Microturbulence in O Supergiants

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Abstract. We derive atmospheric parameters for 11 late-O Galactic supergiants by non-LTE model-atmosphere analysis of high signal-to-noise, high-resolution spectra. We find that by including microturbulent broadening in the line-formation calculations it is possible to obtain self-consistent fits to the singlet lines of He I at near-solar helium abundances in most morphologically normal O stars. This finding may have wider implications for the so-called 'helium discrepancy' in OB-type stars. Our analysis suggests that there is a decrease in the atmospheric C/N abundance ratio along the sequence OC→O→ON. This is consistent with Walborn's hypothesis that morphologically normal O supergiants and (to a greater extent) ON supergiants exhibit the products of nucleosynthesis at their surfaces.

1. Introduction: The OBC/OBN Problem

The surface compositions of massive OB stars represent one of the most powerful diagnostics of their evolutionary status, and should serve as an instrument of choice for disentangling the relative influences of metallicity, turbulent mixing, convection, and rotation in collectively shaping evolutionary channels. Among several outstanding problems is the suggestion of nucleosynthetically processed material in the atmospheres of apparently *young* OB stars, manifested in the OBC/OBN system of spectral morphology described by Walborn (1976). Walborn's proposed interpretation of that system sees *only* OBC stars as chemically normal – all *morphologically* normal OB stars, and to a greater extent (the relatively rare) OBN stars, are enriched with partially processed material. That hypothesis, which would have important implications for evolutionary theory if true, has never been tested in a quantitatively convincing manner. We have been carrying out a spectroscopic study of a sample of ON/OC stars to investigate Walborn's hypothesis, basing our analysis on classical plane-parallel, hydrostatic, H/He-blanketed, non-LTE models. In this paper we discuss the potential role of microturbulence in such an analysis, and point out how it might have implications for helium abundances derived for luminous OB stars in general.

2. Neutral-Helium Lines: The Role of Microturbulence

The now-classical O-star analysis involves finding a single set of atmospheric parameters $T_{\rm eff}$, $\log g$, and y which best reproduces observations of H I, He I, and He II lines (Kudritzki 1976). The He I lines play a crucial role in this respect as a constraint on y, and yet previous studies have exposed significant line-to-line inconsistencies when plane-parallel, hydrostatic, non-LTE models are applied to luminous O stars. For example, Voels et al. (1989) have shown that singlet and triplet lines are systematically discrepant, with the latter being anomalously strong in luminous O stars; they attribute this so-called 'generalized dilution effect' to the extended nature of supergiant atmospheres. The practical significance of these inconsistencies, as Lennon (1994) has highlighted, is that it is difficult to ascribe any degree of confidence to the helium abundances derived for OB supergiants.

In an attempt to sidestep these problems, our analyses have concentrated on singlet lines, which as an ensemble tend to yield better consistency with the other diagnostics (Smith & Howarth 1994; Smith 1997). Nevertheless, even within the singlet system there remain systematic discrepancies which compromise the analysis; for example, relatively strong lines such as $\lambda4922$ and (to a lesser extent) $\lambda4143$ typically indicate *higher* helium abundances than weaker lines such as $\lambda4009$, $\lambda4388$, and $\lambda5047$.

Classically, this can be interpreted as a signature of desaturation due to intrinsic (e.g., atmospheric or atomic) line broadening. Indeed, evidence for desaturation is frequently encountered in analyses of metallic elements such as CNO and Si in OB-type stars, and is compensated by invoking 'microturbulence' – an *ad hoc* isotropic atmospheric velocity field with a gaussian velocity distribution and a scale length less than the photon mean free path. For example, recent non-LTE studies of B dwarfs obtain microturbulent velocity amplitudes of up to $10\,{\rm km\,s^{-1}}$ (Gies & Lambert 1992), whereas B supergiants can yield values well in excess of the adiabatic sound speed (Lennon et al. 1991).

Leaving aside the physical feasibility of the microturbulence concept as applied to the analysis of metallic species, we note that its concomitant impact on He I line formation appears to have been largely overlooked. This may be a consequence of the comparatively large atmospheric thermal velocity of helium and the mitigating influence of pressure broadening in the diffuse He I lines favoured by most analyses (e.g., $\lambda4388$, $\lambda4922$, $\lambda4026$, and $\lambda4471$). Supergiants are an exception, however, because the implied microturbulent velocities are comparable with the atmospheric thermal velocity (typically $v_{\rm th} \simeq 10\,{\rm km\,s^{-1}}$) and the electron density (and hence pressure broadening) is low in the line-forming zone (typically $n_{\rm e} \simeq 10^{13}\,{\rm cm^{-3}}$).

With this motivation in mind, we explored the effect of classical isotropic, gaussian microturbulence on He I line formation, initially concentrating on its direct influence on the radiation transfer and neglecting indirect effects via changes in the gross atmospheric structure or statistical equilibrium of helium. Our preliminary calculations were carried out using a $T_{\rm eff} = 32\,{\rm kK}$, $\log g = 3.0$, $y = 0.09$ model, these parameters being typical of the late-O supergiants in our survey. We find that the effect of microturbulence on the shapes and strengths of He I lines can be quite dramatic, even at low values of $v_{\rm turb}$, as can be appreciated from Fig. 1. Crucially, the strong saturated lines such as $\lambda4922$ show a

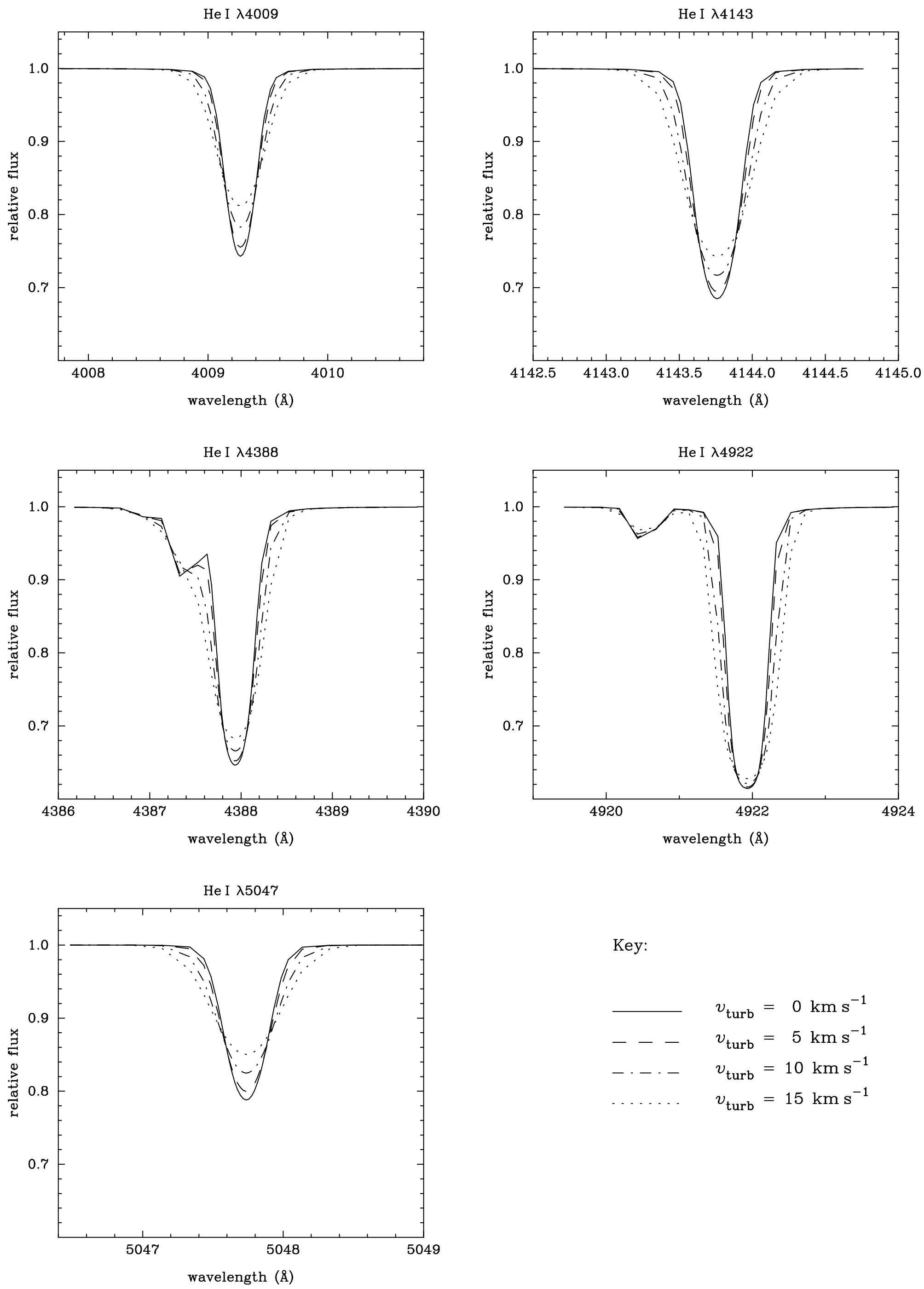

Figure 1. Theoretical He I profiles for a ($T_{\rm eff} = 32$kK, $\log g = 3.0$, $y = 0.09$) model assuming several values of the microturbulence parameter $v_{\rm turb}$ as indicated. Note the dramatic changes in shape and strength with increasing $v_{\rm turb}$.

Table 1. Derived atmospheric parameters and abundance ratios.

HD	Spectral type	$T_{\rm eff}$ (kK)	$\log g$ (cgs)	y	C/N
154811	OC9.7 Iab	31.0	3.10	0.09	0.79
152249	OC9.5 Iab	32.5	3.15	0.08	0.62
152424	OC9.7 Ia	31.5	2.95	0.09	0.22
152147	O9.7 Ib N-wk	30.0	3.15	0.09	1.4
156212	O9.7 Iab N-wk	29.5	3.15	0.08	0.56
152003	O9.7 Iab N-wk	30.5	3.00	0.09	0.40
152405	O9.7 Ib–II	30.5	3.20	0.09	0.55
149038	O9.7 Iab	30.0	3.05	0.09	0.24
154368	O9.5 Iab	32.0	3.00	0.13	0.048
149404	O9 Ia C-wk	32.5:	2.95:	0.12:	···
123008	ON9.5 Iab	33.0	3.05	0.15	0.0012

proportionally greater response to microturbulence, thereby offering a potential mechanism by which to reconcile them with weaker lines such as λ4009.

3. Analysis of Galactic Late-O Supergiants

In order to investigate the implications of microturbulence for the *diagnostic* properties of He I lines, we extended our grid of non-LTE synthetic H/He spectra to incorporate $v_{\rm turb}$ as a fourth parameter, using velocity amplitudes of 0, 5, 10, and 15 km s^{-1}. Applying the extended grid in an analysis of the 11 late-O supergiants comprising our survey, we find that it is now possible to obtain consistent fits to the singlet lines at near-normal helium abundances for most of the morphologically normal stars. This point is illustrated in Fig. 2 by a series of diagnostic $T_{\rm eff}$–$\log g$ diagrams for the O9.7 supergiants HD 152003 and HD 154811, based on assumed microturbulence parameters in the range $v_{\rm turb}$ = 0–15 km s^{-1}. The improved consistency at higher values of $v_{\rm turb}$ is self evident and is repeated in every one of the supergiants we have examined to date.

A non-LTE analysis of CNO lines in the spectra of our programme stars tends to support the high values of microturbulence obtained by demanding consistency among the He I diagnostics. We have therefore adopted $v_{\rm turb}$ = 15 km s^{-1} throughout, and derived atmospheric parameters and abundances for our programme stars, summarized in the Table 1. The C/N ratio, given in Table 1, is a sensitive indicator of the presence of nucleosynthetically processed material (Schönberner et al. 1988); although the absolute values may be biased by our neglect of metal-line blanketing, the results correlate quite closely with the helium number fraction in all of the programme stars (results are not yet finalized for HD 149404). This confirms that the O9.5 Iab star HD 154368 is both helium-enriched and has a relatively depleted C/N ratio, despite its apparent morphological normality.

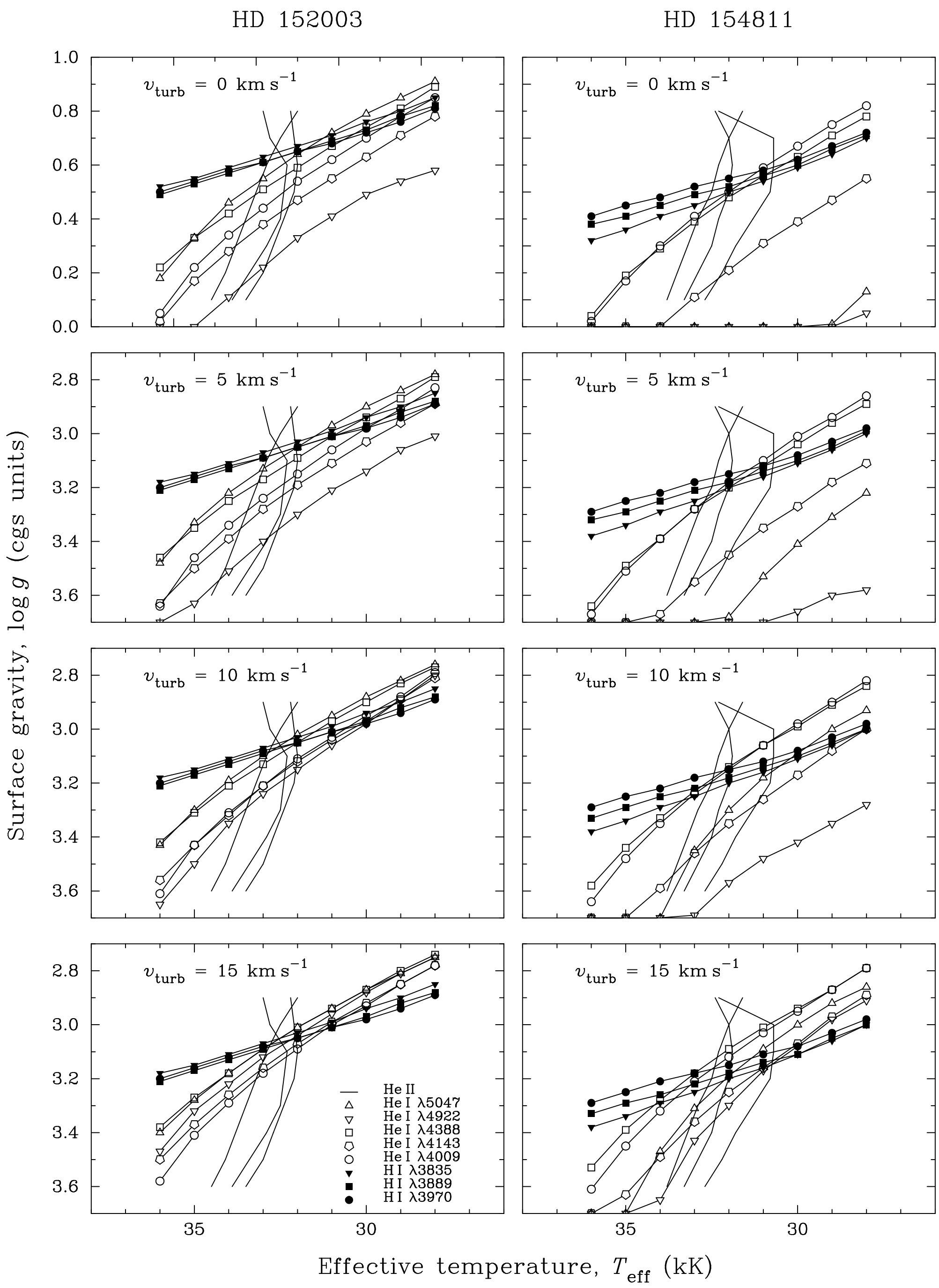

Figure 2. Diagnostic temperature–gravity diagrams for the O supergiants HD 152003 and HD 154811 assuming several values of the microturbulence parameter $v_{\rm turb}$ as indicated. Fits to the He II, H I, and He I lines are represented by curves of minimum χ^2. Note the improved consistency between the He I lines with increasing $v_{\rm turb}$.

4. Conclusions: Implications for the Helium Discrepancy

We have shown that introducing microturbulence into line-formation calculations results in excellent consistency between weak and strong He I singlet lines at unique, near-solar values of y for most (but not all) morphologically normal O stars. Preliminary calculations suggest that microturbulence may also play a role in shaping the statistical equilibrium of He I, exerting a differential impact on the populations of singlet and triplet states. This finding may have implications for the 'helium discrepancy' – a luminosity-dependent pattern of surface helium enrichments in OB-type stars derived primarily from analysis of *strong* lines such as λ4922 (Herrero et al. 1992). We have not addressed the origins of the putative velocity fields implicated in the microturbulent-like desaturation of He I lines identified here, but possibilities include atmospheric mass outflow (Kudritzki 1992) and non-radial pulsations (Townsend 1997).

Our supergiant abundances provide tentative support for a systematic decrease in the C/N ratio along the sequence OC$\rightarrow$O$\rightarrow$ON. This would tend to endorse Walborn's suggestion that OC stars have solar-composition atmospheres, whereas some morphologically normal O stars (and to a greater extent ON stars) display the products of nucleosynthetic processing at their surfaces. A follow-on study of a comparable sample of northern-hemisphere O supergiants (including several ON types) is currently underway and will exploit enhancements in our model-atmosphere grid, including a fully self-consistent implementation of microturbulence.

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