IL NUOVO CIMENTO Vol. 25 C, N. 5-6 Settembre-Dicembre 2002

Line ratios and temperature structure in the deep photosphere(*)

B. Caccin(**) and V. Penza(***)

Università di Roma "Tor Vergata" - Via della Ricerca Scientifica 1, Rome, Italy

(ricevuto il 10 Giugno 2002; approvato il 7 Agosto 2002)

Summary. — A program to monitor solar cycle variations of the solar flux by using suitable spectral line ratios is going on at Kitt Peak since 1976; the most sensitive to $T_{\rm eff}$ variations are the ratios involving the C I 538.032 nm, whose formation depth is almost coincident with that of the continuum, and either the Fe I 537.958 or the Ti II 538.103. The temperature sensitivities of those line ratios have been empirically calibrated by observing the spectra of several solar-like stars by Gray and Livingston, while several attempts to obtain the same calibration theoretically, through Kurucz's models of stellar atmospheres, showed difficulty in reproducing quantitatively the experimental results. Because the observed/computed ratio was approximately the same for both couples of lines, we argued that the problem was in the behaviour of C line, that is more affected than the others by the temperature structure of the deep photosphere, where it is formed. As, in these layers, the gradients of the average temperature are sensibly affected by different treatments of the convection, we compared, first of all, several theoretical models, distinguished from each other in including or not convective overshooting. Then we explored the effects due to variations of the value of the free parameter ($\alpha = \ell/H_P$) and those ensued by different versions of the mixing-length theory.

PACS `97.10.Ex` – Stellar atmospheres (photospheres, chromospheres, coronae, magnetospheres); radioactive transfer; opacity and line formation.
PACS `97.10.Ri` – Luminosities; magnitudes; effective temperatures, colors, and spectral classification.
PACS `96.60.Vg` – Particle radiation, solar wind.
PACS `01.30.Cc` – Conference proceedings.

(*) Paper presented at the International Meeting on THEMIS and the New Frontiers of Solar Atmosphere Dynamics, Rome, Italy, March 19-21, 2001.

(**) E-mail: caccin@roma2.infn.it
(***) E-mail: penza@roma2.infn.it

1. – Introduction

We may reasonably expect that magnetic activity produce cyclic variations of all global parameters of the Sun [1]. In fact, the occurrence of structural changes has been inferred by the detection [2] of small variations in the observed spectrum of acoustic modes [3-5]. Measurements of the total irradiance at 1 AU [6] reveal an increase, corresponding to about 1.5 K in T_{eff}, from minimum to maximum of the sunspot cycle, if we can neglect radius variations. A possible indicator monitoring T_{eff} variations is the central depth ratio r of suitable spectral lines. In particular the C I 538.032 nm line, formed in the deep photosphere, together with the Fe I 537.958 and Ti II 538.102 lines (both formed about 150–200 km higher) have been systematically observed at Kitt Peak for more than two 11y cycles. Gray and Livingston [7, 8], through an extremely careful calibration of these line depth ratios in spectra of solar-like stars with slightly different values of T_{eff} (± 300 K), found the following approximate relation:

$$\delta T_{\text{eff}} = C_0 \frac{\delta r}{r} \,, \tag{1}$$

where the experimental value of C_0 is equal to 346 for the C/Fe couple and 468 for the C/Ti one. A similar relation (with different values of the constant C_0) was obtained also for the equivalent width ratios, but the experimental uncertainties are somewhat larger. These line ratios seem rather insensitive to the presence of faculae and other magnetic structures due to the activity cycle, showing no signal of rotation in solar data and no correlation with the index of chromospheric activity in stellar data. The variation of T_{eff} with the solar cycle, deduced from Kitt Peak observations [8] through such an empirical calibration, follows very closely that deduced from irradiance data. If taken at their face values, these results leave no room for a contribution to irradiance variations due to faculae and other magnetic structures, unless some other concurrent effect of opposite sign is present. Actually, Caccin and Penza [9] showed that pluridimensional effects in line formation cannot be neglected and, in particular, the observed variations of granular size [10] might produce an opposite effect on line depth ratios, as compared with the observations. An attempt to derive a theoretical calibration similar to eq. (1) with suitable grids of Kurucz [11] atmospheric models [12, 13] provided a value of C_0 about two times larger, for both line ratios, than the corresponding estimates of Gray and Livingston. In the present paper, we want to study how much the sensitivity of these ratios to T_{eff} variations can be affected by modifications of the mean temperature structure of the atmosphere caused by different treatments of the convection.

2. – Theoretical models

For our calculations we used a small grid of model atmospheres extracted from those available at `http://cfaku5.harvard.edu/grids.html`. The explored range of free parameters is the following: $5500 \leq T_{\text{eff}} \leq 6250$, $4.0 \leq \log(g) \leq 4.5$ and $1 \leq \xi_{\text{micro}} \leq 4$; the only value available for the mixing length is $\alpha = \ell_{\text{mix}}/H_P = 1.25$. In addition to the former, we used also Castelli *et al.* models obtained with the same free parameters but with a different treatment of the convection [14], which neglects the overshoot effect currently included in Kurucz's models. The comparison in fig. 1 immediately shows that, whenever the efficiency of convection is greater, the gradient $\nabla \equiv \mathrm{d}\ln T/\mathrm{d}\ln P$ is smaller. In all cases, the temperature structure $T(\tau_{\text{R}})$ scales approximately with T_{eff}, like

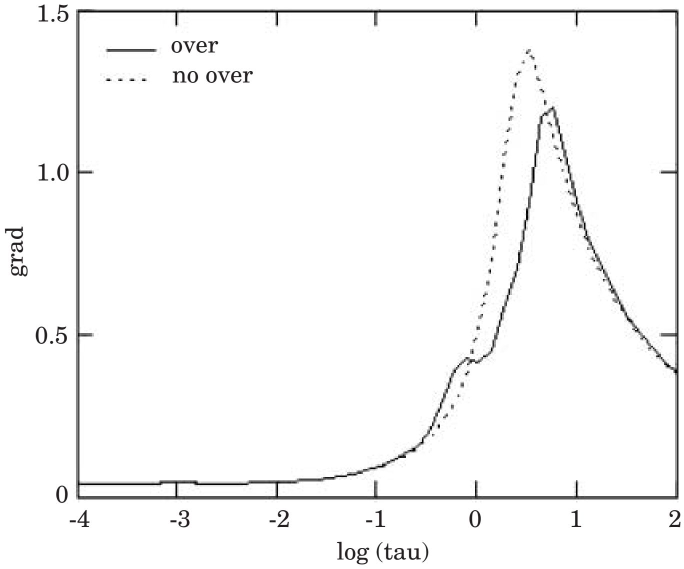

Fig. 1. – Gradients *vs.* $\log(\tau_\mathrm{R})$ corresponding to $T_\mathrm{eff} = 6000$ K with and without overshooting.

it does for gray radiative equilibrium models, until rather large values of τ are reached; the approximation is better for the models without overshooting (fig. 2). In order to get an idea about what might happen if we change the value of α or modify the details of the mixing-length theory, we used the radiative equilibrium part of Castelli *et al.* [14] models and, starting from the point τ_0, for which $\nabla = \nabla_A = (\gamma - 1)/\gamma$, we extended it with a suitable temperature gradient. For our exploratory intents, we were satisfied

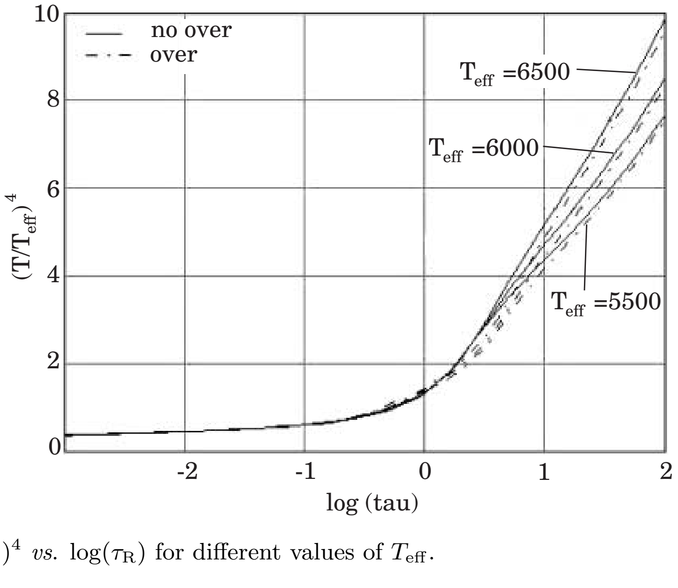

Fig. 2. – $(T/T_\mathrm{eff})^4$ *vs.* $\log(\tau_\mathrm{R})$ for different values of T_eff.

TABLE I. – *Line parameter. ζ is a fudge factor multiplying the Unsöld value of γ in the Lorentz term of the absorption profile.*

Line	$\log(gf)$	χ_{ion} (eV)	χ_{ex} (eV)	ζ	ξ_{micro} (km/s)
C I 538.032 nm	−1.8	11.26	7.68	1.0	2
Fe I 537.959 nm	−1.6	7.87	3.695	7.5	1
Ti II 538.102 nm	−2.08	13.58	1.566	44	1

with calculating the gradient either from the classic version (STD: $\ell_{\text{mix}} = \alpha H_P$), or from a modified form of the mixing-length theory (MLT1: $\ell_{\text{mix}} = z^* + \alpha H_P^*$, where z^* is the distance from the top of the convection zone and H_P^* is the pressure scale height at that level). We know that in MLT1 the temperature gradient is generally steeper than in STD [15]. In both cases the new gradient is obtained from the following formula:

$$\nabla(P,T) = x^2(P,T) + \nabla_A - U^2(P,T)\,, \tag{2}$$

where $x(P,T)$ is the solution of the well-known cubic equation

$$\frac{9}{8U}(x-U)^3 + x^2 - U^2 - \nabla_{\text{R}} + \nabla_A = 0\,, \tag{3}$$

while ∇_{R} is the radiative gradient and

$$U(P,T) = \frac{24\sqrt{2}\sigma T^3 P^{1/2}}{c_P k(P,T) g \ell_{\text{mix}}^2 \rho^{5/2}}\,. \tag{4}$$

We adopted, for the equation of state $\rho(P,T)$, that of a perfect gas with constant molecular weight, and for the opacity $k(P,T)$ a simple power law, already used by Caccin and Staro [12], which proved to be a reasonably good approximation:

$$k(P,T) = k_0 \left(\frac{P}{P_0}\right)^a \left(\frac{T}{T_0}\right)^b \tag{5}$$

with $a = 0.5$ and $b = 8$. Once we know $\nabla(P,T)$, the temperature structure $T(P)$ can be obtained by solving (numerically) the differential equation $\mathrm{d}\ln T/\mathrm{d}\ln P = \nabla$ from a suitable value of P inward.

Note (fig. 3) that, starting from the departure point ($\log(\tau_0) \simeq -0.03$), the two models remain very similar to each other in the layers where most of the emergent intensity is formed.

3. – Computed line ratios

The line parameters used to compute the line depths are listed in table I.

In fig. 4 we show a comparison between the relations $\log(r)$ *vs.* $\log(T_{\text{eff}})$ obtained using models with and without overshooting. We see that, even though the intercepts are changed, the overshooting does not alter critically the slopes. The values of C_0

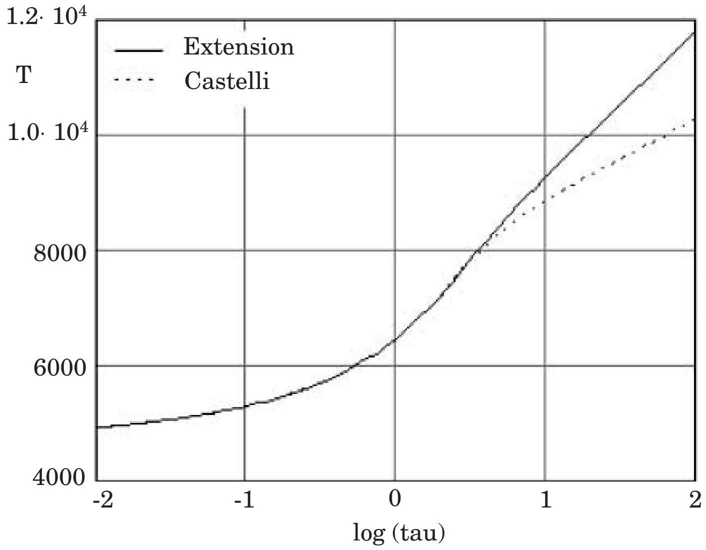

Fig. 3. – Temperature structure of our analytic model, extension of Castelli *et al.* model [14] for $T_{\mathrm{eff}} = 6000$.

($\simeq 800$ for C/Fe and $\simeq 1380$ for C/Ti) are more than twice those obtained by Gray and Livingston and the suppression of overshooting produces only a slight overestimate of C_0 (about 2–5%). Notice, however, that the effect is much smaller on the depth ratios than on the depths themselves (where it can reach 15%).

As clearly shown in fig. 5, even a substantial change of α leaves C_0 (hence the T_{eff} sensitivities of the line ratios) practically unchanged (3–4%), but the line ratios might

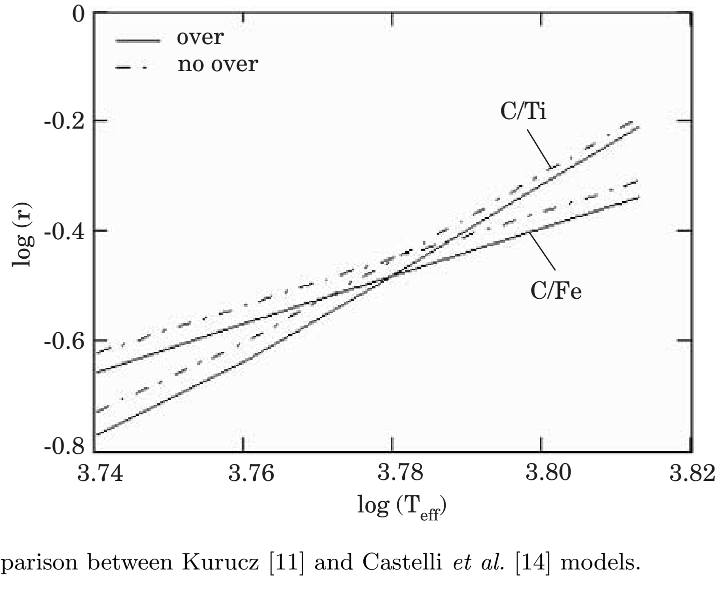

Fig. 4. – Comparison between Kurucz [11] and Castelli *et al.* [14] models.

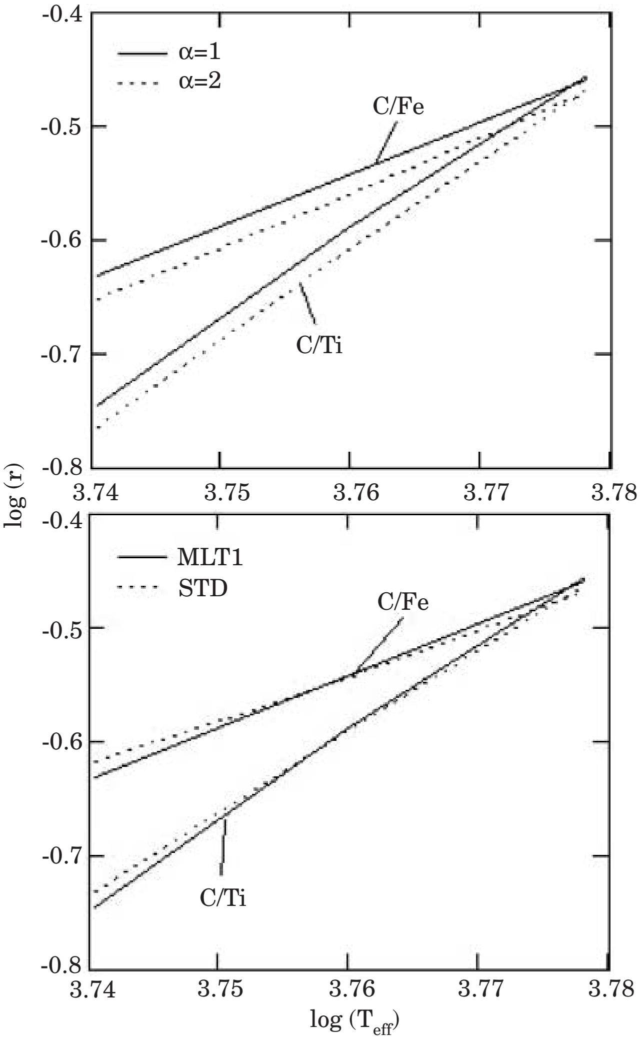

Fig. 5. – Comparison between line ratios calculated with $\alpha = 1$ and $\alpha = 2$ and those calculted with the classical (STD) and the modified form (MLT1) of the mixing-length theory.

be sensibly affected by minor changes of α with the solar cycle or among the different stars used for the calibration. Larger effects on C_0 (15–20%) can be obtained if we pass from STD to MLT1, going up to 3 times the empirical values.

4. – Conclusions

It seems impossible, with simple "refinements" of the MLT, to reduce the computed values of C_0 to those "observed" by Gray and Livingston [7]. The fact that both ratios "go together" suggests that the problem might be due to the C line, which is formed substantially deeper (where the atmospheric structure is essentially determined by convection). The argument is supported by the fact that Caccin and Staro [12] could reproduce the stellar calibration of Gray and Johanson [16], which uses the ratio of a V I and a C I line, both formed in relatively higher atmospheric layers, for $5000 \leq T_{\mathrm{eff}} \leq 6500$. We might be tempted to say that the larger effects on line ratios corresponding to solar irradiance variations by means of our calibrations, might be partially compensated by multidimensional line formation effects like those computed by Caccin and Penza [9], which are approximately of the right size. Unfortunately the variations of the same ratios observed in solar-like stars [7] are, in any case, not reproduced by our calculations. The results of Gray and Livingston [8], anyway, are inconsistent with the fact that more than half of the observed solar cycle irradiance variations can apparently be explained with the balance of facular excess and sunspot deficit, unless some additional effect of opposite sign is present (*e.g.*, a suitable variation of the granular size with the 11y cycle). Careful observations of the same lines, at high spatial resolution, with THEMIS might help to disentangle different effects.

REFERENCES

[1] Sofia S. and Li L. H., preprint (2000).
[2] Libbrecht T. J. and Woodard M. F., *Nature*, **345** (1990) 779.
[3] Lydon T. J., Gunther D. B. and Sofia S., *Astrophys. J.*, **456** (1996) L127.
[4] Balmforth N. J., Gough D. O. and Merryfield W. J., *Mon. Not. R. Astron. Soc.*, **278** (1996) 437.
[5] Antia H. M., Chitre S. M. and Thompson M. J., *Astron. Astrophys.*, **360** (2000) 335.
[6] Fröhlich C. and Lean J., *IAU Symposium*, edited by F. L. Deubner, **185** (1998) 89.
[7] Gray D.F. and Livingston W. C., *Astrophys. J.*, **474** (1997) 798.
[8] Gray D.F. and Livingston W. C., *Astrophys. J.*, **474** (1997) 802.
[9] Caccin B., and Penza V., *ESA*, **SP-463** (2000) 293.
[10] Muller R. and Roudier T., *Solar Phys.*, **94** (1984) 33.
[11] Kurucz R. L., *Astrophys. J. Suppl.*, **40** (1979) 1.
[12] Caccin B., and Staro F., Publ. de l'Obs. de Paris-Meudon (1998).
[13] Caccin B., Gomez M. T. and Staro F., *Mem. SAIt.*, **69** (1998) 595.
[14] Castelli F., Gratton R. and Kurucz R. L., *Astron. Astrophys.*, **328** (1997) 841.
[15] Kiefer M., Grabowski U., Mattig W. and Stix M., *Astron. Astrophys.*, **355** (2000) 381.
[16] Gray D. F. and Johanson H. L., *PASP*, **103** (1991) 439.