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# Visible neutral helium lines in main sequence B-type stars: observations and NLTE calculations

**F. Leone**[1,⋆] **and A.C. Lanzafame**[2]

[1] Osservatorio Astrofisico di Catania, Città Universitaria, I-95125 Catania, Italy
[2] Istituto di Astronomia, Città Universitaria, I-95125 Catania, Italy

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**Abstract.** Spectra in the visible range 410 - 710 nm have been obtained for a sample of main sequence B-type stars to determine the behavior of neutral helium lines with effective temperature and gravity. Equivalent widths have been compared with new calculations which combine the capabilities of LTE atmospheric models of including millions of lines contributing to the opacity and accurate NLTE treatment of the line formation. The latter take advantage of accurate atomic cross-sections. We find a satisfactory agreement between theory and observations with differences probably due to the microturbulence.

We also investigate the effects of blending and find that the He I 412.1 nm is severely blended with oxygen lines for spectral types earlier than B3.

**Key words:** line: formation – stars: abundances – stars: early-type

## 1. Introduction

Information regarding neutral helium lines in main sequence B-type stars can still be considered fragmentary and contradictory. Satisfactory models of the helium lines formation in such stars are very important if we have to understand, for instance, helium abundance peculiarities, stratification of chemical elements and the like.

Noticeably, Heasley et al. (1982) compared the observed equivalent widths (EW) of He I 402.6, 438.7, 447.1, 471.3, 492.2, 587.6 and 667.8 nm lines for a sample of 19 B-type stars with $16000\,\mathrm{K} < T_{\mathrm{eff}} < 27500\,\mathrm{K}$ and $3.0 < \log g < 4.0$ with Auer & Mihalas (1973) NLTE calculations. The best agreement was found for lines in the blue-violet region of the spectrum where departures from LTE are relatively small. For the He I 587.6 and 667.8 nm lines, Heasley and coworkers found that the observed lines are stronger than NLTE predictions for stars with high effective temperature or low surface gravities, i.e., where the departures from LTE are largest.

More recently, Grigsby et al. (1992) have analysed a sample of B-type stars with $21000\,\mathrm{K} < T_{\mathrm{eff}} < 38000\,\mathrm{K}$ and $3.7 < \log g < 4.2$, computing simultaneously atmospheric models and profile for several lines. Grigsby and co-authors concluded that the Stark wings and the forbidden components of He I 447.1, 492.2 nm are well reproduced, but the core of synthetic profiles is generally shallower than observed. For He I 587.6 nm, they found that the slope of the computed EW vs. $T_{\mathrm{eff}}$ does not reproduce the observations, the predicted equivalent widths being too large. Note that this discrepancy is opposite to that found by Heasley et al. (1982).

Jaschek et al. (1994) have observed some red and infrared helium lines in a sample of O4 - B5 stars. They found that the agreement with the equivalent widths computed by Auer & Mihalas (1973) is acceptable for He I 667.8 nm, very good for He I 1012.3 nm, but He I 706.5 nm theoretical EW's are too small.

Comparing with Gies & Lambert (1992) observations of a sample of B-type stars with $15000\,\mathrm{K} < T_{\mathrm{eff}} < 28000\,\mathrm{K}$ and $3.7 < \log g < 4.2$, Leone & Manfrè (1997) found that LTE calculations of the He I 501.5 and 504.7 nm lines underestimate the equivalent widths for $T_{\mathrm{eff}} < 20000\,\mathrm{K}$ and overestimate them for $T_{\mathrm{eff}} > 20000\,\mathrm{K}$.

Leone & Lanzafame (1997) observed He I 587.6, 667.8, 706.5 and 728.1 nm lines in a sample of B-type stars with $12000\,\mathrm{K} < T_{\mathrm{eff}} < 24000\,\mathrm{K}$ and $3.4 < \log g < 4.4$ and found that only the equivalent widths of the He I 587.6 nm line is adequately reproduced by Auer & Mihalas (1973) and Dufton & McKeith (1980) NLTE calculations.

With the aim to organize this fragmentary information and outline the present capability of reproducing the behavior of neutral helium lines in main sequence B-type stars, we have observed a sample of stars with spectral type between B9 and O9.5. The observed EW's have been compared with other observations and with new calculations. These have been carried out using

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*Send offprint requests to*: F. Leone

[⋆] Visiting astronomer, Complejo Astrónomico El Leoncito, which is operated under agreement between the Consejo Nacional de Investigaciones Científícas y Técnicas (CONICET) and the National Universities of La Plata, Córdoba and San Juan

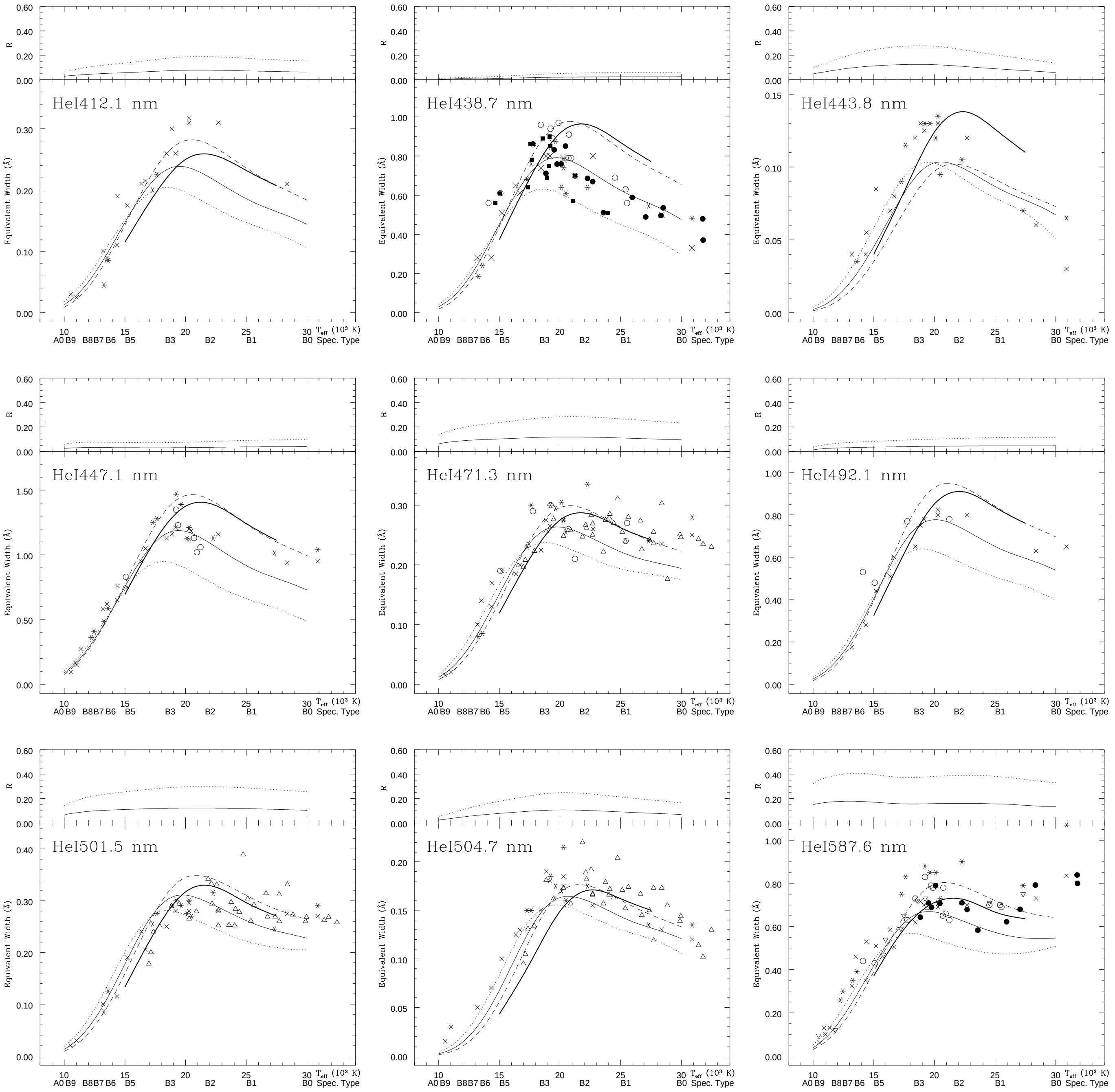

**Fig. 1.** Measured equivalent widths versus the effective temperature for main sequence stars. $*$ Norris (1971), ○ Heasley et al. (1982), ■ Wolff & Heasley (1985), ● Grigsby et al. (1992), △ Gies & Lambert (1992), ▽ Leone & Lanzafame (1997) and × this paper. Solid lines represent Auer & Mihalas (1973) NLTE calculations. Dotted, continuum and dashed lines indicate our new calculations for log $g$= 3.5, 4.0 and 4.5 respectively. On the top of each box, we report R, the relative increment of the EW due to a microturbulent velocity $\xi$ = 6 km s$^{-1}$ (continuum line) and $\xi$ = 10 km s$^{-1}$ (dotted line) for log $g$= 4.0 .

ATLAS9 (Kurucz 1993) LTE model atmospheres, which take into account $5.8 \cdot 10^7$ spectral lines in the opacity, and MULTI (Carlsson 1986) NLTE calculations for HeI lines formation, following the same approach which has been successfully applied to the formation of HeI 1083.0 nm in late B-type stars by Leone, Lanzafame & Pasquini (1995).

## 2. Observations and data reduction

Echelle spectra with $R$ = 13000, covering the 410 - 710 nm range have been obtained for the stars listed in Table 1 from December 5 to 11, 1995 at the 2.1 m telescope at CASLEO by using a Boller & Chivens cassegrain spectrograph. Data have been reduced by using the IRAF package. The achieved S/N was

**Table 1.** Measured equivalent widths (in mÅ ) and adopted effective temperature and gravity for the programme stars.

| Star<br>HD | *ST* | $T_{\rm eff}$<br>K | $\log g$ | 412.1<br>mÅ | 438.7<br>mÅ | 443.8<br>mÅ | 447.1<br>mÅ | 471.3<br>mÅ | 492.1<br>mÅ | 501.5<br>mÅ | 504.7<br>mÅ | 587.6<br>mÅ | 667.8<br>mÅ | 706.5<br>mÅ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 886 | B2IV | 20290 | 3.62 | 317 | 780 | 130 | 1200 | 275 | 825 | 280 | 185 | 690 | 600 | 420 |
| 2884 | B9V | 10920 | 4.34 | – | – | – | 165 | – | – | – | – | 130 | 60 | 20 |
| 15318 | B9III | 10540 | 4.07 | 30 | – | – | 95 | 15 | – | 20 | 15 | 60 | 30 | 15 |
| 16582 | B2IV | 20620 | 3.44 | 310 | 790 | 130 | 1120 | 275 | 800 | 295 | 175 | 705 | 625 | 425 |
| 24626 | B6V | 14350 | 4.06 | 110 | 280 | 40 | 650 | 130 | 280 | 115 | 70 | 350 | 210 | 150 |
| 35039 | B2IV – V | 18860 | 3.40 | 300 | 800 | 130 | 1160 | 275 | 750 | 290 | 190 | 715 | 600 | 430 |
| 35299 | B1.5V | 22700 | 3.87 | 310 | 800 | 120 | 1160 | 260 | 800 | 280 | 155 | 700 | 620 | 410 |
| 38666 | O9.5V | 30890 | 4.17 | – | 330 | 30 | 950 | 250 | 650 | 270 | 120 | 835 | 665 | 545 |
| 42690 | B2V | 19170 | 3.58 | 260 | 800 | 125 | 1210 | 265 | 780 | 280 | 180 | 700 | 575 | 400 |
| 43107 | B8V | 11020 | 3.91 | 25 | – | – | 150 | 20 | – | 30 | 30 | 100 | 30 | – |
| 45813 | B4V | 16370 | 3.99 | 210 | 650 | 70 | 950 | 185 | 510 | 240 | 125 | 585 | 400 | 280 |
| 56779 | B2IV – V | 18430 | 3.76 | 260 | 740 | 120 | 1130 | 225 | 650 | 250 | 150 | 620 | 520 | 360 |
| 62542 | B3V | 16690 | 3.80 | 215 | 610 | 80 | 1050 | 200 | 600 | 205 | 130 | 505 | 400 | 315 |
| 72350 | B4IV | 14390 | 2.81 | 190 | – | 55 | 760 | 170 | – | – | – | 530 | 365 | 260 |
| 72798 | B3III | 15200 | 4.00 | 175 | 510 | 85 | 750 | 190 | 440 | 190 | 100 | 510 | 350 | 280 |
| 75821 | B0III | 28370 | 3.90 | 210 | 500 | 60 | 940 | 235 | 630 | 275 | 130 | 730 | 600 | 480 |
| 209952 | B7IV | 13520 | 3.86 | – | – | – | 620 | 140 | – | – | – | 460 | 220 | 65 |
| 210424 | B5III | 13200 | 4.00 | 100 | 280 | 40 | 580 | 100 | 175 | 100 | 50 | 325 | 190 | 130 |
| 214923 | B8V | 11380 | 3.73 | – | – | – | 270 | – | – | – | – | 130 | 60 | – |

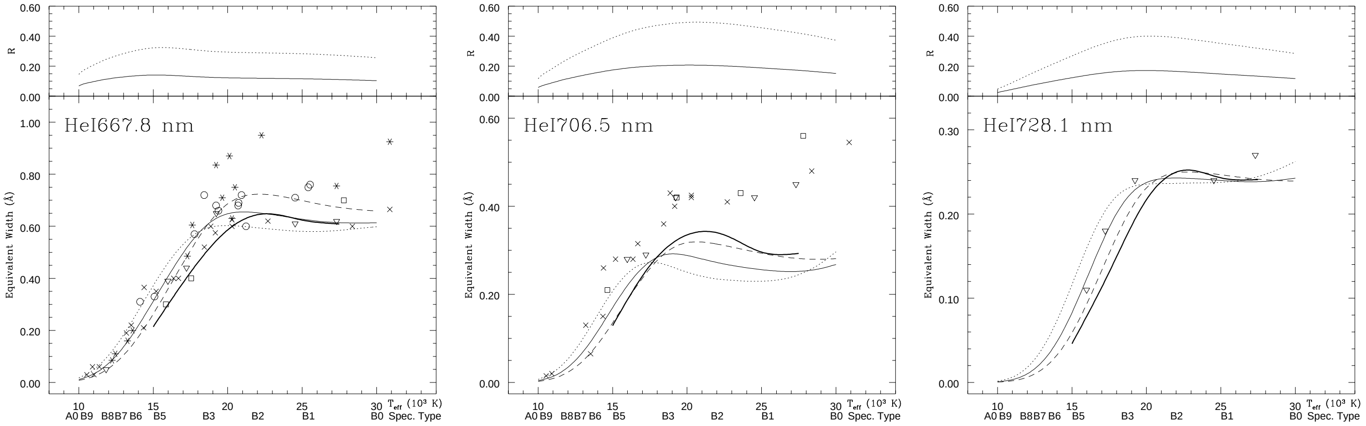

**Fig. 2.** Measured equivalent widths of the HeI667.8, 706.5 and 728.1 nm lines versus the effective temperature for main sequence stars. See caption of Fig. 1 for symbol meaning.

between 150 and 250. Main sequence stars have been observed at least twice. Table 1 reports the measured equivalent widths of the neutral helium lines present in our spectra together with the spectral type (ST) given by the *Bright Star Catalogue* (Hoffleit & Jaschek 1982).

## 3. HeI equivalent widths calculations

In order to test the present capability of reproducing the behavior of neutral helium lines in main sequence B-type stars, we have carried out new calculations, which combine ATLAS9 (Kurucz 1993) LTE model atmospheres and NLTE calculations for HeI lines formation using MULTI (Carlsson 1986), following the same approach which has been applied to the formation of HeI 1083.0 nm in B stars by Leone, Lanzafame & Pasquini (1995). We refer to this paper for a description of the atomic model and parameters used with the exception of energy levels, for which we have preferred the assessed values of Martin (1973, 1987) to the energy levels listed in Gieske & Griem (1969), and oscillator strengths, for which we have preferred the assessed values by Wiese at al. (1966) to the theoretical $f$ values of Fernley, Taylor and Seaton (1987).

LTE model atmospheres have been preferred to NLTE models because the former represent, at present, the most complete description for the atmospheric structure in radiative equilibrium through the inclusion of $5.8 \cdot 10^7$ spectral lines for the computation of line-blanketing effects.

Meridional circulation should be at the origin of a microturbulence with velocity of the order 1 - 10 km s$^{-1}$ for O, B and A-type stars (Dolginov & Urpin 1983). The average value

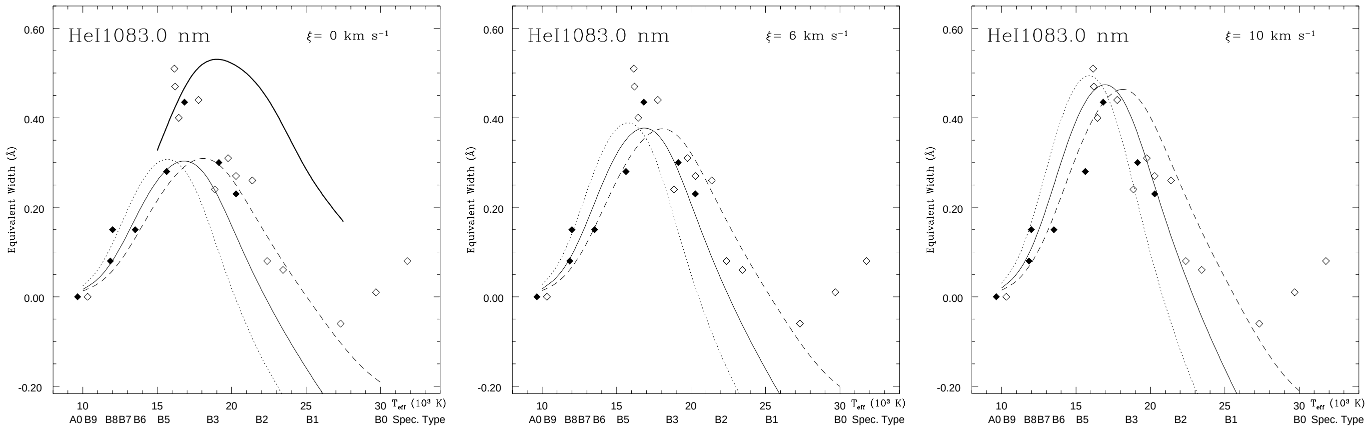

**Fig. 3.** Measured equivalent widths of the He I 1083.0 nm lines versus the effective temperature for main sequence stars. Filled circles are from Lennon & Dufton (1989). Open circles are from Leone, Lanzafame & Pasquini (1995). The left figure reports NLTE calculations for a zero microturbulent velocity and right figure for a microturbulent velocity equal to 6 km s$^{-1}$. Solid lines represent Auer & Mihalas (1973) NLTE calculations. Dotted, continuum and dashed lines indicate our new calculations for log g=3.5, 4.0 and 4.5 respectively.

of the microturbulent velocities determined by Gies & Lambert (1992) for a sample of main sequence B-type stars is $\xi$ = 5.6±2.0 km s$^{-1}$. To compare our results with those obtained by Auer & Mihalas, we have, in the first instance, computed the EW's assuming null turbulent velocities, and then examined the importance of microturbulence, which will be discussed in Sect. 5.

## 4. The behavior of helium lines in main sequence B-type stars: observations and theory

The effective temperatures and gravities of the main sequence stars have been derived from Strömgren photometry according to the grid of Moon & Dworetsky (1985) as coded by Moon (1985). The photometric colours have been de-reddened with the Moon (1985) algorithm. The source of the Strömgren photometric data was SIMBAD. The adopted parameters are reported in Table 1.

In Figs. 1-2 we compare our observations (× symbol) with our new calculations, those of Auer & Mihalas (1973) and with observational data from the following sources:

- Norris (1971) for the He I 412.1, 438.7, 443.8, 447.1, 471.3, 501.5, 504.7, 587.6 and 667.8 nm lines($\ast$ symbol),
- Heasley et al. (1982) for the He I 438.7, 447.1, 471.3, 492.1, 587.6 and 667.8 nm, lines (○ symbol),
- Wolff & Heasley (1985) for the He I 438.7, 447.1, 471.3, 492.1, 587.6 and 667.8 nm lines (■ symbol),
- Gies & Lambert (1992) for the He I 501.5 and 504.7 nm lines (△ symbol),
- Grigsby et al. (1992) for the He I 438.7 and 587.6 nm lines (● symbol),
- Jaschek et al. (1994) for He I 667.8 and 706.5 nm lines (□ symbol),
- Leone & Lanzafame (1997) for the He I 587.6, 667.8 and 706.5 nm lines (▽ symbol).

We have also compared our calculations with He I 728.1 nm (Fig. 2, ▽ symbol) observed by Leone & Lanzafame (1997) and He I 1083.0 nm observed by Dufton & Lennon (1989) and Leone, Lanzafame & Pasquini (1995) (Fig. 3, filled and open diamonds respectively)

The importance of line blending has been investigated by computing the expected EW's of lines present in a one ångstrom interval around the line centre. Metal lines and the respective atomic parameters have been selected from the Kurucz (1993) list. Calculations have been performed using SYNTHE (Kurucz 1993), adopting ATLAS9 (Kurucz & Avrett 1981) model atmospheres with $T_{\rm eff}$ = 15000, 20000 and 25000 K and a microturbulent velocity equal to 2 km s$^{-1}$. We found that the He I 412.1 nm line is severely blended with oxygen lines, the theoretical EW's due to line blending being 6, 56 and 150 mÅ for $T_{\rm eff}$ = 15000, 20000 and 25000 K, respectively. In the same range of $T_{\rm eff}$, the EW's of lines blending the He I 501.5 nm line increase from 13 to 24 mÅ and those blending He I 504.7 nm decrease from 24 to 5 mÅ .

For $N(He)/N(H)$ = 0.1, Fig. 1-3 include the expected behavior according to our new calculations performed for a grid of $T_{\rm eff}$ between 10000 and 30000 K and log $g$ = 3.5, 4.0 and 4.5 and the calculations of Auer & Mihalas (1973) for log $g$ = 4.0 (solid line). We note that the comparison of observations with our new calculations is very satisfactory in the linear regime. The agreement is closer than Auer & Mihalas presumably because of the use of more realistic model atmospheres as far as line-blanketing is concerned and of more accurate transition probabilities. At the highest temperatures, observed EW's of He I 412.1 nm line are larger than computed because of the blend with oxygen lines. The He I 438.7, 447.1 and 492.1 nm are well reproduced over the whole range of effective temperature. The He I 443.8 nm line is underestimated at effective temperatures around 20000 K. The He I 706.5 nm line is always underestimated. The remaining lines present, at $T_{\rm eff} > 20000$ K, a scatter in the observations larger than predicted in the range 3.5 $\leq \log g \leq$ 4.5, but are well reproduced for $T_{\rm eff} < 20000$ K.

## 5. Effects of the microturbulence

There is a considerable spread in the observed EW's especially for $T_{\rm eff} > 20000$ K and, in certain cases, this is larger than accountable by the range of $\log g$ assumed in our calculations. We suggest that this is partly due to our poor understanding of microturbulence, but observational uncertainties play also an important role. We note, in fact, that sometimes different authors obtain different EW's for the same line in the same star despite there is no known variable in the sample considered here. For example, the He I 667.8 nm EW in HD 144470 is 755 mÅ according to Norris (1971) and 620 mÅ according to Leone & Lanzafame (1997); the He I 438.7 nm EW in HD 35299 is 686 mÅ according to Grigsby et al. (1992) and 800 mÅ according to the present work. Such differences are likely due to the continuum determination, whose accurate values are difficult to obtain for what are, in some cases, very broad lines.

To investigate the effects of the microturbulence, we have computed the EW's for $\xi$=0, 6 and 10 km s$^{-1}$. The choice of $\xi$=6 km s$^{-1}$ has been driven by the fact that it represents the average value of the microturbulent velocities measured by Gies & Lambert (1992) for a sample of early main sequence B-type stars. A larger value has been also considered because of the suggestion, made by Killian (1992), that the microturbulent velocity should increase for the smallest gravities. Figs. 1 - 2 report on the top of each box the relative increment of the equivalent widths due to the microturbulence.

Our results indicate that the He I lines at 438.7, 447.1 and 492.1 nm, for which we have the better agreement with calculations, are also the least affected by microturbulence, unlike the He I 706.5 and 1083.0 nm lines, which are found to be critically dependent on the $\xi$ value (Fig. 2 -3).

## 6. Conclusion

We have measured equivalent widths of the neutral helium lines in the 410-710 nm interval for a sample of B-type main sequence stars. Such measurements have been compared with new calculations which combine ATLAS9 LTE model atmospheres, and NLTE radiative transfer for the line formation with updated atomic parameters. We have investigated the effects of line blending and found that the observed He I412.1 nm is larger than computed for $T_{\rm eff} > 15000$ K because of the presence of oxygen lines at a close wavelength. Computed He I 438.7, 447.1 and 492.1 nm lines are found insensitive to microturbulent velocity so that their EW's should be preferred to derive helium abundance. The agreement with observations is also closer for these lines. Our work suggests that the spread of the observed EW's could be mainly due to the variation of microturbulence from one star to the other and calls for a deeper understanding of such phenomena.

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