Metallicity effects in the spectral classification of O-type stars. Theoretical consideration.

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Abstract. Based on an extended grid of NLTE line-blanketed models of atmospheres with stellar winds, as calculated by means of FASTWIND, we have investigated the change in the strengths of strategic Helium transitions in the optical as caused by a 0.3 decrease in metallicity with respect to solar abundances. Our calculations predict that only part of the observed increase in T_{eff} of O-type dwarfs could be explained by metallicity effects on the spectral type indicators, while the rest must be attributed to other reasons (e.g., different stellar structures as a function of metallicity or differences between observed and theoretical wind parameters etc.). In addition, we found that using the He II 4686 line to classify stars in low metallicity environments ($Z \leq 0.3Z_{\odot}$) might artificially increase the number of low luminosity (dwarfs and giants) O-stars, on the expense of the number of O-supergiants.
Key words: stars: early-type - stars: fundamental parameters

Ефекти на металичността при спектраланата класификация на звзди от тип О. Теоретични разглеждания.

Невена Маркова, Лучиана Бианчи, Боряна Ефремова, Йоахим Пулс

Базирайки се на обширна мрежа от атмосферни модели отчитащи ефектите на нело-кално термодинамично равновесие (NLTE), на бланкитиране и на звезден вятър (FAST-WIND), ние изследвахме изменението на интензитета на стратегически хелиеви линии при металичност с 0.3 по-ниска от слънчевата. Нашите изчисления предсказват, че само част от наблюдаваното нарастване на ефективната температура при звезди-джуджета от тип О може да бъде обяснено с влияние на металичността върху спектрал-ните инидикатори, докато остатъкът може да бъде атрибут на други причини (напр. различни звездни структури като функция на металичността, различия между наблю-даваните и теоретичните параметри на вятъра и т.н.). В добавка ние намерихме, че използването на линията He II 4686 за класифициране на звезди в околност с ниска металичност ($Z \leq 0.3Z_{\odot}$) може да повиши изкуствено броя на О-звездите с ниска светимост (джуджета и гиганти) за сметка на О-свръхгигантите.

Introduction

Thanks to the outstanding work by N. Walborn and collaborators over the last 30 years, a detailed classification scheme for OB-stars of solar metallicity has been developed, based on the morphology of the line spectrum. For the specific case of O-type stars, an alternative scheme relying on quantitative criteria has been provided by Conti & Alschuler [1971] and Mathys [1988] as well. Consequently, the classification of Galactic OB stars is rigorously defined.

The classification of extragalactic stars, on the other hand, is still somewhat problematic. In particular, the calibration between spectral types and physical parameters differs as a function of metallicity when criteria for Milky Way stars are applied. With respect to B-stars, this point has been extensively discussed by various authors (e.g., Monteverde et al. [1996], Lennon [1997], Urbaneja et al. [2005]) who pointed out that the use of the MK classification criteria for stars with metallicities different than solar can significantly influence the derived spectral types and luminosity classes.

Unlike B-type stars, where the relative strengths of metal to He I optical lines are used for classification purposes, O-type stars are generally classified by comparing the strengths of He I and He II lines[4] (see, e.g., Conti & Alschuler [1971]; Mathys [1988], Walborn [1971, 1973]; Walborn & Fitzpatrick, [1990]). Thus, one might conclude that there should be no problem to employ the standard classification schemes of either Walborn or Conti to O-type stars in various metallicity environments. However, theoretical considerations predict that Helium line strengths should also depend, though indirectly, on metallicity, due to the processes of mass-loss and EUV line-blocking/blanketing (e.g., Abbott & Hummer [1985], Sellmaier et al. [1993], Herrero et al. [2000]). Whilst in stars with weaker winds (e.g., dwarfs) the effect is controlled, to a major extent, by the blanketing alone, in stars with stronger winds (e.g., supergiants), the processes of wind emission and additional wind-blanketing seem to be of similar or even dominating impact (e.g., Repolust et al. [2004]).

1   Metallicity effects in optical Helium line strengths

As noted in the previous section, the classification of O-type stars in the optical band relies either on the Walborn or on the Conti classification schemes, both developed to be used at solar metallicity. In the Walborn scheme visual estimates of individual line strengths or line strength ratios of strategic Helium transitions are used as classification criteria, while in the Conti scheme the logarithm of the equivalent width (EW) ratio of He I 4471 to He II 4541 is used instead. Given that an eye-estimated ratio is roughly equivalent to the logarithmic ratio of the corresponding EWs, these two approaches should lead to similar results (but see Heap et al. [2006]).

To address the metallicity issue regarding the spectral classification of O-type stars, we developed the following strategy. As a first step and using the FASTWIND code (Puls et al. [2005]), we constructed 6 model grids, corresponding to two values of metallicity, solar, $Z_\odot$, and 0.3 $Z_\odot$[5], and three luminosity classes: dwarfs (DWs), giants (Gs) and supergiants (SGs). By

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[4] At the very early O2-3 subtypes, the Helium ionization balance can no longer be employed (due to very weak/missing He I), and specific classification criteria based on the strengths of optical N V and N IV transitions have been developed by Walborn et al. [2002].

[5] This investigation was designed and carried out as a first step of a project to study the massive stellar content in NGC 6822, for which a mean iron abundance, [Fe/H], of about -0.5 was found, corresponding to an average metallicity of about 0.3 $Z_\odot$ (for more information, see Efremova et al. [2009] and references therein).
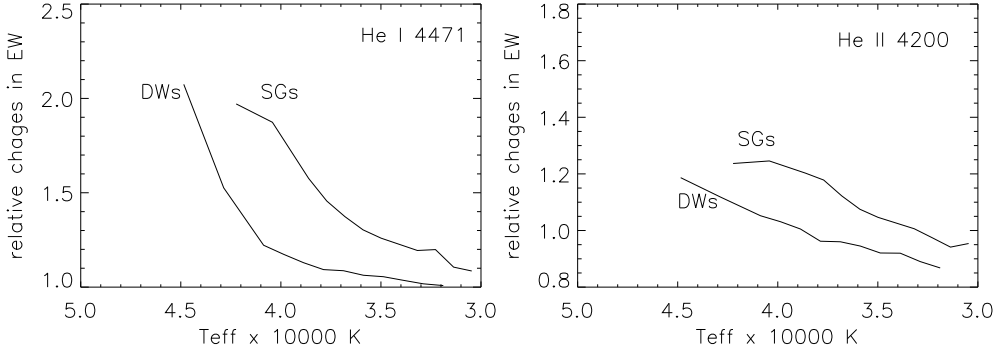
Fig. 1. Exemplary changes in Helium line strengths (in units of $\mathrm{EW}(Z = 0.3\,Z_\odot)/\mathrm{EW}(Z_\odot)$) as caused by the adopted decrease in metallicity.

means of these models we investigated the predicted variations in Helium line strengths, caused by the adopted change in metallicity, as a function of T_{eff} and luminosity class. Subsequently, we evaluated the shifts in spectral type (and T_{eff}) and luminosity class, that would eventually appear if Galactic classification criteria were used to O-type stars of metallicity $0.3\,Z_\odot$.

1.1   Model grids

Our model grids comprise 64 NLTE, line-blanketed models with stellar winds. For all models and independent of metallicity, stellar parameters (T_{eff}, $\log g$, and $R_\star$) were taken from the empirical calibrations of Martins et al. [2005] for Galactic stars of luminosity classes I, III and V. We used a solar chemical composition as derived by Asplund et al. [2005], subsequently scaled to Z=0.3 $Z_\odot$.

A standard β-velocity law with β=0.9 was adopted for all models. Terminal velocities, v_∞, for solar metallicity models were determined by means of the spectral type - v_∞ calibration from Kudritzki & Puls [2000]. The effects of metallicity on v_∞ were taken into account by employing the scaling relation from Leitherer et al. [1992], namely $v_\infty\, Z^{\mathbf{0.13}}$. Mass-loss rates were calculated using the mass-loss recipe from Vink et al. [2001]. A microturbulent velocity of 10 km s^{-1}was used to calculate the atmospheric structures, whilst values of 5, 10 and 15 km s^{-1}were assumed for calculating the emergent spectrum.

1.2   Temperature classification

Based on these model grids, the EW variations of several strategic He I (e.g., He I 4026, He I 4471 and He I 4387) and He II (e.g., He II 4200, He II 4541 and He II 4686) lines were investigated, as a function of metallicity ($Z_\odot$ and $0.3\,Z_\odot$), T_{eff} and luminosity class.

Our results, partly illustrated in Figures 1 and 3, indicate that in the O-star temperature domain He I and He II are both influenced by metallicity.
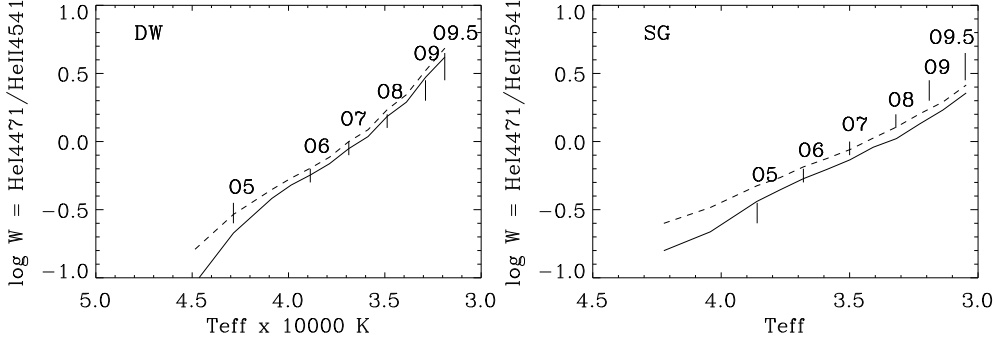
Fig. 2. Predicted He I 4471/He II 4541 line ratios for Z=Z$_\odot$ (solid) and Z=0.3 Z$_\odot$ (dashed). Vertical lines mark the range of values determining each spectral type according to the Mathys $\log W$ - spectral type calibration.

The effect is opposite to that for metal lines, i.e., while metal lines become weaker due to the lower metal content, the Helium line strengths are predicted to increase in absorption.

Moreover, individual lines react differently. Members of the He I singlet series are more sensitive to metallicity than those of the triplet series[6], which in turn are more sensitive than He II transitions (except for He II 4686, see next section). In addition, the effect depends on $T_{\rm eff}$ and $\log g$, being more pronounced in hotter SGs (where mass loss effects are strongest), and almost negligible (within $\pm 10\%$)[7] at intermediate and cooler temperature DWs.

Our findings imply that, due to the lower metal content, the optical Helium line spectrum of low metallicity O-stars would appear somewhat different from that of their Galactic conterparts. In particular, at Z=0.3 Z$_\odot$ and if the strength of the primary classification lines, He I 4471 and He I 4387, were to be considered, these lines would resemble those of a Galactic star with *lower* $T_{\rm eff}$ (assuming the same $\log g$ and $R_\star$): about 2 kK lower for SGs and up to 1 kK lower for DWs. Vice versa, if compared to Galactic counterparts with the *same observed* EWs in He I, stars with a lower metal content should be hotter.

For the strategic He II 4200 and He II 4541 transitions we find the following situation: for intermediate and low temperature DWs ($39 \le T_{\rm eff} \le 32$ kK) and cooler SGs ($T_{\rm eff}$ below 34kK), the corresponding lines strengths are predicted to remain rather unaffected by metallicity, whilst at higher $T_{\rm eff}$ they are amplified by up to 20 percent, mimicking the lines of a Galactic star of *higher* $T_{\rm eff}$.

The effect of metallicity on the spectral classification of O-stars can be evaluated by investigating the behaviour of He I/He II line ratios instead of individual line strengths. Thus, we have calculated and compared the logarith-

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[6] This fact has been pointed out by Herrero et al. [2000]; see also Najarro et al. [2006] for problems in modeling the singlet lines.
[7] For good quality spectra the error of individual EW measurements is typically of the order of about 10 percent.

mic He I(+II) 4026/He II 4200, He I 4471/He II 4541 and He I 4387/He II 4541 line ratios, as a function of $T_{\rm eff}$, for the cases of DWs, Gs and SGs and for the two values of metallicity, $Z_{\odot}$ and 0.3 $Z_{\odot}$. The results of these calculations are partly illustrated in Figure 2, where the lower and upper limits of the line strength ratios from the Mathys $\log W$ - spectral type calibration[8] are overplotted as vertical lines. The x-position of each of these lines has been placed at the appropriate $T_{\rm eff}$-value following from the Martins et al. empirical calibration for the corresponding spectral type.

Apparently, this criterion to classify O-stars with Z=0.3 $Z_{\odot}$ would lead to temperature differences that increase with $T_{\rm eff}$ and luminosity class. In particular, for SGs these differences are predicted to range from about 1 to about 2 kK (i.e. about one sub-type), while for DWs the expected values are a factor of 2 smaller.

Another important result to be noted is that whilst for Galactic DWs a good correspondence between the calculated and the calibrated values of the He I 4471/He II 4541 line ratios is found, for cooler SGs (subtypes later than O7) the calculated values are systematically smaller. This discrepancy results from the (still not understood) so-called "generalized dilution effect", which makes the synthetic He I 4471 lines in low temperature SG models weaker than observed (see Repolust et al. [2004] and references therein). Since this effect seems to be independent on metallicity, it is not expected to influence our general findings though.

1.3   Luminosity classification

In the Walborn classification scheme, the main luminosity criterion is He II 4686. In SGs this line appears only in emission, while in DWs it is observed as a pure absorption feature. Since the amount of emission depends on the wind properties, which in turn depend on metallicity, one expects the strength of He II 4686 to depend on metallicity as well (see, e.g., Massey et al. [2004]).

In Figure 3 the behaviour of the He II 4686 EWs (positive for emission and negative for absorption) are shown as a function of $T_{\rm eff}$, for two luminosity classes (SGs and DWs) and for Z=$Z_{\odot}$ and 0.3 $Z_{\odot}$. Expectedly, our calculations for solar metallicity models produce He II 4686 in emission for SGs and in absorption for DWs. Interestingly, however, our calculations predict that the metallicity effects on this line can be so strong that at Z=0.3 $Z_{\odot}$ its sensitivity to luminosity vanishes almost completely, and He II 4686 appears in absorption for all calculated models.

Finally let us note that although an increase in microturbulent velocity (from 5 to 15 km s^{-1}) is predicted to shift the assigned spectral types by half (for DWs)[9] to one (for SGs) subtype towards later spectral types, this effect does not seem to depend on metallicity. Due to this reason model predictions corresponding to $v_{\rm mic} = 10$ km s^{-1} only are shown throughout this paper.

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[8] The Conti classification scheme has been extended by Mathys [1988] to cover the earliest and latest O-subtypes.

[9] This estimate is consistent with Mokiem et al. [2004] who found a similar result for the case of a hot (O5) dwarf.
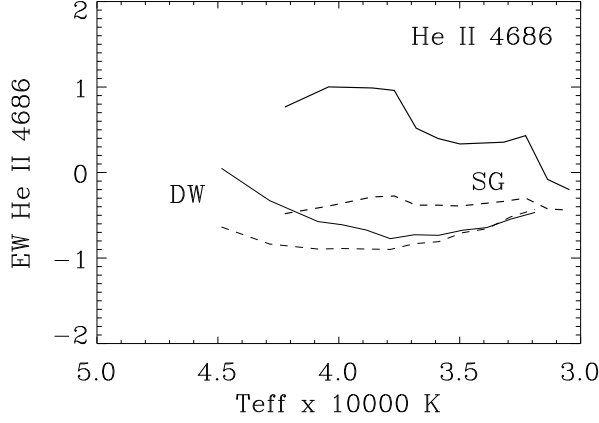
Fig. 3. Equivalent widths (positive for emission) of He II 4686 as a function of T_{eff}, calculated for two values of metallicity - $Z_\odot$(solid) and 0.3 $Z_\odot$(dashed), and for two luminosity classes (SGs and DWs).

2   Discussion and Conclusions

Based on a grid of NLTE, line blanketed model atmospheres with stellar winds as calculated by means of FASTWIND, we found that
• in O-stars the optical Helium spectrum can be significantly influenced by metallicity effects, where a decrease in metal content results in stronger He line absorptions *from both ionization stages*, where lines from He I are more severely affected than those from He II. Individual lines react differently in dependence of T_{eff} and luminosity class, but do not depend on microturbulence. This result is particularly important when *individual line strengths* are used to classify stars, as it is the case for the Walborn scheme where the detection of weak He I 4471 and He I 4387 is used to fix the subtypes O4 and O6, respectively. According to our calculations at $Z{=}0.3$ $Z_\odot$, the use of these lines as classification indicators would shift the assigned spectral types by up to one subtype to the later side, provided the detection threshold is the same.
• Furthermore, our calculations showed that not only individual Helium lines, but Helium line ratios are also varying with metallicity. In particular, the use of the He I 4471/He II 4541 ratio to classify O-stars of $Z{=}0.3$ $Z_\odot$ would shift the derived temperature scale by up to 2 kK (i.e., about one sub-type) for SGs, and up to 1 kK (i.e., about half a sub-type) for DWs to the hotter side. The latter result is consistent with the predictions by Mokiem et al. [2004], who found, using CMFGEN (Hillier & Miller [1998]), that variations in the metal content from $Z{=}2$ $Z_\odot$ to $Z{=}0.1$ $Z_\odot$ can change the spectral type of a hot DW by up to one and a half sub-type.
    Extended extragalactic surveys of hot massive stars showed that O-stars in low metallicity environment are systematically hotter than their Galactic counterparts with the same spectral type (e.g., Mokiem et al. [2006], Massey et al. [2004, 2005], Efremova et al. 2009), thus confirming our principal pre-

dictions. However, the observed shifts in T_{eff} are significantly larger than those predicted to appear from a shift in the assigned spectral types, as calculated here and in other work. In particular, for O-type DWs temperature differences of 3 to 4 kK, i.e., a factor of 3 to 4 larger than those predicted by Mokiem et al. [2004] were established between objects in our Galaxy and in the SMC (Z=0.2 $Z_{\odot}$)[10]. The corresponding results for DWs in NGC 6822 are roughly the same (Efremova et al. [2009]).

Thus, only part ($\sim$25 to 30 percent) of the observed differences in T_{eff} of O-type DWs in the SMC and in NGC 6822 could be explained by metallicity effects on the spectral type indicators, while the rest must be attributed to other, more "physical" reasons, such as, e.g., different stellar structures as a function of metallicity or differences between observed and theoretical wind parameters etc. Additional calculations are required to separate and evaluate these effects.

• Our calculations predict that the amount of wind emission in He II 4686 diminishes towards lower metallicities, so that at $Z \leq$0.3 $Z_{\odot}$ this line would appear only in absorption and could no longer serve as a reliable luminosity indicator. In particular, using this line to classify stars in low metallicity environments might artificially increase the number of low luminosity (DWs and Gs) O-stars identified in galaxies with lower metallicity, on the expense of the number of O-SGs.

Some hints about such effects seem to have been established already. For instance, Massey et al. [2004] recently noted that in several of their MC targets the He II 4686 emission is weaker than it might be expected, given their absolute magnitudes, M_{V}. And although one might argue that a discrepantly high M_{V} could be due to spectroscopic binarity, an alternative explanation in terms of metallicity effects is also possible, accounting for our present results. Moreover, the number of SGs identified in the SMC appears to be less than expected (D. Lennon, priv. comm.), in agreement with what might be expected from our calculations.

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[10] According to the computations by Mokiem et al., a factor of 5 decrease in $Z/Z_{\odot}$ would result in a shift of only 1 kK in T_{eff} of a hot DW, i.e., about half a subtype.

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