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THE LINES He I λ3187 AND He II λ3203 IN O-TYPE STARS*

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ABSTRACT

High-dispersion observations of the lines He I λ3187 and He II λ3203 in 19 O and B0.5-type stars are presented. For the purpose of comparing their equivalent widths with the predictions of non–LTE model atmospheres, effective temperatures and gravities of the O-type stars observed are derived from the equivalent widths of other lines of H and He. For supergiants, these temperatures and gravities differ systematically from those derived by the method of spectral classifications, and the reason for the difference is discussed. Theoretical predictions for He I λ3187 have not been made, but the form of the dependence of equivalent width on effective temperature is similar to that predicted for He I λ3889, which arises from the same lower state. For stars with He II λ4686 in absorption, the observed equivalent widths of He II λ3203 agree reasonably well with the theory, except that this line is weaker than predicted in two stars that are hotter than 40,000 K. For three stars with λ4686 in emission, λ3203 is much weaker than predicted.

Subject headings: atmospheres, stellar — early-type stars — line formation — Of-type stars

I. INTRODUCTION

As the ion most characteristic of the spectra of O-type stars, He II is of great interest. Auer and Mihalas (1972) have calculated equivalent widths of lines of He I and He II from non–LTE model atmospheres for O stars and have shown that these equivalent widths are reliable and sensitive indicators of both effective temperature and surface gravity. In addition, some Of stars are peculiar in displaying selective emission in He II λ4686, which is the transition from level 4 to level 3. In the plane-parallel non–LTE models, however, this line is never found in emission. Therefore, the opinion has been expressed (e.g., Mihalas 1974) that emission at λ4686 is due to some effect in an extended atmosphere that causes level 4 to be more overpopulated than it is in a plane-parallel model. The particular mechanism proposed by Auer and Mihalas (1972) for overpopulating level 4, which involves pumping by Lα of hydrogen and which originally prompted the present work has, however, been discredited (Mihalas and Lockwood 1972; Mihalas 1974). Since the statistical equilibrium of He II in hot extended atmospheres seems to be unusual in this regard, it is desirable to have observations of lines arising from as many of the low-lying levels of this ion as possible. Unfortunately, all of the unblended lines in the blue region of the spectrum arise from level 4 itself, and therefore our knowledge of the effective temperatures of the O stars depends on a correct understanding of the statistical equilibrium of this level. Observations of a line that does not involve level 4 would provide a worthwhile check on the theory. Such a line is λ3203, which is the transition from level 3 to level 5. Since it is not in an easily accessible region of the spectrum, very few equivalent widths exist in the literature. In order to study this line systematically, I have obtained a homogeneous set of high-dispersion spectrograms, exposed for this wavelength, of 19 sharp-lined stars well-distributed in spectral type and luminosity class over the O-star region. Exposures of each star in the blue region were also obtained, in order to use the H and He lines to derive new effective temperatures and gravities and to make a precise comparison with the theory.

II. OBSERVATIONS

The spectrograms were obtained with the coudé spectrograph of the 2.2-m telescope of Mauna Kea Observatory at a reciprocal dispersion of 6.7 Å mm^{-1}. The emulsion was IIa-O baked in air. On nearly all plates, both an ultraviolet and a blue exposure were made, with exposure times that were typically twice as long at 3200 Å as at 4200 Å. A calibration wedge was exposed in both spectral regions on a plate cut from the same original 8 × 10-inch (20 × 25 cm) plate as the spectrum plate, and calibration and spectrum were developed together.

The plates were traced with the digital microphotometer described by Bonsack (1971), which sampled with a 5 μ slit every 2.5 μ. The calibration was applied by the computer, the continuum was adjusted to a constant value, and the data were smoothed with a clipped Gaussian function of total width 20 sample points. In the blue spectra, equivalent widths were measured by means of a computer program that integrates the spectrum between specified beginning and end points; where necessary, blends were

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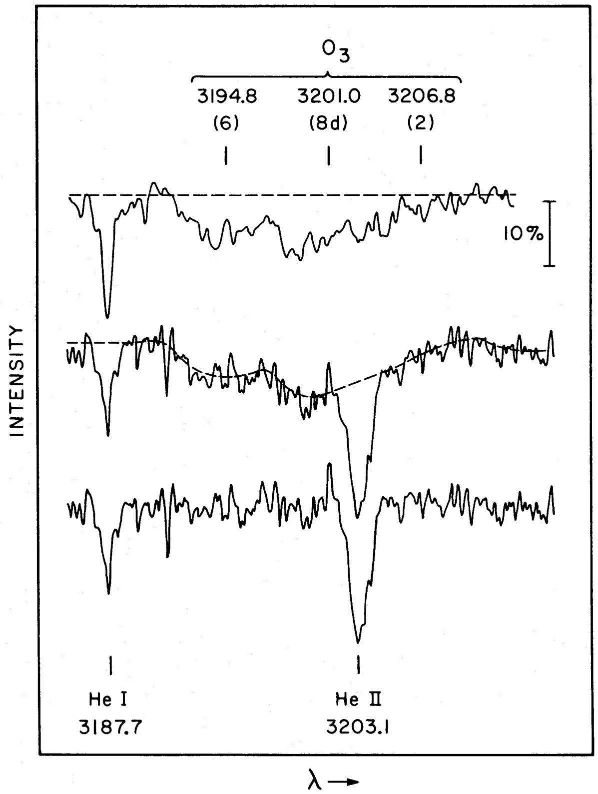

FIG. 1.—The spectral region near 3200 Å. All three tracings have the same intensity scale and are drawn with an artificially level continuum. The positions and laboratory intensities of ozone band heads given by Pearse and Gaydon (1965) are marked. The top tracing shows the spectrum of 40 Per (B0.5 V), in which He II λ3203 is absent. The vertical bar indicates a central depth of 10%. The second and third tracings show the spectrum of HD 46966, in which λ3203 is prominent. In the third tracing, the stellar continuum within the ozone band has been normalized to that outside, and the true profile of the He II line is shown.

removed by hand. Measurement of equivalent widths in the ultraviolet spectra is described below.

Figure 1 shows intensity tracings of the spectral region near 3200 Å. The top tracing shows 40 Per (B0.5 V), in which, consistent with the calculations of Auer and Mihalas (1972) for $T_{\rm eff} = 30{,}000$ K and $\log g = 4.0$, He II λ3203 appears to be absent. The positions of three band heads of ozone are labeled with the wavelengths and laboratory intensities given by Pearse and Gaydon (1965). The positions and relative intensities agree well with those of three dips in the broad depression between roughly 3190 and 3210 Å, and it is clear that this and other broad features between 3100 and 3300 Å are due to telluric ozone.

Although He I λ3187 is free of blending with the ozone band, He II λ3203 is not, as the middle tracing of Figure 1 shows. Removal of the blend proceeded as follows. Three plates of 40 Per, all taken at air mass 1.04, yielded a mean profile of the ozone band. Multiplying this profile point-by-point by the mean air mass during the observation and adding these corrected depths to the observed profile yielded a rough profile of λ3203. A check of other ozone bands vindicated this procedure by showing that the depth of a band is proportional to the air mass. This approximation also requires that the depth of the ozone band be small, as is the case (see Fig. 1). An equivalent method of correction is illustrated in the bottom two tracings of Figure 1. The shape of the ozone band was assumed to represent the true stellar continuum, drawn as a dotted line in the middle tracing, and the computer was used to flatten this continuum. This method depends slightly on the measurer's prior knowledge of the shape of the ozone band, but is adequate at small air masses. Both of these methods were used in the reductions. When they were used for the same plate, the derived equivalent widths of λ3203 agreed to within 10 percent. Unfortunately, several plates were taken at air masses near 1.8, and HR 6245 had to be observed at air mass 2.1. Since the agreement of the observed profile of the ozone band with the product of the standard one and the air mass is good for this star, the derived equivalent width of λ3203 is not less reliable than it is in other stars.

Due to the blending with the ozone band, one might expect that the uncertainties of measurement of λ3203 are unusually large. The mean difference between plates of the same star, however, is no larger than it is for He II λ4686, even if Of stars, in which λ4686 may vary, are excluded from the mean. Comparison of λ4686 with the equivalent widths obtained by Conti and Alschuler (1971) yields a mean difference of 0.01 dex and an rms difference of 0.10 dex. Since both sets of equivalent widths presumably contribute equally to the scatter, a reasonable estimate for the standard deviation in a single equivalent width in either set is ±0.05 dex. Systematic errors may increase this uncertainty slightly. Fluctuations in the ozone content of the atmosphere seem to have occurred, since removal of the ozone band resulted in a continuum level that sometimes differed from the level outside the band by up to 3 percent. This problem is significant only at airmasses greater than about 1.5 and in any case causes the equivalent width of λ3203 to be underestimated as often as overestimated. The presence of the band renders it nearly impossible to determine the shape of the wings of the He II line. These effects seem unlikely to produce a systematic error that is itself larger than the accidental uncertainty quoted above.

Table 1 lists, for each star, the name, HD number, and spectral type; the measured equivalent widths of He II λ3203 and He I λ3187 and the number of ultraviolet exposures measured; the measured equivalent widths of Hγ, He I λ4388, He I λ4471, and He II λ4542 and the number of exposures; and the effective temperature and surface gravity derived below. The spectral types are from Conti and Leep (1974), except that those for the B0.5 stars come from the Bright Star Catalog (Hoffleit 1964).

TABLE 1

Measured Equivalent Widths (in Å) and Derived Effective Temperatures and Surface Gravities

Star	HD Number	Spectral Type	W_λ (3203)	W_λ (3187)	N_u	W_λ (Hγ)	W_λ (4388)	W_λ (4471)	W_λ (4542)	N_b	$T_{\rm eff}$ (K)	Log g
40 Per.......	22951	B0.5 V	0.00	0.18	3	...	...	...	...	...	(30,000)	(4.0)
AE Aur......	34078	O9.5 V	0.29	0.16	3	3.13	0.40	0.98	0.46	3	34,000	4.0
	34656	O7 I ((f))	0.54	0.18	2	2.14	0.24	0.80	0.79	2	39,000	4.0
	46150	O5.5 ((f))	0.51	0.04	3	2.11	NP	0.33	0.91	2	45,000	4.0
	46966	O8.5 V	0.39	0.12	2	2.37	0.31	0.85	0.52	2	35,500	3.7
S Mon.......	47839	O8 III ((f))	0.51	0.11	2	2.40	0.24	0.68	0.53	2	36,000	3.8
HR 2467.....	48099	O6.5 V	0.45	≤0.05	2	2.21	0.19	0.37	0.55	1	37,500	3.5
HR 2679.....	53975	O7.5 V	0.59	0.71	2	2.56	0.24	0.66	0.58	2	37,500	4.0
HR 2694.....	54662	O7 III	0.67	0.10	2	2.39	0.15	0.61	0.61	1	37,500	3.8
HR 2806.....	57682	O9 V	0.48	0.21	2	2.58	0.32	0.84	0.37	1	35,000	3.9
HR 6245.....	151804	O8 If	0.04	P?	1	0.78	0.11	0.89	0.51	1	35,000	{3.3 3.9
9 Sgr........	164794	O4 ((f))	0.55	0.05	2	1.83	NP	0.14	0.70	1	50,000	3.9
16 Sgr.......	167263	O9 III	0.25	0.22	3	2.10	0.47	0.86	0.31	1	32,000	3.6
κ Aql........	184915	B0.5 III	...	0.15	2	...	...	...	...	...	(30,000)	(3.7)
9 Sge........	188001	O8 If	0.34	0.24	2	1.52	0.26	0.64	0.61	1	37,500	3.8
HR 7589.....	188209	O9.5 I	0.28	0.27	2	1.43	0.40	1.10	0.22	2	{30,000 32,500	3.3 4.1
HR 8023.....	199579	O6.5 III	0.60	0.05	3	2.40	0.18	0.48	0.72	3	39,500	3.8
λ Cep........	210839	O6 ef	0.33	0.06	2	1.53	0.10	0.56	0.70	2	40,000	3.8
26 Cep.......	213087	B0.5 Ib	≤0.10	0.24	2	...	...	...	...	...	(28,000)	(3.3)
10 Lac.......	214680	O8 III	0.48	0.21	2	2.58	0.37	0.87	0.50	2	35,000	3.8

III. COMPARISON WITH THEORY

a) *Effective Temperatures and Surface Gravities*

I have used the measured equivalent widths given in Table 1 for lines in the blue region to derive effective temperatures and surface gravities. The derivation followed the method of Auer and Mihalas (1972), in which the equivalent widths of lines of H, He I, and He II are used to find $T_{\rm eff}$ and log g simultaneously. In Figure 2, these temperatures and gravities are compared with those derived by Conti (1973*a*). Stars of luminosity class V are plotted with log g = 4.0, class III with 3.7, and class I with 3.3. For all stars of luminosity classes III and V but one, the agreement is within the observational uncertainties.

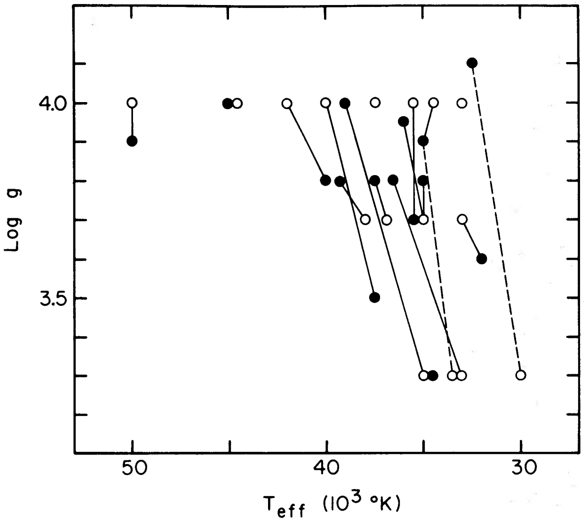

Fig. 2.—A comparison of two sets of effective temperatures and gravities for O-type stars. *Open circles*, values derived by Conti (1973*a*); *filled circles*, values derived in the present work; symbols for the same star are connected. Where a filled circle is absent, the two values agree. When the connecting line is dashed, the method of the present work yields an ambiguous result.

In determining log g for stars of luminosity class I, the present analysis encounters a difficulty, which Conti's (1973*a*) analysis avoided by assuming log g = 3.3 for the supergiants. The problem is that the strengths of Hγ and He I λ4388 yield log $g \approx 3.3$, while He I λ4471 yields log $g \approx 4.0$; i.e., relative to the predictions, the observed strength of λ4471 is too large compared with that of Hγ and He I λ4388. This ambiguity is also indicated in Conti's (1973*b*) Figures 1, 3, and 6, which show that the strength of λ4471 matches the prediction of the model atmospheres for log $g \approx 4.0$, while the strengths of the other two lines match the predictions for log $g \approx 3.3$. Thus the plane-parallel models are evidently not capable of yielding a consistent determination of effective temperature and gravity in the supergiants.

A little independent information is available on the surface gravities of early-type supergiants. For the B1 Ib–II component of the eclipsing binary V448 Cyg, the mass and radius given by Stothers (1973) yield log g = 3.2, and for δ Ori A (O9.5 II + B1), the mass and radius given by Hutchings (1975) yield log g = 3.3. In addition, both the stellar-interior models for the terminal main sequence by Stothers (1972) and the models with mass loss by Chiosi and Nasi (1974) also have log g near 3.2.

Since the true value of log g for the supergiants is, therefore, probably near 3.3, the models predict equivalent widths for λ4471 that are too small by roughly 0.2 dex. This failure might be due to failure of the assumption of plane-parallel geometry. Morrison (1975) argues that models including radiation pressure and spherical geometry are required to explain the colors of the supergiants (except for type O7), and Conti and Leep (1974) have argued that such models are needed to account for the presence of emission lines at He II λ4686 and Hα. Recently, Kunasz *et al.* (1975) have calculated the equivalent widths of several He II lines in extended model atmospheres. For a set of models with $T_{\rm eff} \approx 40{,}000$ K, the calculated equivalent widths of λ4542 decrease as atmospheric extent increases, and never are as large as they are in the plane-parallel case or in the observed spectra of stars such as HD 34656 and 9 Sge. Therefore, these models do not properly reproduce the observations of this line. Since these calculations did not include lines of He I, it is not possible to make a statement about λ4471. Further theoretical work is needed.

For the purposes of the present work, temperatures and gravities are needed for comparison of the observations of He I λ3187 and He II λ3203 with theory in four supergiants. For HD 34656, both the color and the line strengths are consistent with a gravity near 4, and this gravity will be adopted here. For the other supergiants, $\log g = 3.3$ will be assumed. Then consistency requires that temperatures based on He I λ4388, not λ4471, be adopted. Accordingly, the lower temperature given in Table 1 (30,000 K) will be adopted for HR 7589. For 9 Sge and HR 6245, λ4388 yields the same temperature as λ4471, and the values in Table 1 may be allowed to stand. Note that HR 7589 is the only supergiant for which the conclusions of this paper concerning λ3203 will be influenced by the choice of effective temperature.

b) *Equivalent Widths*

Figure 3 shows the equivalent width of He I λ3187 as a function of the effective temperature. The three B0.5 stars are plotted for assumed temperatures, which are listed in Table 1 in parentheses. Plotted also are the equivalent widths predicted by Auer and Mihalas (1972) for He I λ3889, which arises from the same lower level. Generally, the measured equivalent widths for λ3187 are smaller, but the run of equivalent width with temperature is similar. If 9 Sge, HR 7589, and 26 Cep have $\log g = 3.3$, however, their position in this graph is inconsistent with the predicted dependence of equivalent width on gravity. The line is also stronger than predicted in 10 Lac and 16 Sgr. Theoretical predictions for λ3187 itself would be of interest.

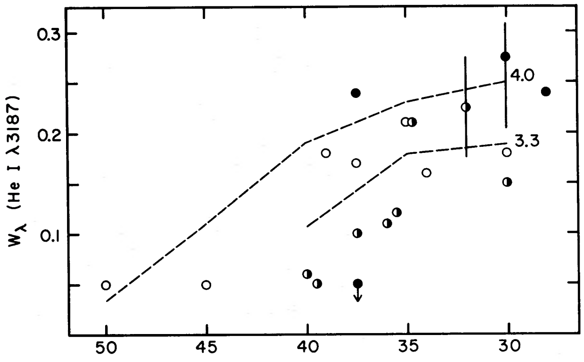

FIG. 3.—The observed equivalent width of He I λ3187 as a function of effective temperature. Symbols are as follows: *open circles*, $3.9 \leq \log g < 4.1$; *half-filled circles*, $3.5 \leq \log g \leq 3.8$; *filled circles*, $\log g \leq 3.4$. Points with arrows are upper limits, and two representative error bars are drawn. The one on the left is typical for all the stars (±0.05 Å), and the one on the right represents an unusually large uncertainty for HR 7589. The dashed lines represent equivalent widths predicted by Auer and Mihalas (1972) for He I λ3889 for $\log g = 4.0$ (*upper*) and 3.3 (*lower*), as labeled.

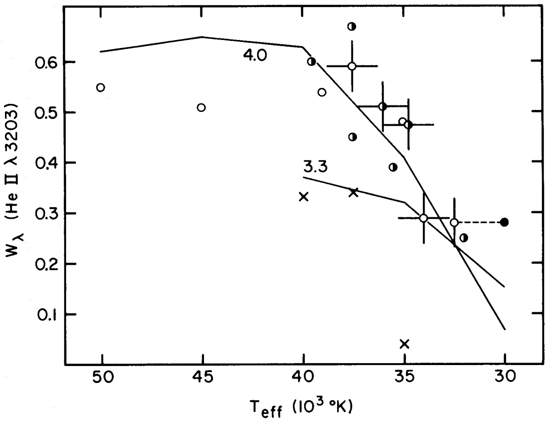

FIG. 4.—The observed equivalent width of He II λ3203 as a function of effective temperature. Symbols are as in Fig. 3; in addition, crosses represent stars with He II λ4686 in emission. Error bars are drawn for a few representative points. The solid lines are the predictions for this line by Auer and Mihalas (1972) for the values of log *g* with which they are labeled.

Figure 4 compares the observations of He II λ3203 with the prediction for this line by Auer and Mihalas (1972). Representative error bars are drawn to show standard deviations of ±1000 K in the effective temperature and ±0.05 Å (roughly equal to ±0.05 dex) in the equivalent widths. HR 7589 is plotted for both values of effective temperature and gravity that were derived.

Of the 12 stars with $T_{\rm eff} < 40{,}000$ K and without He II emission, six lie within a little over one standard deviation of the prediction, which for stars plotted as half-filled circles is intermediate between the two lines. The agreement with theory is best for the highest-gravity stars; for medium-gravity stars, the line is slightly too strong with respect to the prediction. For HR 7589, the larger effective temperature would have led to close agreement of the predicted strength of λ3203 with the observed one, but the lower temperature, which is adopted here, leads to a predicted strength that is much too small.

Table 2 lists the ratio of observed to predicted equivalent widths of λ3203 for predictions based on the temperature scale of Conti (1973*a*) and on the temperatures and gravities of the present work. Only stars cooler than 40,000 K and without emission at λ4686 are listed; the remainder are discussed below.

TABLE 2

RATIO OF OBSERVED TO PREDICTED EQUIVALENT WIDTHS OF He II λ3203

Star	Obs./Pred. (Conti 1973*a*)	Obs./Pred. (this work)
AE Aur	0.97	0.85
HD 34656	1.70	0.91
HD 46966	0.88	1.11
S Mon	1.42	1.13
HR 2467	0.71	1.04
HR 2679	1.10	1.14
HR 2694	1.56	1.28
HR 2806	1.26	1.18
16 Sgr	0.89	1.19
HR 7589	1.85	1.85
HR 8023	1.32	1.18
10 Lac	1.33	1.27

The table shows that λ3203 is typically slightly stronger than predicted for these stars, whichever temperature scale is used.

For the two stars, 9 Sgr and HD 46150, that have $T_{\mathrm{eff}} > 40{,}000$ K, λ3203 is weaker than predicted, as it also is for the two stars, HR 6245 and λ Cep, in which He II λ4686 is strongly in emission. The star in which λ3203 is nearly absent is HR 6245, which shows very strong emission at λ4686. According to the present analysis, λ Cep has $\log g = 3.8$, and therefore its equivalent width for λ3203 is well below the prediction.

In a general sense, this weakening of λ3203 is similar to that shown by the calculations with extended geometry by Kunasz *et al.* (1975). It is interesting to compare their predictions with the data for other He II lines as well. In λ Cep, the equivalent width of λ4686 is −1.01 Å, and the line is much stronger than predicted by any model except the one that makes the physically unrealistic assumption of complete overlap with the hydrogen lines; nevertheless, λ3203 in this star falls within the predicted range. In 9 Sge, λ4686 is weakly in emission (equivalent width −0.24 Å), while λ3203 is fairly strongly in absorption; none of the models produces this combination. In HR 6245, the equivalent widths of λ4686 and λ3203 (−0.46 Å, +0.04 Å) are not too different from those predicted by model number 10 of Kunasz *et al.* (−0.40 Å, −0.07 Å). While, in general, those authors' doubts concerning the physical validity of the models appear to be justified, for the case of HR 6245 the agreement is encouraging. For all three stars, however, the predicted equivalent widths of λ4542 and λ5412 (Conti 1974) are too small by 0.2 Å or more.

IV. CONCLUSIONS

The data on λ3203 lead to tentative conclusions about the statistical equilibrium of He II in Of stars. In the two hottest stars observed, which both happen to have λ4686 in absorption but weakened, λ3203 is also weak. In the cooler Of stars, λ3203 is weakened if λ4686 is in emission. One infers that level 5 is overpopulated with respect to level 3 under these conditions, but less so than is level 4. This inference is consistent with the presence of emission at He II λ10125 (level 5 to level 4) in ζ Pup and λ Cep (Mihalas and Lockwood 1972), since decay from level 5 to level 4 is more probable than from level 5 to level 3.

A first glance at Figure 4 shows that the present observations of He II λ3203 are in reasonable agreement with the non–LTE calculations for the rest of the stars observed. If the observations are free from systematic error, as § II argues is probably the case, then it is possible to assert that the observations disagree to a small extent with the theory. For the stars in Table 2, the equivalent widths are systematically larger than predicted by about 15 percent. This discrepancy is a little larger for the stars with values of log *g* between 3.5 and 3.8 than for the highest-gravity stars. In other words, the observed equivalent width does not depend systematically on the surface gravity of the star. Conti's (1973*b*) observations of He I λ4471 and He II λ4542 behave similarly, in spite of the fact that the quoted observational errors are small enough so that the data should show the predicted decrease in equivalent width toward lower gravity if it exists. For the non–emission-line supergiants in particular, the equivalent widths of all three lines are consistent with $\log g \approx 4.0$, the gravity appropriate to main-sequence stars. Since independent evidence suggests that $\log g \approx 3.3$ for supergiants, it is reasonable to conclude that the plane-parallel models for this gravity predict equivalent widths that are too small. Even in the extended models by Kunasz *et al.* (1975), He II λ4542 and λ5412 are too weak. Perhaps the next generation of extended models, which will incorporate velocity fields, will remove this discrepancy.

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REFERENCES

Auer, L. H., and Mihalas, D. 1972, *Ap. J. Suppl.*, **24**, 193.
Bonsack, W. K. 1971, *Astr. and Ap.*, **15**, 374.
Chiosi, C., and Nasi, E. 1974, *Astr. and Ap.*, **34**, 355.
Conti, P. S. 1973*a*, *Ap. J.*, **179**, 181.
———. 1973*b*, *ibid.*, p. 161.
———. 1974, *ibid.*, **187**, 539.
Conti, P. S., and Alschuler, W. R. 1971, *Ap. J.*, **170**, 325.
Conti, P. S., and Leep, E. M. 1974, *Ap. J.*, **193**, 113.
Hoffleit, D. 1964, *Catalog of Bright Stars* (New Haven: Yale University Observatory).
Hutchings, J. B. 1975, *Contr. Dom. Ap. Obs.*, No. 266.
Kunasz, P. B., Hummer, D. G., and Mihalas, D. 1975, preprint.
Mihalas, D. 1974, *A.J.*, **79**, 1111.
Mihalas, D., and Lockwood, G. W. 1972, *Ap. J.*, **175**, 757.
Morrison, N. D. 1975, *Ap. J.*, **200**, 113.

Pearse, R. W. B., and Gaydon, A. G. 1965, *The Identification of Molecular Spectra* (3d ed; London: Chapman and Hall), p. 246.
Stothers, R. 1972, *Ap. J.*, **175**, 431.
———. 1973, *Pub. A.S.P.*, **85**, 363.

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