**Astronomy
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On the effective temperature scale of O stars

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Abstract. We rediscuss the temperature of O dwarfs based on new non-LTE line blanketed atmosphere models including stellar winds computed with the *CMFGEN* code of Hillier & Miller (1998). Compared to the latest calibration of Vacca et al. (1996), the inclusion of line blanketing leads to lower effective temperatures, typically by ∼4000 to 1500 K for O3 to O9.5 dwarf stars. The dependence of the $T_{\rm eff}$–scale on stellar and model parameters – such as mass loss, microturbulence, and metallicity – is explored, and model predictions are compared to optical observations of O stars. Even for an SMC metallicity we find a non-negligible effect of line blanketing on the $T_{\rm eff}$–scale. The temperature reduction implies downward revisions of luminosities by ∼0.1 dex and Lyman continuum fluxes Q_0 by approximately 40% for dwarfs of a given spectral type.

Key words. stars: general – stars: temperature – stars: fundamental parameters – stars: atmospheres

1. Introduction

As a significant fraction of the flux of O stars is emitted in the inaccessible Lyman continuum ($\lambda < 912$ Å) reliable direct determinations of their effective temperatures are not possible. Indirect methods, primarily based on atmospheric modeling, are therefore employed (e.g. Böhm-Vitense 1981; Crowther 1998). Given the need for a detailed treatment of non-LTE effects and the presence of stellar winds (Kudritzki & Hummer 1990), a complete modeling of such atmospheres including also the effects of numerous metal-lines ("line blanketing") remains a complex task (cf. Schaerer & Schmutz 1994; Hillier & Miller 1998; Pauldrach et al. 2001).

For these reasons, most published spectral analysis have so far been based on simple non-LTE models. For example, the most recent calibration of stellar parameters of O and early B type stars of Vacca et al. (1996, hereafter VGS96) is based only on results from plane parallel, pure hydrogen and helium (H-He) non-LTE models. Their derived temperature scale for O stars is found to be significantly hotter than most earlier calibrations (see references in VGS96). Such differences lead to non-negligible changes in the fundamental parameters of O stars – e.g. luminosities, Lyman continuum fluxes etc. – when estimated from spectral types. Accurate calibrations are crucial for

various astrophysical topics, such as comparisons with stellar evolution models, determinations of the initial mass function and cluster ages, studies of H II regions, and others.

Indications for a decrease of $T_{\rm eff}$ due to line blanketing effects have been found since the first non-LTE + wind modeling attempts by Abbott & Hummer (1985, and subsequent investigations based on the same "wind blanketed" models), the improved models of Schaerer & Schmutz (1994) and Schmutz (1998), and the fully-blanketed plane parallel non-LTE models of Hubeny et al. (1998). Similar indications are obtained by Fullerton et al. (2000) from recent modeling of *FUSE* spectra with the code of Pauldrach et al. (2001) and by Crowther et al. (2001).

The effective temperature scale of O stars is revised here based on the recent *CMFGEN* code of Hillier & Miller (1998), which treats the problem of a non-LTE line blanketed atmosphere with a stellar wind in a direct way, thereby avoiding possible shortcomings due to opacity sampling techniques employed by Schaerer & Schmutz (1994), Schmutz (1998), and Pauldrach et al. (2001). First results on the dwarf sequence are presented here. A more detailed account including all luminosity classes will be presented in a subsequent publication.

In Sect. 2 we describe our method and the calculated models. The results, their dependence on model/stellar parameters, and first comparison with observations are

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presented in Sect. 3. Implications of the revised T_{eff} scale and remaining uncertainties are discussed in Sect. 4.

2. Model ingredients

We have constructed spherically expanding non-LTE line-blanketed model atmospheres using the *CMFGEN* comoving-frame code of Hillier & Miller (1998). This code solves the equations of statistical equilibrium, radiative transfer, and radiative equilibrium, and allows for a direct treatment of line blanketing through the use of a super-level approach. The following ions are included in our calculations: H, He I–II, C II–IV, N II–V, O II–VI, Si II–IV, S IV–VI, and Fe III–VII, whose ∼2000 levels are described by ∼700 super-levels, corresponding to a total of ∼20 000 bound-bound transitions.

For simplicity a constant Doppler profile (thermal width corresponding to the mass of Helium and $T = 20\,000$ K plus a microturbulent velocity of $v_{\mathrm{turb}} = 20$ km s^{-1}) is assumed for all lines in the statistical equilibrium and radiative transfer computation. To examine if a constant thermal width and the use of the large microturbulent velocity does not artificially enhance the photospheric blanketing, we have made test calculations with the correct depth and ion dependent thermal width and $v_{\mathrm{turb}} = 0.1$ km s^{-1}. No significant changes in atmospheric structure, level populations, and the emergent spectrum were found. This is explained in part by the high density of lines in the UV part of the spectrum, which implies an average spacing between lines which is smaller than the typical Doppler width. The opacity in the wing of a line is therefore mostly dominated by the core opacity of the neighbouring line, and the exact intrinsic line profile is of little importance. With our standard choice, ∼80 000 frequency points are necessary to correctly sample all lines.

The input atmospheric structure, connecting smoothly the spherically extended hydrostatic layers with the wind (parametrised by the usual β-law), is calculated as in Schaerer & de Koter (1997) with the *ISA-WIND* code of de Koter et al. (1996) As the approximate temperature structure in *ISA-WIND* differs from the final radiative equilibrium temperature structure, the atmosphere structure in the quasi-hydrostatic part may be inconsistent with the final gas pressure gradient. However, for the issues discussed here the differences are small (corresponding to a change of $\lesssim 0.1$ dex in $\log g$). In any case, the lines considered here are formed in the transition region whose structure/dynamics remain largely parametrised. The formal solution of the radiative transfer equation yielding the detailed emergent spectrum allows for incoherent electron scattering and includes standard Stark broadening tables for H, He I, and He II lines. Our standard calculations assume $v_{\mathrm{turb}} = 5$ km s^{-1}.

We have computed a grid of models representative of O dwarfs in the temperature range between ∼30 000 and 50 000 K. The model parameters are taken from the *CoStar* models A2-E2 of Schaerer & de Koter (1997), with an additional model Y2 at $(T_{\mathrm{eff}}, \log g) \sim (31\,500, 4.0)$ and

the remaining parameters[1] taken from stellar tracks of Meynet et al. (1994). For each parameter set a line blanketed model with solar metallicity and a pure H-He model was computed.

3. Results

3.1. Blanketing effect on the temperature scale

The optical He I $\lambda 4471$ and He II $\lambda 4542$ classification lines are used to assign spectral types to our models. Figure 1 shows the effective temperature as a function of $\log W' \equiv \log W(4471) - \log W(4542)$ and the corresponding spectral type according to Mathys (1988). The pure H-He models (open circles) follow closely the T_{eff}–scale for dwarfs of VGS96, which is based on a compilation of stellar parameters determined using pure H-He plane parallel non-LTE model atmospheres. The comparison shows that if we neglect line blanketing our dwarf model grid would yield nearly the same absolute T_{eff}–scale as the pure H-He plane parallel models adopted for the spectral analysis included in the compilation of VGS96.

The line blanketed model sequence (Fig. 1, filled symbols) shows a systematic shift to earlier spectral types for a given temperature, or equivalently a shift to *lower* T_{eff} *for line blanketed models at a given spectral type*. The difference ranges from ∼1500 K at spectral type O9.5 to ∼4000 K at spectral type O3 (cf. Fig. 1, solid line in lower panel). The difference with the VGS96 scale is shown as the dotted line. Our line blanketed scale smoothly joins earlier calibrations at O9.7V (see VGS96, Fig. 1).

As a spectral type corresponds to a given ionisation state of Helium in the line formation region, blanketed models must be more ionised than unblanketed models. The introduction of line blanketing leads to three main effects illustrated in Fig. 2 for the case of model C2 (cf. Figs. 13 and 14 of Schaerer & Schmutz 1994). Qualitatively the same trends are obtained for all models.

1) Blanketing leads to the backscattering of photons towards the inner atmosphere which forces the local temperature to rise so that flux conservation is fulfilled (backwarming effect; see upper panel);
2) At the same time the radiation field becomes more diffuse, as quantified by the dilution factor $\tilde{W} = 1 - \frac{1}{4} F/J$ shown in the middle panel, causing an increase of the mean intensity (cf. Abbott & Hummer 1985; Schaerer & Schmutz 1994);
3) In the outer part of the atmosphere ($\log \tau_{\mathrm{Ross}} \lesssim -2$ in Fig. 2) the ionisation is essentially controlled by the EUV flux, which is quite strongly reduced due to the blocking by numerous metal lines shown in Fig. 3. Here this effect dominates over 2), in contrast with the finding of Schaerer & Schmutz (1994), leading to a lower ionisation.

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[1] $M = 16.83\ M_{\odot}$, $\log T_{\mathrm{eff}} = 4.498$, $\log(L/L_{\odot}) = 4.552$, $R = 6.358\ R_{\odot}$, $\log \dot{M} = -7.204\ M_{\odot}/\mathrm{yr}$, and $v_{\infty} = 2500$ km s^{-1}.
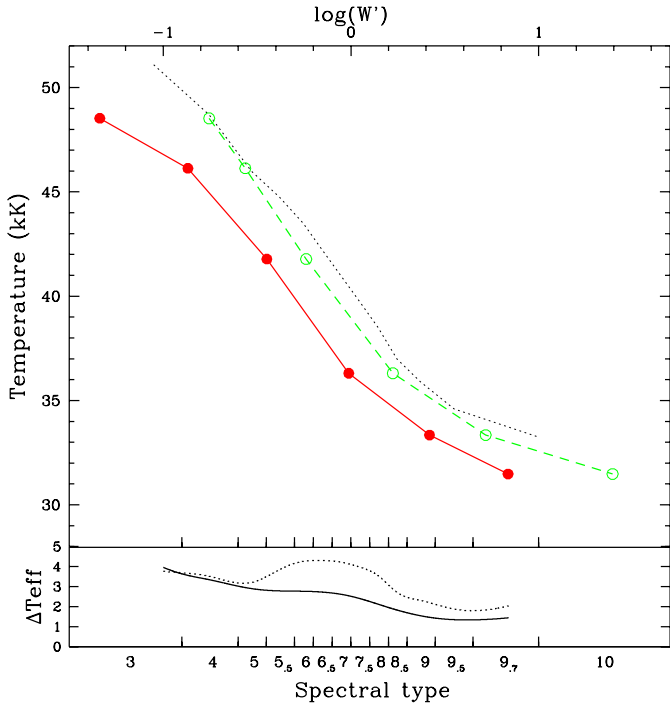
Fig. 1. *Upper panel:* effective temperature of O dwarfs as a function of the spectral subtype (lower scale). The correspondance between $\log W'$ (upper scale) and spectral type is given by Mathys (1988). For values $\log W' > 1.0$ we assign a spectral type of 10. Filled circles show our line blanketed models, open circles pure H-He models. The VGS96 relation (dotted line) is well reproduced by our pure H-He models. *Lower panel:* T_{eff} shift between H-He and line blanketed models (solid line) and between VGS96 scale and our line blanketed models (dotted line). Note the decrease of T_{eff} due to line blanketing.

Fig. 2. Comparison of atmosphere structures of model C2 ($T_{\mathrm{eff}} = 41.8$ kK, $\log g = 4.0$). Solid line is for the line-blanketed model and dashed line for the pure H-He model. *Upper panel:* temperature structure. *Middle panel:* dilution factor $\tilde{W} = 1 - \frac{1}{4}F/J$ where F is the flux and J the frequency averaged mean intensity (cf. Schaerer & Schmutz 1994). *Lower panel:* Populations of the ground levels of Helium and of the lower and upper levels of the transitions He I $\lambda4471$ and He II $\lambda4542$. Given are the relative number population n_i with respect to total H population $n_{\mathrm{tot}}(\mathrm{H})$.

Effects 1) and 2) lead to a higher ionisation in the formation region of the classification lines. This results predominantly in an increase of $W(4542)$ at $T_{\mathrm{eff}} \lesssim 38\,000$ K and a decrease of $W(4471)$ at higher T_{eff} (cf. Fig. 4).

Given the stronger mass loss and the corresponding increase of the wind density, one expects even larger temperature differences between non-blanketed and line blanketed models for giant and supergiant luminosity classes (cf. Abbott & Hummer 1985; Schmutz 1998; Crowther et al. 2001).

3.2. Dependence on model and stellar parameters

How strongly do our results depend on poorly known parameters such as the velocity law in the photosphere-wind transition zone, v_{turb}, and variations of gravity and $\dot{M}$ expected within the dwarf class? Do our calculations still miss opacity sources?

As pointed out by Schaerer & Schmutz (1994) changes in He line profiles due to modifications of the velocity law $v(r)$ in the photosphere–wind transition zone can lead to similar equivalent widths variations as line blanketing.
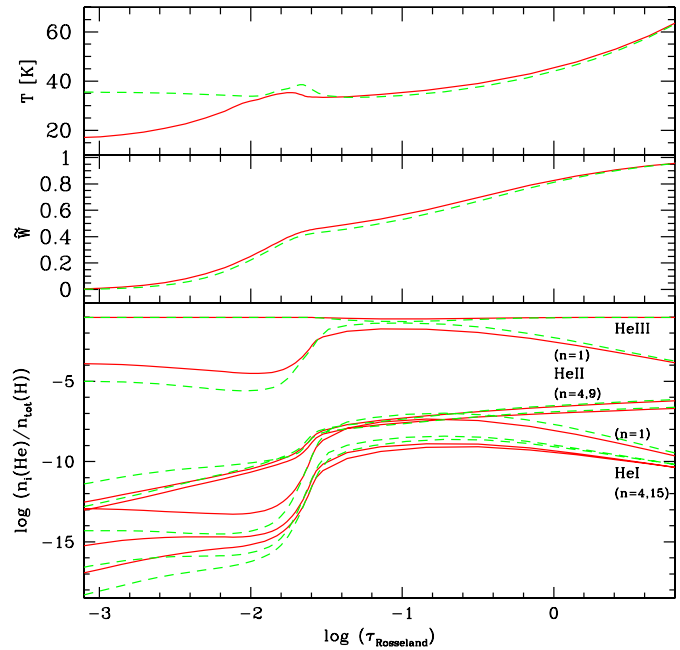
Test calculations for models A2 and C2 varying the slope β from 0.8 (our standard value) to 1.5 show that both H-He and line blanketed models exhibit a similar shift in $\log(W')$. The obtained *relative* T_{eff} difference between H-He and blanketed models remains thus identical. The blanketed models with $\beta = 1.5$ have $\log(W')$ lowered by ~0.1–0.2 dex. However, as Hα profile fits for O dwarfs are generally quite compatible with $\beta \sim 0.8$ (e.g. Puls et al. 1996), we do not expect drastic changes of the absolute scale from this effect.

An increase of the microturbulent velocity v_{turb} from 5 to 20 km s^{-1} in blanketed models increases the strength of He I $\lambda4471$ (cf. Smith & Howarth 1998; Villamariz & Herrero 2000), and leads to a shift of $\sim+0.05$ to 0.1 dex in $\log(W')$ (i.e. towards later types) for models with $T_{\mathrm{eff}} \lesssim 42\,000$ K. For hotter stars the difference is negligible.

The effect of line blanketing is strengthened further in denser winds (cf. Abbott & Hummer 1985; Schmutz 1998). Models C2 and D2 with an increased mass loss rate by a factor of 2 show a shift of $\log(W')$ between ~-0.05 and -0.1 dex.

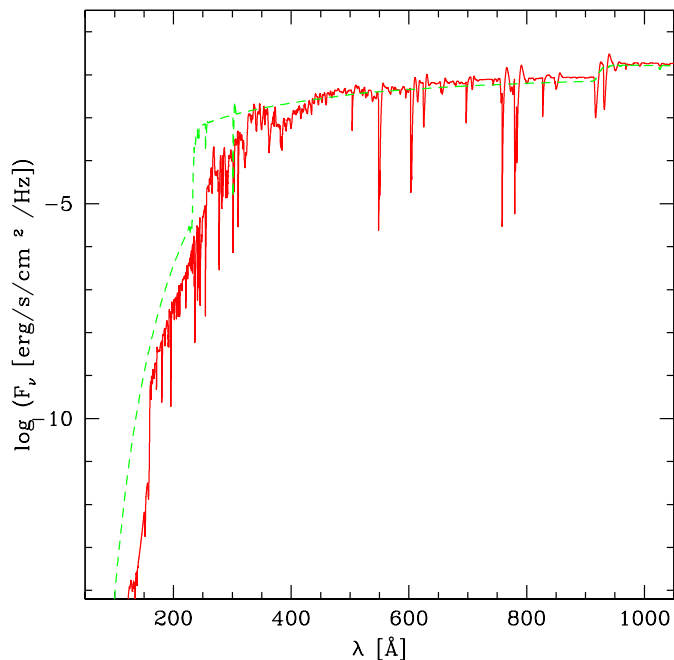Test calculations for model C2 including also Nickel (Ni IV–VI) show unchanged He lines. Other models

Fig. 3. UV spectrum of model C2 with line blanketing (solid line) and pure H-He model (dashed line). Note the reduction of the EUV flux below $\sim$500 Å due to the inclusion of metals.
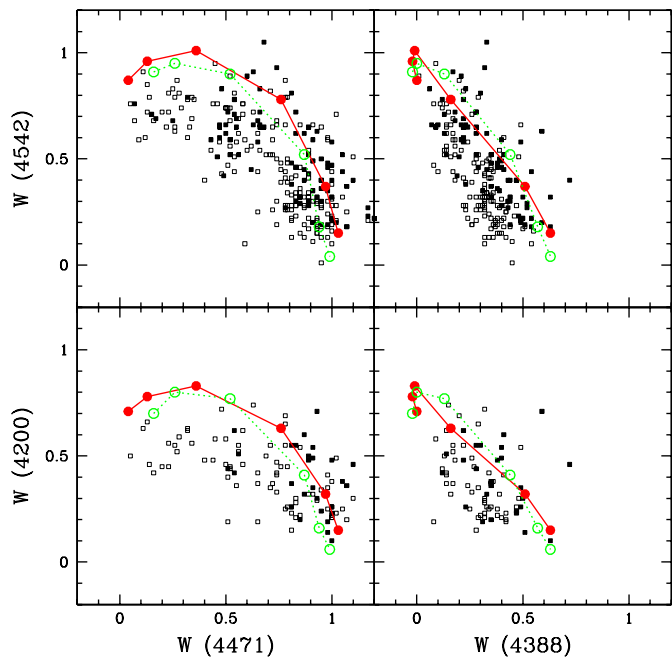
Fig. 4. Comparison between observed (filled squares: luminosity class V; open squares: other luminosity classes) and calculated equivalent widths of He I $\lambda4471$, He I $\lambda4388$, He II $\lambda4542$, and He II $\lambda4200$ (in Å). Line blanketed models are indicated by full circles, pure H-He models by open circles. See discussion in text.

including also Ar, Ne, and Ca confirm that Fe blanketing dominates.

While microturbulence and mass loss affect (though in opposite ways) the exact T_{eff}-scale, their exact importance will have to be studied in future comparisons.

3.3. Comparison with observations

As a first comparison of our models with observations we show in Fig. 4 the predicted and observed equivalent widths of He I and He II classification lines and other strong He lines frequently used in spectral analysis. The observational data is taken from Mathys (1988, 1989) and Conti & Alschuler (1971). The observational scatter is real, as the typical measurement errors are $\sim$5–7%. The general trend is that the He I $\lambda4471$ and He I $\lambda4388$ equivalent widths are well represented by the models, while He II $\lambda4542$ seems to be overestimated by $\sim$20% for spectral types earlier than O7. He II $\lambda4200$ behaves as He II $\lambda4542$. The other equivalent widths remain essentially unchanged by all other parameter variations discussed above (Sect. 3.2). A value of $\beta \gtrsim 1.5$, a stronger increase of $\dot{M}$, or an unrealisticly large reduction of $\log g$ would be necessary to reduce the predicted equivalent widths of the Stark broadened He II lines.

Strictly speaking, if we were simply to reduce $W(4542)$ by $\sim$20% while keeping $W(4471)$ constant for early spectral types, this would result in a change of $\sim$−0.08 dex in $\log(W')$ thus reducing the shift in the T_{eff}–scale between line blanketed and pure H-He models from $\sim$4000 K

to 3000 K in the high temperature part. Future tailored spectral analysis should allow to assess more precisely the achievable fit accuracy and the precise importance of the parameters discussed in Sect. 3.2 on the stellar parameters.

3.4. Comparison with previous analysis

As discussed in Sect. 1, few earlier studies have addressed the effect of line blanketing in O stars. Essentially all investigations concur with a reduction of T_{eff} when blanketing is included.

Abbott & Hummer (1985) have constructed a core-halo model where backscattered radiation due to multiple line scattering in the wind modifies the plane parallel photosphere. Their so-called "wind blanketed" models yield a decrease of T_{eff} by $\sim$10% for O4 types (similar to our results), $\sim$−2000 K for an O9.5 supergiant, but essentially no shift for O9.5 dwarfs (Bohannan et al. 1990; Voels et al. 1989). The latter finding is likely due to lack of photospheric blanketing (inherent to their method) and modest wind blanketing due to the comparatively low mass loss rates of O9.5 dwarfs.

An improved Monte-Carlo opacity sampling method of a unified photosphere–wind model was used by Schaerer & Schmutz (1994), Schaerer & de Koter (1997), and subsequently applied to a larger parameter space by Schmutz (1998). For mass loss rates comparable to the values

adopted here (typical for dwarfs with low mass loss) the models of Schmutz (1998) indicate differences from ~ -600 K at O8 to ~ -2000 K at O4, which is half the shift deduced from Fig. 1 and roughly the difference obtained with $Z = 1/8\,Z_\odot$ (see Sect. 4). This indicates that their method underestimates line blanketing compared to *CMFGEN*.

Using plane parallel line blanketed non-LTE models based on opacity distribution functions Hubeny et al. (1998) found that a pure H-He model with $T_{\rm eff} \sim 37\,500$ K and $\log g = 4.0$ is necessary to reproduce the H and He lines of a line blanketed model with $T_{\rm eff} = 35\,000$ K and same gravity. As can be seen from Fig. 1 our results are in excellent agreement with their result.

LTE line blocking has been included in plane parallel models by Herrero et al. (2000) primarily to resolve discrepancies between He I singlet and triplet lines. For stars with $T_{\rm eff} \gtrsim 40\,000$ K this leads to a strengthening of He I $\lambda4471$, opposite to the effect found in all above studies including ours. This results must be due to an incomplete treatment of the various effects of line blanketing (cf. above), and appears to be unphysical. This discrepancy with line blanketed models has also been noted by the authors.

4. Implications and concluding remarks

The importance of line blanketing obviously depends on metallicity Z. Therefore one may wonder at which Z the stellar parameters will again correspond to the results obtained with pure H-He (metal-free) atmosphere models, i.e. close to the VGS96 scale. Test calculations for models A2 and D2 with a metallicity close to the SMC value $(1/8\,Z_\odot)$ show still a reduction of $T_{\rm eff}$ compared to pure H-He models: $\Delta T_{\rm eff}$ is $\sim 60\%$ that found at solar metallicity.

As the bolometric correction is essentially unchanged by line blanketing, and the M_V versus spectral type (Sp) calibration independent to first order from modeling, we can use the BC-$T_{\rm eff}$ relation of VGS96 to derive luminosities through $\log(L/L_\odot) = 2.736\log\,T_{\rm eff}({\rm Sp}) - 0.4\,M_V({\rm Sp}) - 9.164$. This relation shows that the predicted reduction of $T_{\rm eff}$ by $\lesssim 0.04$ dex implies a downward revision of L by $\lesssim 0.1$ dex for dwarfs of a given spectral type.

Since line blanketing is mostly efficient in the EUV, the ionising spectrum below 912 Å is modified. The total number of Lyman continuum photons Q_0 predicted by our models is in good agreement with the calculations of Schaerer & de Koter (1997). The change of Q_0 due to the shift in the $T_{\rm eff}$-Sp calibration, taking into account the change of both the radius and the ionising flux per unit surface area q_0, is given by $\Delta(\log Q_0) = -1.264\Delta(\log T_{\rm eff}) + \Delta(\log q_0(T_{\rm eff}))$, where the latter term is dominant (see Schaerer & de Koter 1997). For a given spectral type between O4V and O9V this amounts typically to a reduction of Q_0 by $\sim 40\%$.

While the results presented here provide a clear improvement over earlier calibrations, and a general reduction of $T_{\rm eff}$ due to line blanketing is unavoidable, we wish to caution that the absolute $T_{\rm eff}$ scale may still be subject to revisions for the following reasons. First, tailored multi-wavelength analysis of individual objects are required to test the present models in more depth for O stars, as recently started by Bouret et al. (2001), Hillier et al. (2001), and Crowther et al. (2001). Second, the effect of X-rays on the overall ionisation balance and in particular on the Helium lines remains to be studied. Indeed for late O and B stars, depending on the relative X-ray to photospheric flux at energies close to the relevant ionisation potentials and the wind density, X-ray emission (likely due to shocks) is expected to increase the ionisation of most ions (MacFarlane et al. 1994). Nonetheless, first test calculations with *CMFGEN* seem to indicate that photospheric lines are not affected by X-rays generated in the wind. Finally, we note that comparisons of photoionisation models calculated using fluxes from recent atmosphere models (including *CMFGEN* and Pauldrach et al. 2001 models) with *ISO* observations of H II regions possibly reveal a flux deficiency at energies $\gtrsim 34.8$–40.9 eV (Morisset et al. 2001, but cf. Giveon et al. 2001). The importance of the latter two findings – possibly related to each other – on the lines used here as $T_{\rm eff}$ indicators remains to be studied.

As UV and optical classification lines of O stars depend in fact on several parameters ($T_{\rm eff}$, gravity, mass loss rate, metallicity, rotation; e.g. Abbott & Hummer 1985; Schmutz 1998; Walborn et al. 1995), spectral type and luminosity class calibrations must ultimately account for this multi dimensionality. Some of these issues will be addressed in subsequent publications.

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