling factors of 25%–40% appear appropriate. Possibly still better fits could be achieved with still flatter runs of temperature. We note that closer correspondence would not be justified by the data and would not give deeper insight.

In Fig. 4 we compare the temperature structures of the flux tube and the ambient atmosphere, as found here, with structures determined by inversion techniques by Keller et al. (1990) and Bellot Rubio et al. (1997). While Keller et al. use only Stokes V profiles and thus work out the structure of the flux tube alone, Bellot Rubio et al. give also the properties of the outside medium, but without the constraint of a close radiative coupling between the gas in the flux tube and that in the ambient atmosphere. As both papers state, the inversion techniques do not yield very accurate temperatures in very high and very low layers. We notice in Fig. 4 the general trend of flat temperature structures of flux tubes and ambient medium compared to the quiet Sun (see Fig. 1). In the models by Keller et al. and Bellot Rubio et al., they are even flatter than the structure presented in the present work, at least for the flux tube alone. As noted above, such temperature structures are consistent with ours. Likewise, the continuum-forming layers are still cooler in the tube models of Keller et al. and of Bellot Rubio et al. than in the present work. As a consequence, intensities from flux tubes are not expected to be very bright in the continuum (at 6170 Å). Regarding the magnetic field strengths at $z_0 = 0$, our model yields 1580 gauss, Keller et al. find about 1520 G, and Bellot Rubio et al. find 1430 G. We consider this good agreement and note that the values are not deduced from line splitting or the separation of Stokes V extrema, but rather from the requirements to reproduce the continuum and Stokes I and V intensities.

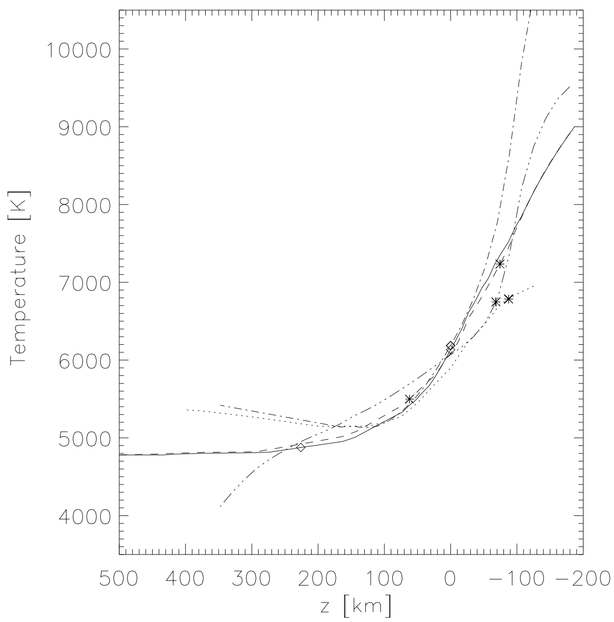

Fig. 4. Comparison of the flux tube model in this paper with results from inversion techniques. Solid: ambient atmosphere; dashed: tube model (this paper); dotted: tube model obtained by an inversion calculation from network Stokes V profiles by Keller et al. (1990); dash-dotted: ambient atmosphere from the inversion calculation by Bellot Rubio et al. (1997); dash-dot-dot-dot-dashed: tube model by Bellot Rubio et al. (1997). The asterisks and diamonds have the same meaning as in Fig. 1.

5. Discussion and conclusions

We have modelled the atmospheres in the flux tube and the ambient medium by first constructing a model of the ambient medium and then determining a flux tube model consistent with the radiation field coming from the ambient medium (in the grey approximation). For the initial guess, we assumed that the ambient medium, as well as the flux tube, had the same temperature structure as the quiet Sun, i.e., in the photosphere it agreed with the VAL-C model (Vernazza et al. 1981) and in deeper layers it followed Spruit's (1977) model of the convection zone.

From the models we determined the emergent intensity of the radiation field as the weighted mean of the contributions from the flux tube and the surrounding gas. We then reduced the mismatch between observed and computed intensities by modifying the atmosphere external to the flux tube and adjusting the internal atmosphere consistent with the modification. This process was repeated until we arrived at models of the flux tube and the surrounding atmosphere which satisfactorily reproduce the observations (cf. Figs. 1 and 3).

From the comparison in Fig. 1 of the flux tube and the ambient medium with the quiet Sun we note that, below $z = 200$ km, the flux tube (and the ambient medium) is cooler than the quiet Sun, reflecting the strong inhibition of convection by the magnetic field in the flux tube, an effect that extends into the surrounding medium (see the review by Schüssler 1995 and references therein). Numerical simulations reveal that the radiative cooling induces inflow from the sides towards the magnetic tube and convective downflow, which increases the region involved. Above $z = 200$ km, the flux tube is hotter than the quiet Sun.

The comparison of our model with those of other investigations shows that our model is cooler than the inversion models of Keller et al. (1990) and Bellot Rubio et al. (1997) in the surface layers, and hotter than that of Keller et al. in most of the photosphere. The model of Bellot Rubio et al. (1997) is hotter than all other models in the middle photosphere and cooler in the surface layers and the deep photosphere. Below approximately $z = -100$ km, all models are ill-defined. In the line-forming layers all tube models are thus hotter than the empirical model of the quiet Sun.

Comparing our models for the flux tube and the ambient medium we see that the flux tube is hotter than the ambient medium above $z = 0$, showing the effect of the longer mean free path in the tube (Kalkofen et al. 1986) and cooler below, presumably owing to the reduced convective flux because of the strong magnetic field in the flux tube.

Our models of the flux tube and the surrounding atmosphere reproduce the observed intensities. There is agreement among the models in the investigations discussed here that small-scale flux tubes, including also the nearby outside atmosphere, have a much flatter temperature structure than the quiet solar atmosphere. To arrive at the observed average continuum intensities (at moderate spatial resolution) and the observed Stokes profiles, the flux tube alone should appear only moderately brighter in the continuum than the quiet Sun, at disc centre, while the nearby gas exhibits lower intensity. This is in agreement with observations by Title & Berger (1996). In contrast, the higher layers in the flux tube are hotter than the undisturbed atmosphere. This can be understood by the radiative heating from the subphotospheric layers of the partially evacuated magnetic flux tube (Fabiani Bendicho et al. 1992).

The empirical models that were built by adjusting the external atmosphere and then constructing a flux tube atmosphere consistent with it give satisfactory agreement with observations. Further improvement may be expected for models that take into account not only the effect of ambient medium on the flux tube but also that of the flux tube atmosphere on the ambient medium (see Hasan & Kalkofen 1997).

Acknowledgements. We thank Drs. L.R. Bellot Rubio, B. Ruiz Cobo, and M. Collados Vera for providing their model data. SSH is thankful to the Smithsonian Institution for travel support under SMIN grant no. 9411FR00007 and the award of a Fellowship. The National Science Foundation provided support for his stay in Cambridge.

References

Bellot Rubio L.R., Ruiz Cobo B., Collados M., 1997, ApJ 478, L45
de Boer C.R., Kneer F., 1992, A&A 264, L24
del Toro Iniesta J.C., Ruiz Cobo B., 1996, Solar Phys. 164, 169
del Toro Iniesta J.C., Collados M., Sánchez Almeida J., et al., 1990, A&A 233, 570
Fabiani Bendicho P., Kneer F., Trujillo Bueno J., 1992, A&A 264, 229
Grossmann-Doerth U., Knölker M., Schüssler M., et al., 1994, A&A 285, 648

Hasan S.S., Kalkofen W., 1994, ApJ 436, 355 (HK)
Hasan S.S., Kalkofen W., 1997: The influence of magnetic flux tubes on their surroundings. In: Tenth Cambridge Workshop on Cool Stars, Stellar Systems and the Sun, Donahue R. A. and Bookbinder J. (eds.), A.S.P. Conf. Ser., in press
Kalkofen W., Rosner R., Ferrari A., et al., 1986, ApJ 304, 519
Keller C.U., Solanki S.K., Steiner O., et al., 1990, A&A 233, 583
Kneer F., Stolpe F., 1996, Solar Phys. 164, 303
Kneer F., von Uexküll M., 1991, A&A 247, 556
Kneer F., Hasan S.S., Kalkofen W., 1996, A&A 305, 660 (Paper I)
Narain U., Ulmschneider P., 1996, Space Sc. Rev. 75, 453
Rüedi I., Solanki S.K., Livingston W., et al., 1992, A&A 263, 323
Sánchez Almeida J., Landi Degl'Innocenti E., 1996, Solar Phys. 164, 203
Schüssler M., 1995, Rev. Mod. Astron. 8, 11
Solanki S.K., 1995: Magnetic Field Measurements in the Infrared. In: Infrared Tools for Solar Astrophysics: What's Next? Kuhn J. R., Penn M. J. (eds.), Proc. 15th Sacramento Peak Workshop, Sunspot, NM, Singapore: World Scientific.
Spruit H.C., 1977, Ph.D. thesis, Utrecht University
Steiner O., Grossmann-Doerth U., Schüssler M., et al., 1996, Solar Phys. 164, 223
Steiner O., Grossmann-Doerth U., Schüssler M., et al., 1997, ApJ (in press)
Stolpe F., Kneer F., 1997, A&A 317, 942
Title A.M., Berger T.E., 1996, ApJ 463, 797
Vernazza J.E., Avrett E.H., Loeser R., 1981, ApJS 45, 635