1992A&A...262L..29S

Astron. Astrophys. 262, L29–L32 (1992)

ASTRONOMY
AND
ASTROPHYSICS

Letter to the Editor

Continuum brightness of solar magnetic elements

S.K. Solanki and V. Brigljević

Institute of Astronomy, ETH-Zentrum, CH-8092 Zürich, Switzerland

Received June 11, accepted June 18, 1992

Abstract. Ratios between the Stokes V profiles of C I lines and Fe II lines are used to determine the temperature of the continuum-forming layers of solar magnetic features. From the derived temperature stratification the continuum intensity of the spatially unresolved magnetic features is obtained independently of spatial-resolution. First results suggest that whereas magnetic features have, on average, a brighter continuum than the quiet sun in a region of small magnetic filling, they are darker in a region with large filling factor. Consequences for flux-tube sizes and the interpretation of the global solar luminosity variation are discussed.

Key words: Sun: magnetic fields – Sun: faculae – Sun: global luminosity variation.

1. Introduction

The continuum intensity, I_c^m, or the continuum contrast to the quiet sun, $\delta_c = I_c^m/I_c^q$, of small-scale magnetic features has often been investigated. Unfortunately, δ_c is a difficult quantity to measure directly since many of the magnetic features are still spatially unresolved at the best currently achievable spatial resolution of 0.2–0.3″ (Ramsey et al. 1977, Keller, private communication). It is therefore not surprising that the δ_c values derived by different investigators disagree by large amounts, even when obtained from observations with high spatial resolution ($\lesssim 0.5''$). For example, Koutchmy (1977) finds $\delta_c \approx 1.6$–2, while Topka et al. (1992) propose that $\delta_c < 1$ for all magnetic features at disc centre.

In contrast to almost all other attempts at determining δ_c, which have aimed at improving the spatial resolution, we apply an indirect, Stokes-V-based technique that is basically independent of the spatial resolution of the observations (recall that Stokes V obtains its contribution overwhelmingly from within the magnetic features). We determine the temperature of the continuum-forming layers of magnetic elements using Stokes V profiles of lines that are formed very deep in the photosphere. Weak, high-excitation C I lines, which are both temperature sensitive and formed close to the $\tau_c = 1$ level (Livingston et al. 1977, Elste 1985), are ideal for this purpose (τ_c is the continuum optical depth at 5000 Å).

2. Spectral lines, observational data and analysis technique

Characteristics of the four C I and three Fe II lines in the visible spectrum that are suitable for the present analysis are listed in Table 1. Here, χ_e is the excitation potential of the lower atomic level involved, W_λ and d_I are the line's equivalent width and depth in the quiet sun, $\log g^{\star}f$ is the logarithmic, statistically weighted oscillator strength (taken from Stürenburg & Holweger 1991) and $g_{\rm eff}$ is the effective Landé factor. For the carbon and iron elemental abundances ϵ we adopt 8.58 and 7.46, respectively. The adopted $\log g^{\star}f\epsilon$ reproduce the observed quiet-sun profiles of the tabulated lines. Errors in $\log g^{\star}f\epsilon$ that are sufficiently large to seriously affect our results, also give quiet-sun profiles incompatible with the data. Finally, the last column lists the amount by which the V profile of each line is weighted during the χ^2 minimisation prodecure. This weight reflects uncertainties introduced by noise and small blends, which are particularly large for C I 4770.0 Å and 4775.9 Å. These two lines have only been retained because they are formed the deepest.

Since Stokes V profiles scale with the often poorly known magnetic filling factor, only the ratio between the V profiles of lines with different temperature sensitivities provides a reliable temperature diagnostic. Not surprisingly, test calculations show that all four C I lines have very similar temperature sensitivities, so that their ratios contain no temperature information. We have therefore included three weak, unblended Fe II lines in our analysis (see Table 1). They are relatively insensitive to the temperatures typical of magnetic elements (e.g. Solanki & Stenflo 1985). Detailed test calculations confirm that ratios of C I to Fe II lines are good temperature diagnostics. All line-profile calculations have been performed in LTE, an excellent approximation for both the C I (Stürenburg & Holweger 1991) and the Fe II lines (e.g. Solanki & Steenbock 1988).

We have analysed Stokes I and V spectra obtained close to disc centre in a network (having low magnetic filling factor α) and a plage region (having high α), with the Fourier transform Spectrometer (FTS) polarimeter at the McMath telescope on Kitt Peak. The spectra cover the wavelength range 4570–5580 Å at a resolving power of 420 000 and a noise level approaching 10^{-4}. The spatial resolution is roughly 10″. More details on the data are given by Stenflo et al. (1984) and Solanki (1987).

Send offprint requests to: S.K. Solanki

[⋆] Based on data obtained at the National Solar Observatory, operated by the Association of Universities for Research in Astronomy, Inc. (AURA), under cooperative agreement with the National Science Foundation.

Table 1. Analysed spectral lines

Element	λ (Å)	χ_e (eV)	Transition	W_λ (mÅ)	d_I	$\log g^* f$	$g_{\rm eff}$	Weight
C I	5380.323	7.68	$3s\,^1P_1^o - 4p\,^1P_1$	23	0.17	−1.68	1.000	4
C I	5052.147	7.68	$3s\,^1P_1^o - 4p\,^1D_2$	43	0.27	−1.49	1.000	2
C I	4775.907	7.49	$3s\,^3P_2^o - 4p\,^3D_1$	18	0.16	−2.20	2.000	1
C I	4770.005	7.48	$3s\,^3P_1^o - 4p\,^3D_0$	15	0.11	−2.28	1.500	1
Fe II	5414.074	3.22	$a\,^4G_{7/2} - z\,^4D_{7/2}^o$	28	0.30	−3.66	1.190	4
Fe II	5325.556	3.22	$a\,^4G_{7/2} - z\,^4F_{7/2}^o$	44	0.47	−3.31	1.135	4
Fe II	5132.666	2.81	$b\,^4F_{9/2} - z\,^6F_{9/2}^o$	26	0.27	−4.22	1.368	4

Models of the temperature structure of the magnetic features in the observed regions have been derived by Solanki (1986) and Keller et al. (1990) from the same spectra.

Our calculations suggest that the C I/Fe II line ratio cannot clearly distinguish between a change in temperature T near $\tau_c = 1$ and a change in its gradient $dT/d\tau_c$. This is mainly due to the sensitivity of the C I formation height to the temperature gradient, so that a change in gradient causes the line to sample the temperature at a different height. The C I lines, being thermophile, are formed deeper in atmospheres with steeper temperature gradients. Fortunately, the temperature stratification at $\log\tau \lesssim 1$ of the magnetic elements in the analysed regions is well known (Solanki 1986, Keller et al. 1990). Therefore, the $T(\tau_c)$ structure of the models underlying the present line-profile calculations corresponds to that of an empirical flux-tube model for all $\tau_c \le \tau_c^{\rm crit}$. At larger τ_c, the temperature is allowed to vary in such a manner that it is not discontinuous at $\tau_c = \tau_c^{\rm crit}$. One set of models constructed in this manner is shown in Fig. 1. In this case all the models are identical to the network flux-tube model of Solanki (1986) for $\log\tau_c \le -1 = \log\tau_c^{\rm crit}$ (solid curve: original model, based at $\log\tau_c > -1$ on the contrast measurements of Muller & Keil 1983). By fixing the temperature stratification at $\log\tau_c \le -1$, we are effectively coupling $T(\tau_c = 1)$ with $dT/d\tau_c|_{\tau_c=1}$ and thus reducing the number of free parameters.

When modelling the network spectrum, model families based on the empirical network models of Solanki (1986) or Keller et al. (1990) are used (e.g., the one shown in Fig. 1). Similarly, model families based on the corresponding empirical plage models are used to model the plage spectrum. We find that for our simple analysis, the final result is rather insensitive to whether the Solanki (1986) or the Keller et al. (1990) empirical models are used to describe $T(\tau_c < \tau_c^{\rm crit})$. The rest of the atmospheric quantities of each model are recalculated self-consistently in hydrostatic equilibirum from the prescribed $T(\tau)$. An empirical value of the magnetic field is prescribed at one geometrical height. The magnetic stratification is then determined by shifting the magnetized atmosphere down as a whole and imposing horizontal pressure balance with a quiet-sun model (thin-tube model). Since all the employed lines are weakly Zeeman split relative to their non-magnetic widths, the exact value of the field strength is irrelevant for the present analysis. The spectral lines are calculated along multiple rays passing vertically through the model flux tube. The suitably weighted V profiles are then co-added and broadened by a macroturbulence velocity. Subsequently, ratios between the V amplitudes of each C I and Fe II V profile are constructed. These ratios are compared with the corresponding observed ratios. Finally, the differences between the observed and calculated C I/Fe II ratios are squared and added together. The model giving the smallest sum of squared differences (χ^2) is judged to represent the data best.

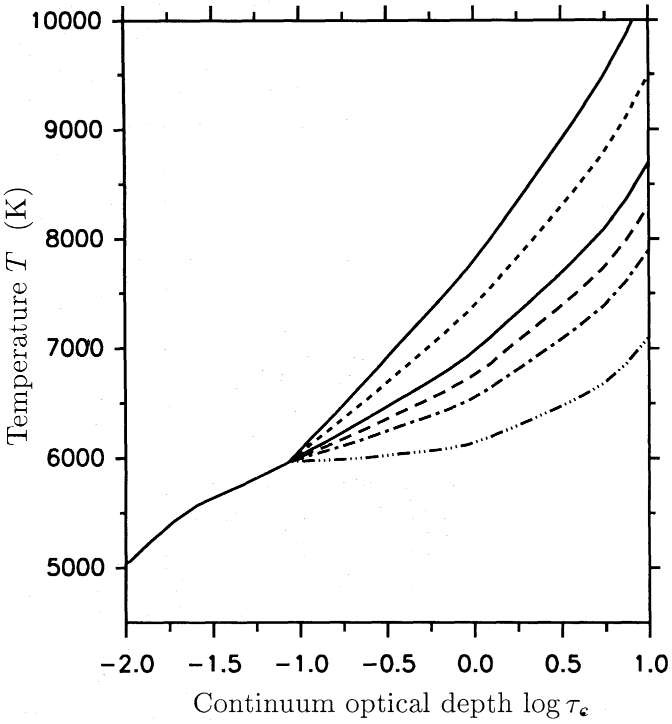

Fig. 1. Temperature T vs. continuum optical depth at 5000 Å, τ_c, for a series of models that have the same $T(\tau_c)$ as the network flux-tube model of Solanki (1986) for $\log\tau_c \le -1$.

3. Results

Figure 2 shows the χ^2 of the fits to the two data sets (solid curve: network data and models, dashed curve: plage data and models) as a function of δ_c of the models at 5000 Å. The absolute minimum of χ^2 has been normalized to unity. According to this figure $0.7 \lesssim \delta_c \lesssim 0.95$ for the magnetic features in the

1992A&A...262L..29S

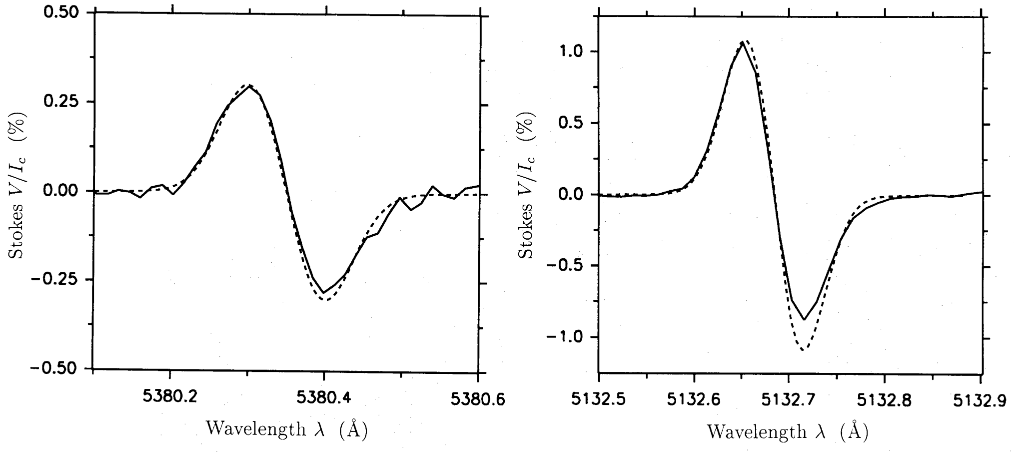

Fig. 3. Observed (solid) and synthetic (dashed) Stokes V profiles of the best fit C I line (λ 5380.3 Å) and the worst fit Fe II line (λ5132.7 Å). The observations were obtained in an active-region plage. The synthetic profiles result from the model with smallest χ^2.

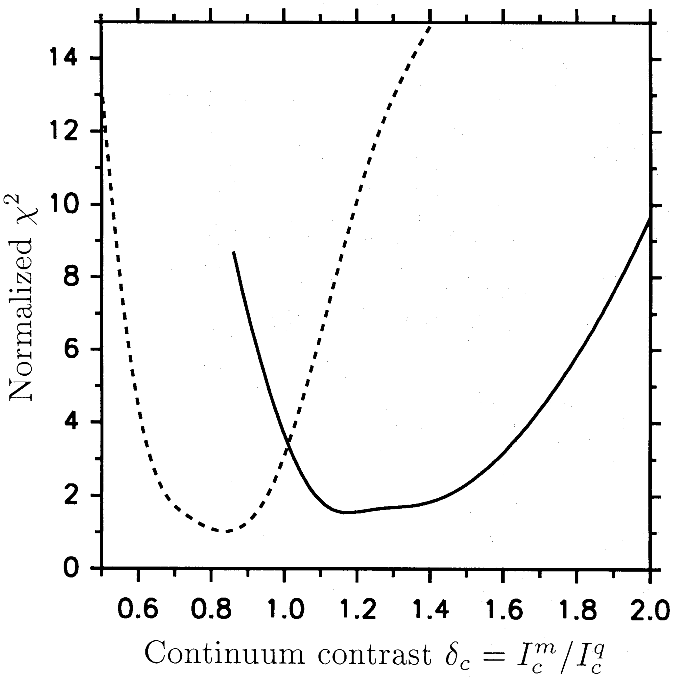

Fig. 2. Normalized χ^2 (sum of squared deviations from the observations) vs. continuum contrast at 5000 Å, $\delta_c = I_c^m/I_c^q$, where I_c^m is the continuum intensity of the magnetic features and I_c^q that of the quiet sun. Dashed curve: plage data and models, solid curve: network data and models.

plage and $1.1 \lesssim \delta_c \lesssim 1.5$ for the magnetic features in the network. Observed and synthetic Stokes V profiles of a C I and an Fe II line each are shown in Fig. 3. The observed V profiles have not been smoothed or filtered and have not been symmetrized, i.e. they still show the typical blue-red asymmetry.

Finally, in Fig. 4 the Stokes V line-depression contribution function (Grossmann-Doerth et al. 1988) of C I 5380.3 Å at the wavelength of maximum V is shown for the quiet sun (dot dashes), the best-fit network model (solid, $\delta_c \approx 1.15$) and the best-fit plage model (dashes, $\delta_c \approx 0.85$). The lower temperature gradient in the network and plage models broadens the contribution function and shifts it to lower $\log \tau_c$. Thus the overlap between the continuum and C I contribution functions is smaller than for the quiet sun. However, this difference in heights of formation is not expected to increase the uncertainty in the resulting δ_c significantly beyond that already visible in Fig. 2. In particular, steepening the relatively flat temperature profiles near $\tau_c = 1$ enhances the contribution to the C I lines from these layers and consequently strengthens these lines, which changes the C I/Fe II ratio.

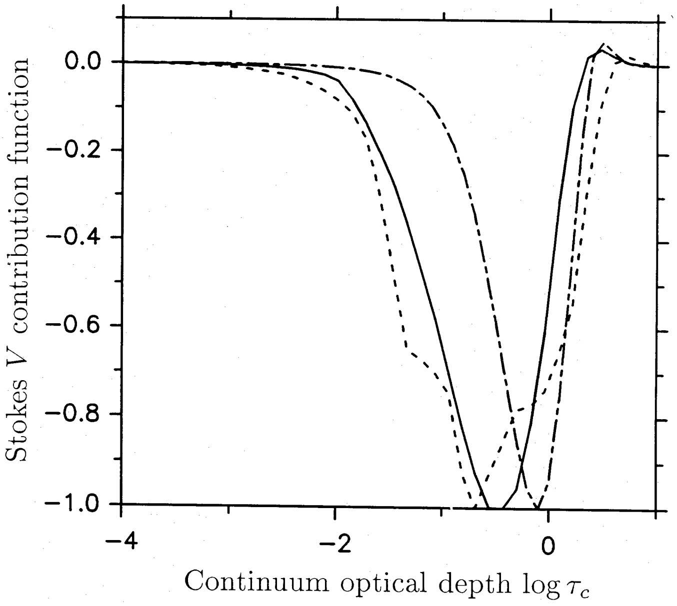

Fig. 4. Normalized Stokes V line-depression contribution functions of C I 5380.3 Å in the quiet sun (dot dashes) and the best-fit network (solid) and plage (dashes) models.

4. Discussion and conclusions

We have presented a new, spatial-resolution independent technique of obtaining the continuum contrast δ_c of small-scale magnetic features relative to the quiet sun. This technique has been applied to a Stokes V spectrum of a network region [estimated $\alpha(z = 0) \approx$ 5–8%] and of an active-region plage [$\alpha(z = 0) \approx$ 15–25%]. $z = 0$ corresponds to $\tau_c(5000\,\text{Å}) = 1$

in the quiet sun. We find that the magnetic features are, on average, bright in the continuum in the region with small α, but are slightly dark for high α. Consequently, the dependence of the temperature of magnetic elements on the filling factor, first identified in the mid-photosphere (e.g. Solanki & Stenflo 1984, Zayer et al. 1990), is present also at the $\tau_c = 1$ level.

The δ_c values we determine are averaged over the magnetic features in the resolution element, but are not further degraded by seeing or finite spatial resolution. They may thus be directly compared with synthetic δ_c values determined from flux-tube models, such as those of Knölker et al. (1988, 1990) and Knölker & Schüssler (1988). There are two main parameters which determine the δ_c of these models, namely, the degree of evacuation and the size of the flux tube. A reduced evacuation leads to a reduced δ_c and a smaller field strength. An evacuation giving $\delta_c \lesssim 1.2$–1.3 for tubes with $d(z=0) = 200$ km produces a field strength which is not compatible with the observations (Schüssler, private communication). Therefore, in the context of these models, our results suggest that the average size of magnetic features increases with increasing filling factor. If we take the models of the Freiburg group as a guide, then we estimate that the *average* diameter d of the magnetic features in the observed network region is roughly $d \approx 250$–350 km, while in the active plage $d \approx 400$–600 km (there may, of course, be a considerable distribution of sizes around each mean value). However, if we accept the proposal of Keller (1992) that most magnetic features larger than 300 km are dark, then we estimate roughly that $d \approx 200$–300 km in the network region and $d \approx 300$–500 km in the plage. In any case, the present results support the existence of magnetic knots (Beckers & Schröter 1968), i.e. slightly dark magnetic features intermediate in size between bright magnetic elements and dark pores, in agreement with the recent theoretical results of Bünte et al. (1992).

Our δ_c values are not consistent with those of Schüssler & Solanki (1988), who found $\delta_c \gtrsim 1.4$. Their result was based on minute differences between Stokes I profiles of two lines (Stokes I line ratio between Fe I 5247.1 Å and 5250.2 Å) as well as on the assumption that the filling factor (at the line-formation height) is smaller than 25%. Tests suggest that a weak blend with a depth of only 1–2 % relative to the continuum in one of the lines, should be sufficient to falsify the results considerably. In addition, the technique of Schüssler & Solanki (1988) is also more model dependent than the present approach (Kneer, private communication). In view of these uncertainties we must warn that all results obtained with the Stokes I based technique (e.g. Sánchez Almeida & García López 1991) must be treated with care.

A good knowledge of δ_c is crucial to a correct determination of the magnetic filling factor (e.g. Grossmann-Doerth et al. 1987). Our results suggest that in the past small filling factors, associated with large δ_c, have generally been overestimated, while larger filling factors have been underestimated.

Finally, knowledge of the true continuum intensity is a necessary step towards identifying the origin of the global solar luminosity variation over the 11-year solar cycle (Willson & Hudson 1988). It has been suggested by Foukal & Lean (1988) that the luminosity variation over the solar activity cycle is to a large part due to the quiet network. Our results suggest one reason for the dominance of the network contribution, if we assume that the physical parameter distinguishing between active plage and network is the magnetic filling factor. Since only the magnetic features in regions of small filling factor are bright in the continuum over much of the solar disc, their contribution to the global luminosity variation is expected to be larger. This raises the question of why, if magnetic elements in active plages have dark continua near disc centre, do plages have an excess of total brightness? We propose that it is caused, to a significant extent, by the reduced line blanketing, due to the heating of the upper photosphere in the magnetic features (cf. Mitchell & Livingston 1991).

Acknowledgements. We thank M. Schüssler and C. Keller for valuable comments on the manuscript.

References

Beckers J.M., Schröter E.H., 1968a, Sol. Phys. 4, 142
Bünte M., Steiner O., Pizzo V., 1992, A& A submitted
Elste G., 1985, in Theoretical Problems in High resolution Solar Physics, H.U. Schmidt (Ed.), Max Planck Institut für Astrophysik, München, p. 185
Foukal P. Lean J., 1988, ApJ 328, 347
Grossmann-Doerth U., Larsson B., Solanki S.K., 1988, A& A 204, 266
Grossmann-Doerth U., Pahlke K.-D., Schüssler M., 1987, A& A 176, 139
Keller C.U., 1992, Nat. submitted
Keller C.U., Solanki S.K., Steiner O., Stenflo J.O., 1990, A& A 233, 583
Knölker M., Grossmann-Doerth U., Schüssler M., Weisshaar E., 1990, Adv. Space Res. 11, 285
Knölker M., Schüssler M., 1988, A& A 202, 275
Knölker M., Schüssler M., Weisshaar E., 1988, A& A 194, 257
Koutchmy S., 1977, A& A 61, 397
Livingston W., Milkey R., Slaughter C., 1977, ApJ 211, 281
Mitchell W.E., Jr., Livingston W.C., 1991, ApJ 327, 336
Muller, R., Keil, S.L., 1983, Sol. Phys. 87, 243
Ramsey H.E., Schoolman S.A., Title A.M, 1977, ApJ 215, L41
Sánchez Almeida J., García López R., 1990, in The Sun and Cool Stars: Activity, Magnetism, Dynamos, I. Tuominen, D. Moss, R. Rüdiger (Eds.), Springer-Verlag, Berlin, IAU Coll. 130, 414
Schüssler M., Solanki S.K., 1988, A& A 192, 338
Solanki S.K., 1986, A& A 168, 311
Solanki S.K., 1987, *Ph.D. Thesis*, No. 8309, ETH, Zürich
Solanki S.K., Steenbock W., 1988, A& A 189, 243
Solanki S.K., Stenflo J.O., 1984, A& A 140, 185
Solanki S.K., Stenflo J.O., 1985, A& A 148, 123
Stenflo J.O., Harvey J.W., Brault J.W., Solanki S.K., 1984, A& A 131, 333
Stürenburg S. Holweger H., 1990, A& A 237, 125
Topka K.P., Tarbell T.D., Title A.M., 1992, ApJ submitted
Willson R.C., Hudson H.S., 1988, Nat. 332, 810
Zayer I., Solanki S.K., Stenflo J.O., Keller C.U., 1990, A& A 239, 356

This article was processed by the author using Springer-Verlag TEX A&A macro package 1991.