The Helium Fractions of Blue Supergiants and the Effect of Microturbulence

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Abstract. We present non-LTE analyses of two B-type supergiants, ϵ and κ Orionis (spectral types B0 Ia and B0.5 Ia, respectively). We have investigated the effect of including a microturbulent velocity in the hydrogen/helium line broadening and find that its inclusion is critical in the modelling of lines of neutral helium. Furthermore, we derive approximately *normal* helium fractions for both supergiants, in contradiction to results obtained without microturbulence.

We believe that the use of an appropriate microturbulent velocity may contribute to resolving the 'helium discrepancy' in hot stars. We discuss the revised evolutionary status of ϵ and κ Ori, and also comment briefly on the expected effect of mass loss on line profiles.

1. Introduction

There are a number of important challenges in modelling the evolution of massive ($M/M_{\odot} \gtrsim 10$) stars, highlighted by the failure of current evolutionary theory to reproduce certain fundamental characteristics of luminous stars (for example, the observed ratio of blue to red supergiants as a function of metallicity – see Langer & Maeder 1995).

It has long been suspected that early-type, luminous stars may consist of two evolutionarily distinct populations. Many such objects can be categorized as either OBN or OBC stars (Walborn 1976) and these differences in surface chemistry have been explained by the suggestion that the two groups are in different stages of stellar evolution. This idea is supported by theoretical calculations (e.g., Schaller et al. 1992), some of which show so-called 'blue loop' phases in a massive star's lifetime (early-type main-sequence $\rightarrow$ blue supergiant (BSG) $\rightarrow$ red supergiant (RSG) $\rightarrow$ blue supergiant). This return to the left-hand side of the HR diagram would lead to the presence of two populations of B supergiants (pre-RSG and post-RSG). It has been further suggested that, during its time as a RSG, a star would convectively mix core-processed material to its surface, leading to CNO anomalies and possibly slight helium enrichments in post-RSG B supergiants. However, such a scenario must be compared closely to the observational evidence in order to establish or negate its validity. In this respect, B supergiants may play an important role, as they occupy the area of the HR diagram into which the blue loops grow. Furthermore, many are known to have anomalous surface chemistries, particularly evident in the elements nitrogen and carbon (see the atlas by Lennon et al. 1992, 1993).

However, previous model-atmosphere analyses have found significant helium enrichments in nearly *all* luminous early-type stars (see, for example, Voels et al. 1989, Lennon et al. 1991, Herrero et al. 1992, and Smith & Howarth 1994). Evolutionary theory does not support uniform enrichments on such a scale, and Voels et al. have referred to this phenomenon as the 'helium discrepancy'.

An investigation (using non-LTE methods) of the photospheric chemistry of a large sample of B supergiants is currently underway, but in this paper we shall limit our discussion to the observed helium fractions in two representative B supergiants, the important effect of microturbulent line-broadening, and its consequences for the modelling of spectral lines of He I in such objects and for the evolutionary status of ϵ and κ Ori.

2. Observational Data and Non-LTE Analysis

The spectra analysed in this paper were obtained at the ESO 3.6-m telescope using CASPEC, and have a spectral resolution of ~20 000, with a signal-to-noise ratio of ~100 in the continuum. Such high quality spectral data allowed us to perform rigorous comparisons between the observed and synthetic line profiles (lines due to H I, He I, and He II were considered here).

The non-LTE analysis used was similar to that described by Lennon et al. (1991), but incorporated some important modifications. Firstly, microturbulence has been included in the calculation of profiles of hydrogen and helium (previous authors have tended to use it only for the metal lines) and its effect has been allowed for *consistently* in the calculation of level populations as well as line profiles. Tests have shown that this requirement of consistency between the two computational stages is important.

In determining atmospheric parameters ($T_{\rm eff}$ & $\log g$) for our two supergiants, we have used the lines Hδ, Hγ as indicators of logarithmic gravity and the He II lines near 4200Å and 4542Å as indicators of effective temperature. Simultaneous fits to these lines were performed at two helium fractions (viz. y=0.1, 0.2), with estimates for atmospheric parameters being similar, but not identical, for the two y-values. Having determined the primary atmospheric parameters, we were able to produce synthetic line profiles of neutral helium, at our two values of y. The determination of the helium fraction constrains all our atmospheric parameters to one set of values.

This method was executed for two values of the microturbulent velocity. We initially adopted $v_{\rm turb}$=0 km s^{-1}, but also considered the value $v_{\rm turb} = 12 \pm 3$ km s^{-1}, as determined from the Si III multiplet near 4560Å, in each supergiant.

3. Results

Test calculations showed that the H I and He II line profiles are fairly insensitive to the microturbulence; however, some of the stronger lines due to He I showed dramatic changes with differing $v_{\rm turb}$. As a direct result of these dependencies, the use of a non-zero microturbulence has a negligible effect on the estimation of effective temperature and logarithmic gravity, but has important consequences for the estimated value of the helium fraction.

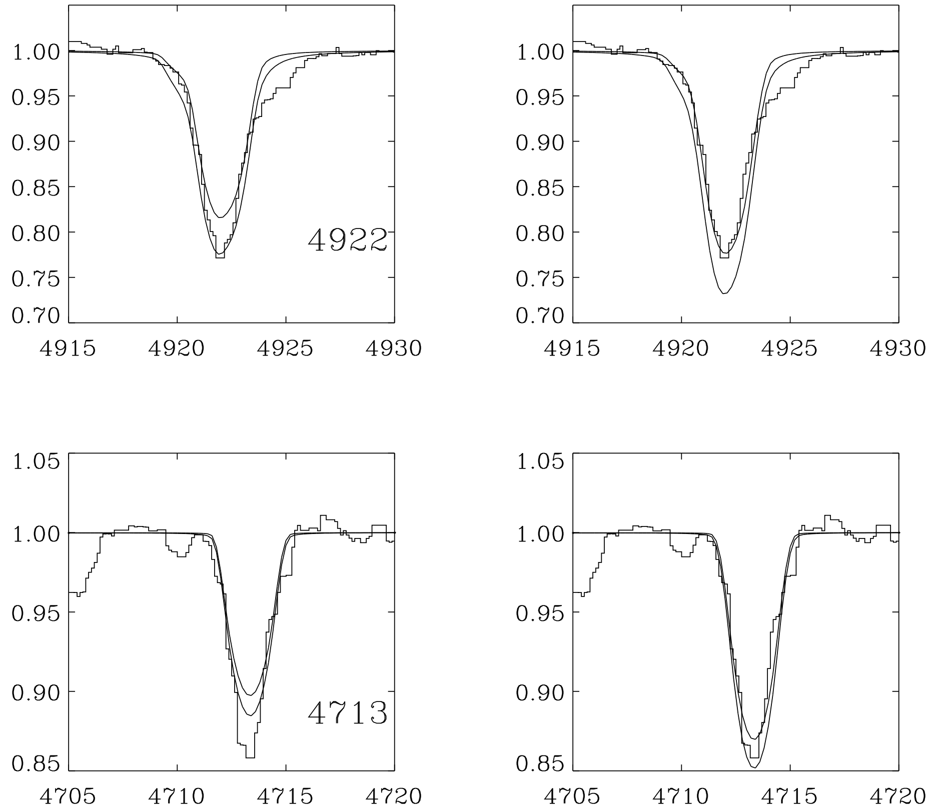

Figure 1. Non-LTE fits for two representative He I lines in ϵ Ori. The plots on the left have $v_{\rm turb} = 0$ km s^{-1} and those on the right have $v_{\rm turb} = 12$ km s^{-1}. In each case synthetic lines are shown for helium fractions, $y = 0.1$, 0.2. The absorption in the red wing of 4922Å is due to O II.

The increase in the strength of the synthetic profiles of He I caused by the microturbulent broadening leads to a reduction in the derived y-value. This is shown in Table 1, which gives y-estimates taken from each He I line considered by us. The effect is also shown graphically in Figure 1, which shows non-LTE fits for two representative lines in ϵ Ori.

The use of a non-zero microturbulence leads to uniformly better fits in most of the lines which were considered. This latter point is an important one, as previous attempts to simultaneously fit all the observed lines of He I have had little success (e.g., Lennon et al. 1991). The fact that most lines now give fits of a consistent high quality is very reassuring.

There are still some problems in successfully modelling all the available lines. The first is a systematic difference between the y-values estimated from the singlet and triplet lines, which we attribute to the neglect of line-blocking in our model atmospheres. We have also found evidence for the 'generalized

Table 1. Helium fractions, y, implied by different He I lines. For each target, we give two estimates for y; viz., that determined from an analysis performed with $v_{\rm turb}$=0 kms^{-1}, and that determined using a value determined from the metal lines. In some cases the strength of the line led to an unphysically large value for the helium fraction, and y-estimates are not given.

He I				ϵ Ori		κ Ori	
λ	f	Transition		$v_{\rm turb}$=0	$v_{\rm turb}$=12	$v_{\rm turb}$=0	$v_{\rm turb}$=12
5047	0.008	$1s2p - 1s4s$	2^1P – 4^1S	0.1	0.08†	0.15	0.1
4437	0.003	$1s2p - 1s5s$	2^1P – 5^1S	0.09†	0.08†	0.1	0.09†
4387	0.0436	$1s2p - 1s5d$	2^1P – 5^1D	0.09†	0.09†	0.1	0.1
4922	0.122	$1s2p - 1s4d$	2^1P – 4^1D	0.2	0.1	0.4:	0.1
5015	0.151	$1s2s - 1s3p$	2^1S – 3^1P	—	0.3:	—	0.3:
4713	0.012	$1s2p - 1s4s$	2^3P – 4^3S	0.4:	0.1	—	0.2
4026	0.047	$1s2p - 1s5d$	2^3P – 5^3D	0.2	0.1	0.2	0.15
4471	0.125	$1s2p - 1s4d$	2^3P – 4^3D	0.4:	0.2	0.4:	0.2

† indicates a small extrapolation outside our grid – estimates should be useful.
: indicates a significant extrapolation outside our grid – estimates are purely illustrative.

dilution effect' (discussed by Voels et al.), whereby the strongest lines, which form highest in the stellar photosphere, are not well modelled by our plane-parallel approach.

4. Discussion

4.1. The Revised Evolutionary Status of ϵ and κ Ori

The inclusion of microturbulence in modelling the lines of neutral helium has allowed us to obtain near-normal helium fractions for both supergiants, *in contradiction to* previously published values, which did not address this important effect. This result is an important one, as both ϵ and κ Ori are considered to be *normal* B supergiants.

The previously published helium enhancements for these two objects implied that they were post-RSG objects, but that evolutionary scenario now appears to be in question. This supports the work of Venn (1995) who, in her analysis of Galactic A supergiants, found no evidence for a post-RSG population. She instead found evidence for the *partial* mixing of carbon and nitrogen which she interpreted as having occurred on or near the main sequence. In this context, it is interesting to note that ϵ and κ Ori have very different carbon and nitrogen line-strengths and may have some differences in their surface chemistry.

Future studies will address the interesting question of CNO abundances and will better constrain the evolutionary history.

Finally, we note that our line fits suggest that κ Ori may be slightly helium rich, compared to ϵ Ori, although the error bars preclude a definite assertion. This is to be expected as κ Ori belongs to the group of B supergiants which have moderate nitrogen enhancements. A slight helium enrichment accompanied by more substantial changes in the surface abundances of carbon and nitrogen is suggestive of chemical mixing occurring on the main sequence, and we tentatively propose such a history for ϵ and κ Ori.

4.2. The 'Reality' of Microturbulence and the Contribution of Mass Loss

It has been shown (Kudritzki 1992; Lamers & Achmad 1994) that mass loss can mimic the effect of microturbulence, if a hydrostatic analysis (such as ours) is applied. However, we would expect hydrodynamic effects to be unimportant in the photospheric analysis of main-sequence B-stars, where mass-loss rates are approximately two orders of magnitude smaller, and yet the use of non-LTE analyses does not remove the need for microturbulence in such objects (Kilian 1994).

Whether our results must be explained by stochastic velocity fields, or if radial mass motions are sufficient, is unclear – our hydrostatic approach does not allow us to address these issues. We simply note that whatever the physics behind the line desaturation, our primary result remains unaffected – that the helium fractions in luminous OB-stars have been overestimated.

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