Chemical abundances and winds of massive stars in M31: a B-type supergiant and a WC star in OB 10

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ABSTRACT

We present high quality spectroscopic data for two massive stars in the OB 10 association of M31, OB 10-64 (B0 Ia) and OB 10-WR1 (WC6). Medium resolution spectra of both stars were obtained using the ISIS spectrograph on the William Herschel Telescope. This is supplemented with Hubble Space Telescope STIS UV spectroscopy and Keck I HIRES data for OB 10-64. A non-local thermodynamic equilibrium (LTE) model atmosphere and abundance analysis for OB 10-64 is presented, indicating that this star has similar photospheric CNO, Mg and Si abundances to solar neighbourhood massive stars. A wind analysis of this early B-type supergiant reveals a mass-loss rate of $\dot{M} = 1.6 \times 10^{-6} \, M_\odot \, yr^{-1}$, and $v_\infty = 1650 \, km \, s^{-1}$. The corresponding wind momentum is in good agreement with the wind momentum–luminosity relationship found for Galactic early-B supergiants.

Observations of OB 10-WR1 are analysed using a non-LTE, line-blanketed code, to reveal approximate stellar parameters of $\log L/L_\odot \sim 5.7$, $T_\ast \sim 75 \, K$, $v_\infty \sim 3000 \, km \, s^{-1}$, $\dot{M}/(M_\odot \, yr^{-1}) \sim 10^{-4.3}$ adopting a clumped wind with a filling factor of 10 per cent. Quantitative comparisons are made with the Galactic WC6 star HD 92809 (WR23) revealing that OB 10-WR1 is 0.4 dex more luminous, though it has a much lower C/He ratio (≈0.1 versus 0.3 for HD 92809). Our study represents the first detailed, chemical model atmosphere analysis for either a B-type supergiant or a Wolf–Rayet (WR) star in Andromeda, and shows the potential of how such studies can provide new information on the chemical evolution of galaxies and the evolution of massive stars in the local Universe.

Key words: stars: abundances – stars: early-type – stars: winds, outflows – stars: Wolf–Rayet – galaxies: individual: M31.

1 INTRODUCTION

The observation and analysis of hot, luminous stars in the Milky Way and other Local Group galaxies allows the investigation of stellar evolution and mass-loss within different environments. For example, Wolf–Rayet (WR) stars, the chemically evolved descendents of massive OB stars, provide keys to our understanding of massive stellar evolution and nucleosynthetic processes, e.g. Dessart et al. (2000).

Studies of the physical nature of the A- and B-type supergiants can also place constraints on evolution models in the upper main-sequence regions, e.g. Venn (1995) and McErlean, Lennon & Dufton (1999). A further use of the A- and B-type supergiants is in using photospheric analysis to constrain the chemical composition of the interstellar medium in their host galaxies. They are visually the brightest quasi-stable objects in galaxies, and being

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descendants of massive OB-type main-sequence objects have small lifetimes (5–20 Myr). Many elements visible in their photospheres should not be affected by internal mixing and contamination with core processed material [e.g. O (only slightly affected in AB-types), Mg, Si, S, Al, Ca, Fe, Ti, Cr, Ni; Venn et al. 2000; Smartt, Dufton & Lennon 1997]. Further, they can also provide new information on the distances of galaxies through the detailed study of the strengths of their radiatively driven winds using the wind momentum–luminosity relationship (hereafter WLR; Kudritzki et al. 1999). An investigation of the stellar wind properties of O-, B- and A-type supergiants in Local Group galaxies with well-defined distances will, therefore, allow us to test the concept of the WLR and its applicability for distance determinations.

Numerous surveys have identified OB and WR stars beyond the Magellanic Clouds, e.g. Massey et al. (1986) and Moffat & Shara (1987), although little quantitative analysis has been carried out to date. The only detailed studies of Wolf–Rayet stars beyond the Magellanic Clouds have been studies of late WN stars in M33 by Smith et al. (1995) and Crowther et al. (1997). Bianchi et al. (1996b) have published UV spectroscopy of OB-type supergiants in M31 and M33, while Monteverde et al. (1997, 2000) derived the oxygen abundance gradient in M33 from studies of B-type supergiants. An indication of the capabilities of 8-m-class telescopes has been presented by Muschielok et al. (1999) for three B-type supergiants in NGC 6822 using the Very Large Telescope (VLT). Recently, Venn et al. (2000) have analysed four A-type supergiants in M31, the first detailed stellar analysis in this galaxy.

The present work demonstrates the capabilities of 4-m-class telescopes by analysing the spectra of two massive stars in the OB 10 association of our nearest giant spiral galaxy, Andromeda (= M31 = NGC224). OB 10 (van den Bergh 1964; Massey et al. 1986) is located at 23.6 arcmin from the centre of M31, and has an apparent size of 2 × 1.0 arcmin. Assuming a distance to M31 of 783 kpc (Holland 1998; Stanek & Garnavich 1998: assumed throughout this paper) the projected size of the association is hence ∼450 × 225 pc. Its stellar content was investigated by Massey et al. (1986) (and later Massey et al. 1995), who found two Wolf–Rayet candidates, OB 10-WR1 (classified as WC6-7) and OB 10-WR2 (classified only as WN) and a late O-type supergiant [OB 10-150; OB.85(a)]. The presence of such massive stars implies that it is a very young association, having formed in the last ∼5 Myr. The de-projected position of OB 10 would suggest it has a galactocentric distance of 5.9 kpc. Blair, Kirshner & Chevalier (1982) have determined an abundance gradient in M31 from a combination of observations of H ii regions and supernova remnants, deriving −0.03 ± 0.01 dex kpc−1. Hence, OB 10 is expected to have a metallicity of ∼9.1 dex, a factor of two greater than the Galactic solar neighbourhood value.

In this paper, William Herschel Telescope (WHT) spectroscopy of OB 10-64 (B0 Ia) and OB 10-WR1 (WC6) are combined to reveal the actual metal abundance of this region of M31, plus the properties of WC-type stars in a galaxy similar to our own. Designations are taken from Massey et al. (1986); OB 10-64 has an alternative designation of 41-2265 from Berkhuizen et al. (1988), while OB 10-WR1 is also known as IT5-19 by Moffat & Shara (1987).

Our observations are presented in Section 2. Since the methods used to analyse the spectra of the M31 B-type supergiant and Wolf–Rayet star differ considerably, they are discussed separately below in Sections 3 and 4, with a general discussion presented in Section 5.

## 2 OBSERVATIONAL DATA AND REDUCTION

WHT spectroscopy was obtained for OB 10-64 and OB 10-WR1 during 1998 September–November as part of a programme to observe early-type stars in the spiral galaxies M31 and M33. For OB 10-64 these data were supplemented by Keck I high-resolution echelle spectrograph (HIRES) data around the Hα region of the spectrum and Hubble Space Telescope (HST) Space Telescope Imaging Spectrograph (STIS) UV spectra.

HD 167264, a Galactic early B-type supergiant, was further observed in 1998 September with exactly the same instrumental setup. For comparison with OB 10-WR1, HD 92809 (WC6) was observed at the Mt Stromlo and Siding Spring Observatory (MSSSO) in 1997 December. Table 1 summarizes the M31 spectroscopic observations and published photometry.

### 2.1 WHT spectroscopy

The double-armed spectrometer ISIS was used to observe OB 10-64 and OB 10-WR1 on the nights of 1998 September 28–29. The spectrograph slit was positioned so that it included both stars, their separations on the sky being only 25 arcsec. Only the blue arm of ISIS was used for the first night, with the R1200B grating and a thinned EEV42-80 CCD (with format 4096 × 2048 13.5-µm pixel). On the second night, a beam-splitting dichroic was used to feed both the blue and red channels; for the latter, the grating was the R1200R with a TEK CCD used as a detector. For the blue spectra, the unvignetted wavelength range was from

<table>
<thead>
<tr>
<th>Star</th>
<th>Epoch</th>
<th>Spectral ranges (Res)</th>
<th>S/N</th>
<th>Exp. Hours</th>
<th>V mag</th>
<th>B − V mag</th>
<th>U − B mag</th>
<th>E(B − V) mag</th>
<th>M_V mag</th>
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<tr>
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<tr>
<td>OB 10-64</td>
<td>Sep 1998</td>
<td>3985−4725 (0.8)</td>
<td>...</td>
<td>50</td>
<td>4.5</td>
<td>18.10 ± 0.04</td>
<td>−0.08 ± 0.08</td>
<td>0.18 ± 0.08</td>
<td>−6.93 ± 0.4</td>
</tr>
<tr>
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<td>Sep 1998</td>
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<td>5650−6400 (1.6)</td>
<td>15</td>
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<td>19.32 ± 0.07</td>
<td>−0.56 ± 0.08</td>
<td>−0.45</td>
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<td>6404−9277 (7)</td>
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<tr>
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<td>Oct 1999</td>
<td>1120−1716 (1.5)</td>
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<td>20</td>
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</table>
approximately 3985 to 4725 Å, with a pixel size of 0.22 Å; the corresponding values for the red spectra were 5650–6400 Å and 0.4 Å.

Since the above setup was primarily geared towards useful photospheric lines for the B-type supergiant, we missed the crucial WC abundance lines between 5000–5600 Å. Subsequently, service observations were taken of OB 10-WR1 on 1998 November 24, at a lower but sufficient spectral resolution. The R300B and R300R gratings were used in the blue and red arms at dispersions of 0.9 Å pixel$^{-1}$ and 1.6 Å pixel$^{-1}$ covering 3640–6227 Å and 6404–9277 Å, respectively.

The CCD frames were reduced to wavelength-calibrated spectra using the IRAF reduction system. Standard procedures were used to bias correct and flat field the stellar images. There is considerable background Balmer line emission from the nebular region of OB 10, which can vary over small spatial scales along the slit. Although nebular emission at the sub-pixel level contaminates our stellar Balmer line observations of OB 10-64, the CCD images showed that the H6 and Hγ regions were less affected than the Hα line. Further, our spectral resolution is high enough that the important wings of H6 and Hγ will be unaffected by the background nebulousity. However, there may be residual errors in the cores of the stellar Balmer line profiles. The nebular emission around WR1 is particularly intense and accurate subtraction proved very difficult; however, as may be seen in Fig. 9 (below), most of the broader WR features can be modelled while recognizing the narrower nebular contamination. The spectra were wavelength calibrated using CuNe + CuAr lamp exposures that interleaved the stellar spectra. Individual stellar exposures were then cross-calibrated using CuNe 1 covering 3640–6227 Å and 6404–9277 Å, respectively.

Unfortunately, conditions in 1998 November prevented an absolute flux calibration for OB 10-WR1. Nevertheless, a relative calibration was achieved, using the spectrophotometric DO white dwarf standard star Feige 110. This star was observed for 300 s with an identical setup, immediately prior to OB 10-WR1 and at a similar air mass.

### 2.2 Keck I HIRES and HST STIS spectroscopy of OB 10-64

OB 10-64 was observed with the 10-m Keck I telescope, using HIRES on 1997 September 27 and again on the 1999 October 6–7, giving a total of 4 × 3600 s exposures. A 1.1-arcsec slit was used giving a resolution of approximately 35 000, yielding a S/N of ~ 60 at Hα after co-addition and binning in the spectral direction to 0.3 Å pixel$^{-1}$. The CCD echelle spectra were reduced in the standard manner, using the same methods as described in McCarthy et al. (1997). The most difficult task was removing the strong background Hα nebular emission from the stellar spectrum. In fact complete removal proved impossible, and we have left in the residual (negative) nebular Hα line in Figs 6 and 7 (below). This led to an unrecoverable 0.9-Å region of the spectrum, which is however not critical to our fitting of the much broader stellar Hα profile.

**HST** spectra were taken with the STIS, as part of an extensive programme (GO7481) to observe the UV wind lines of massive blue supergiants in M31 and M33. Two exposures, giving a total of 8500 s, were taken with the FUV-MAMA detector on 1999 October 1. The G140L grating and the 52 × 0.2 arcsec slit aperture were used. The data were pipeline processed (including wavelength and flux calibration) by the STScI On-The-Fly calibration system. This processes the data with the most up-to-date calibration files, parameters, and software. Further details of the observational material can be found in Table 1.

### 2.3 MSSSO spectroscopy

The Galactic WC6 star HD 92809 was observed with the Double Beam Spectrograph (DBS) at the 2.3-m MSSSO on 1997 December 24–27. Use of a suitable dichroic permitted simultaneous blue and red observations of HD 92809 covering 3620–6085 Å (300B) and 6410–8770 Å (316R), plus 3240–4480 Å (600B) and 8640–11010 Å (316R). A 2-arcsec slit and 1752 × 532 pixel SITE CCDs provided a 2-pixel spectral resolution of ~ 5 Å. Wide-slit observations were also obtained for HD 92809 and the HST spectrophotometric standard star HD 60753 (B3 IV) to achieve reliable flux calibration. Atmospheric correction was achieved by observing HR4074 within an air mass of 0.10 from HD 92809. A standard data reduction was again carried out with IRAF.

These observations were supplemented by high resolution (HIRES), International Ultraviolet Explorer (IUE), large aperture, short-(SWP) and long-wavelength (LWP, LWR) ultraviolet observations of HD 92809. These were combined to provide a single high S/N data set, flux calibrated using the curve obtained by Howarth & Philips (1986). Finally, the spectra were transferred to the STARLINK spectrum analysis program DIPSO (Howarth et al. 1998) for subsequent analysis.

### 2.4 Photometry, distance and reddening to M31

The published photometry of both stars (from Massey et al. 1986) is provided in Table 1. Assuming $(B - V)_0 = -0.26$ for a B0 Ia atmosphere (Deutschman, Davis & Schild 1976), we estimate an interstellar reddening of $E(B - V) = 0.18$ mag towards OB 10-64. Massey et al. (1995) have estimated the mean reddening toward the massive stars with spectrophotometrically confirmed types in OB 10 and OB8+OB9, deriving a value of $E(B - V) = 0.16 ± 0.02$. The reddening directly towards OB 10-64 is hence compatible with the mean value for the region. Assuming the distance of Holland (1998) to M31 of 783 ± 30 kpc implies $M_V = -6.93 ± 0.42$ for OB 10-64 (from the errors quoted in Table 1). We discuss the implications of this in terms of wind and evolutionary models in Section 5.

Our HST STIS data were combined with existing archive Faint Object Spectrograph (FOS) and Goddard High Resolution Spectrograph (GRHS) data to give a flux distribution from 1120–3300 Å. For the value of $E(B - V) = 0.18$, the de-reddened $HST$/FOS flux distribution for OB 10-64 matches theoretical models for $\lambda \approx 2000$ Å but shows a noticeable drop at shorter wavelengths, possibly indicating a far-UV reddening law different from the Galactic case (Seaton 1979). Bianchi et al. (1996a) investigated the extinction in M31 using the $HST$/FOS data for OB 10-64 and additional M31 OB stars and concluded that the 2175-Å bump is weak or absent in M31. The slope of the extinction curve was consistent with the Galactic curve, but the low reddening of

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1 IRAF is written and supported by the IRAF programming group at the National Optical Astronomy Observatories (NOAO) in Tucson, Arizona (http://iraf.noao.edu).

their M31 target stars prevented strong constraints being placed on the exact shape of this extinction curve. We have briefly re-investigated this issue using a slightly different procedure, following Fitzpatrick (1986) in using other B-type supergiants in the LMC as the comparison stars. We chose Sk-67 108 (B0 Ia) and Sk-69 276 (O9-8B0 Ia) as the comparison stars on the basis of the morphology of their UV spectra compared to OB 10-64. These two stars have essentially little or no internal Large Magellanic Cloud (LMC) extinction and the E(B − V) values (0.06 and 0.10 respectively) reflect the reddening from intervening Galactic material. This Milky Way extinction is similar to what we expect for OB 10-64. Using these two stars and OB 10-64, we derive a mean M31 extinction law, which confirms the lack of a 2175-Å feature in M31, similar to the Small Magellanic Cloud (SMC) (Prevo et al. 1984). We find a slope for M31 which is marginally shallower than the SMC, but steeper than that of the Milky Way. A linear fit of \( E(\lambda - V)/E(B − V) \) versus \( \lambda ^{-1}(\mu ^{-1} m) \) gives a slope of approximately 1.8 for M31, compared with approximately 2.2 for the SMC. This analysis suggests that the far-UV extinction in M31 is greater than that predicted by the Galactic extinction law, and that there is a lack of the 2175-Å bump. However, this should be treated with some caution as we have only one star available here, and it is only lightly reddened by dust in M31 itself. Ideally, stars with higher M31 extinction (or preferably a range in values) are needed to investigate the relationship fully.

For the Wolf–Rayet star, broad-band Johnson photometry is (differentially) contaminated by strong emission lines. Consequently, the Massey et al. (1986) V-band magnitude for OB 10-WR1 will overestimate the true continuum flux, and the observed B − V colour does not permit the determination of interstellar reddening. Therefore, we assume a reddening identical to that derived above for OB 10-64 and estimate a Smith narrow V-band magnitude for OB 10-WR1 as follows. We have convolved our WHT spectra of OB 10-WR1 and OB 10-64 with a Johnson V-band filter, revealing \( \Delta V = 1.25 \) mag, in excellent agreement with 1.22 from Massey et al. (1986). Applying the V-band filter to the spectrum of OB 10-WR1 yields \( \langle V - V \rangle = 0.35 \) mag, so we estimate \( V = 19.67 \) mag. This agrees well with the narrow-band 4752-Å continuum magnitude of 19.6 quoted by Massey & Johnson (1998) for OB 10-WR1. Taking the above distance and adopting a reddening of \( E(B − V) = 0.18 \) implies \( M_V = -5.4 \pm 0.4 \) mag. This result is significantly different from the mean absolute magnitudes of \( M_V = -3.7 \) mag and \(-4.8 \) mag for, respectively, Galactic WC6 and WC7 stars (e.g. Smith, Shara & Moffat 1990).

### 2.5 Spectral types

While spectral typing is often neglected when carrying out quantitative atmospheric and wind analysis of massive stars, we quote our revised types to allow the stars to be put into context with other morphological work. Humphreys, Massey & Freedman (1990) and Massey et al. (1995) gave a spectral type of B1 I for OB 10-64 based on spectral data of 2–3.5-Å resolution and moderate signal-to-noise ratio, while Bianchi, Hutchings & Massey (1996b) presented HST ultraviolet spectroscopy of OB 10-64, suggesting approximately B0.5 I. From our higher quality optical and UV spectra we have adjusted the spectral type slightly to B0 Ia (see also Fig. 4, below). Meanwhile, Massey et al. (1986) classified OB 10-WR1 as a WC6-7 star, which Moffat & Shara (1987) revised to WC6+neb. Our high-quality spectrum confirms the WC6 classification using either the Smith et al. (1990) or Crowther, De Marco & Barlow (1998) schemes, plus the strong nebular contamination.

### 3 B-TYPE SUPERGIANT ANALYSIS

The non-LTE model atmosphere techniques have been described in detail by McErlain et al. (1999, hereafter MLD) and here we only provide a summary. A grid of non-LTE model atmospheres was generated using the code TLUSTY (Hubeny 1988) for effective temperatures, \( T_{\text{eff}} \), up to 35 000 K and logarithmic gravities from \( \log g = 4.5 \) down to near the Eddington stability limit. Models were calculated for two helium fractions, i.e. \( y = 0.09 \) (solar) and \( y = 0.20 \), where \( y = N[\text{He}]/N[\text{H+He}] \). The models omit a number of physical processes, including metal line-blanketing and wind effects. Furthermore, the assumption of a plane-parallel geometry may be of limited validity for the low-gravity objects considered here. The consequences of these omissions have been discussed in MLD.

The line formation calculations were performed using the codes DETAIL (Giddings 1981) and SURFACE (Butler 1984). Microturbulent velocities, which are close to the speed of sound, have previously been found for B-type supergiants. Therefore, in the calculation of line profiles, microturbulence has been included as an extra free parameter. Metal ion populations and line profiles were calculated using mainly the atomic data of Becker & Butler (1988, 1989, 1990). Such calculations explicitly include the effects of the relevant ions on the radiation field. However, they do not include the effects of line and continuum blanketing from other metals.

Significant difficulties were encountered in running DETAIL, particularly for the silicon model ion but also for some other species. These difficulties occurred mainly at the lowest gravities for effective temperatures greater than \( \sim 25\,000 \) K. Examination of the line profiles indicated that this was caused by either emission or ‘filling in’ of the profiles. Indeed the DETAIL calculations normally showed an overpopulation of the relevant ion upper levels coupled with large photoionization rates (and subsequent cascades). MLD postulated that the emission was an artefact of their exclusion of line blanketing which leads to an overestimate of the UV flux and hence of the photoionization rates – further discussion of these problems can be found in their paper, while their implications for the current data set are discussed below.

#### 3.1 Atmospheric parameters

A comparison of the spectra of OB 10-64 and HD 167264 indicates that these stars have very similar, if not identical, atmospheric parameters within the errors of our methods. This is illustrated in Fig. 1, where four spectral regions are shown for the two stars. These regions contain diagnostics of the atmospheric parameters as discussed below.

##### 3.1.1 Effective temperature

As discussed by MLD, both the strength of the He II features and the relative strengths of lines arising from Si III and Si IV can be used to estimate the effective temperature for spectral types near B0. The former is an excellent diagnostic with a change of effective temperature of 2000 K leading to changes in the He II equivalent widths of a factor of two or three; additionally, MLD found that the He II line at 4541 Å appeared to be well modelled by the non-LTE calculation. In Fig. 1, two He II lines at 4541 and 4686 Å are shown;
their strengths seem very similar in the two stars. This is confirmed by the observed equivalent widths (see below for details of the procedures used to estimate these values) summarized in Table 2. Although the line strengths are approximately 20–30 per cent larger for OB 10-64, this would correspond to a change in effective temperature of less than 500 K, such is the sensitivity of the line strength to temperature in this $T_{\text{eff}}$ range.

Lines arising from Si III (at approximately 4553, 4568 and 4574 Å) and Si IV (at 4089 and 4116 Å) are also shown in Fig. 1. Again, the agreement is excellent, as is confirmed by the estimates of the equivalent widths listed in Table 2. For OB 10-64, the Si III lines are marginally enhanced and the Si IV lines marginally weakened compared with the standard star. This would imply that OB 10-64 had a lower effective temperature, in contrast to the He II lines that implied that this star was hotter. However, again the differences are marginal and would imply a temperature difference between the two stars of less than 500 K.

### 3.1.2 Surface gravity

The profiles of the Balmer lines are useful diagnostics of the surface gravity, and in Fig. 1, the Hγ (at 4340 Å) and Hδ (at 4101 Å) are shown. In the line wings (which have the greatest sensitivity to the gravity), the agreement between the two stars is excellent and implies that the gravities (assuming that the stars have similar effective temperatures) differ by less than 0.2 dex; the major uncertainty arises from the difference in S/N of the observational data for OB 10-64 compared to the bright standard. In the line cores, there are significant differences but this is likely to be the result of different amounts of rotational or macroturbulent broadening rather than of a difference in the surface atmospheric

<table>
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<th>Species</th>
<th>Wavelength (Å)</th>
<th>$W_{l}$ (mA˚)</th>
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<td>4541</td>
<td>145</td>
</tr>
<tr>
<td>He II</td>
<td>4686</td>
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<tr>
<td>Si III</td>
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<tr>
<td>Si IV</td>
<td>4654.14</td>
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Figure 1. Selected spectral regions for OB 10-64 (solid line) and HD 167264 (dotted line), showing temperature sensitive features (He II lines at 4541 and 4686 Å; Si III lines at 4553, 4568 and 4574 Å and Si IV lines at 4089 and 4116 Å) and the surface gravity diagnostics (Balmer lines: Hγ 4101 and Hδ 4340 Å). The high quality data of this 18" star allow us to identify and measure relatively weak stellar absorption lines due to metals and He I.

Table 2. Equivalent widths, $W_{l}$, for selected lines of He II, Si III and Si IV in OB 10-64 and HD 167264. These lines are very sensitive to $T_{\text{eff}}$, and the similarity of the line strengths indicates that the effective temperatures of the two stars are similar to within 500 K (see Section 3.1). Note that the Si IV line at 4089 is blended with a nearby O II feature, but at this $T_{\text{eff}}$ the Si IV contribution dominates and the ratio of the line strengths is approximately 4:1. The equivalent widths for OB 10-64 should normally be accurate to 10 per cent; and for HD167264 accuracies are normally 5 per cent.
parameters. Additionally, for the OB 10-64 spectra there were significant amounts of background emission from the host galaxy as discussed in the previous section; the discrepancies may in part reflect the difficulty in subtracting this background emission accurately.

Hence we conclude that within the observational uncertainties, these two stars have the same atmospheric parameters. MLD deduced an effective temperature of 29,000 K and a logarithmic gravity of 3.1 dex for HD 167264 from the optical spectroscopy of Lennon, Dufton & Fitzsimmons (1992, 1993). We have used our better quality ISIS observations to check these results using the same diagnostics as MLD, namely the He II lines for effective temperature and the Balmer line profiles for the gravity. At these relatively high effective temperatures, the non-LTE calculations of the Si III spectrum (and to a lesser extent the Si IV spectrum) become problematic (see MLD for details) and hence these lines will not be considered.

The observed and theoretical spectra are shown in Fig. 2, with the latter having been convolved with a Gaussian profile with a FWHM of 0.80 Å to allow for instrumental, rotational and macroturbulent velocity broadening. In general the agreement is good, apart from the He II line at 4541 Å, where the wings of the theoretical profile appear to be too strong. However, even for this case, a decrease of only 1000 K would lead to a theoretical profile that is significantly weaker than the observed profile. Hence we conclude that the atmospheric parameters of MLD are reliable and adopt them for both HD 167264 and OB 10-64. Additionally, MLD found that a microturbulent velocity of 10 km s\(^{-1}\) was appropriate for the Si III lines in B-type supergiant spectra. They also noted that the O II spectra implied a higher microturbulent velocity – a result found independently by Vrancken et al. (1999) for early-B-type giants. Here we adopt a microturbulent velocity of 10 km s\(^{-1}\) for both stars but will consider below the effect of a larger value being appropriate.

### 3.2 Chemical composition

The choice of a standard with atmospheric parameters effectively identical to those for OB 10-64 simplifies the abundance analysis. Our procedure was as follows. First, metal line-absorption features were identified in the spectra of OB 10-64. For marginal features, the spectrum of HD 167264 was used as a template and guide. The equivalent widths of the features were estimated in both stars by non-linear least squares fitting of single or multiple Gaussian absorption profiles to the normalized spectra. Normally both the positions and widths of the Gaussian profiles were allowed to vary. However, for multiplets the relative wavelength separations were fixed, while for marginal features in OB 10-64, the widths were set to the mean value found for well-observed lines. The equivalent widths are listed in Table 3, apart from those for silicon, which are in Table 2; all estimates have been rounded to the nearest 5 mÅ.

For most species, these equivalent widths were analysed using the non-LTE grids of MLD and the atmospheric parameters discussed above (listed in Table 4). As well as absolute abundance estimates, a line-by-line differential analysis was also undertaken. For the N III spectrum and one Si IV line, non-LTE calculations were not available and LTE methods were used; in these cases, the absolute abundance estimates should be treated with caution. However, the similarity in both the observed line strengths and inferred atmospheric parameters for OB 10-64 and HD 167264 imply that the differential abundance estimates should be reliable. This was confirmed by re-analysing the O II line spectrum using an LTE technique, where the differential abundances agreed with the non-LTE estimates to normally within 0.01 dex. Both the absolute and the differential abundance estimates are summarized in Table 5, together with the number of features used and whether an LTE or non-LTE formulation was adopted. Note that the latter information is replicated in Table 3, together with information on which features were included in the abundance analysis. The error estimates in Table 5 are unweighted standard deviations of the samples; where a significant number of features were measured, the uncertainty in the means should be smaller.

### 3.3 Photospheric abundances of OB 10-64

The atmospheric parameters and chemical composition of OB 10-64 appear to be very similar to those of HD 167264. Below, we discuss the abundances of individual elements in detail.

#### 3.3.1 Helium

The helium abundance in OB 10-64 has not been determined explicitly. This was because most of the He I non-diffuse features were either badly blended with metal lines (e.g. the line at 4121 Å) or weak (the lines at 4169 and 4437 Å). The only well-observed non-diffuse feature is the triplet line at 4713 Å and as can be seen from Fig. 1, the profiles for the two stars are very similar. Additionally the moderate quality of the observational data for OB
10-64 would make reliable profile fitting of the helium diffuse lines difficult. However in Fig. 3, selected diffuse helium lines are shown for the two stellar spectra. In general, agreement is excellent and we conclude that within the observational uncertainties, the helium abundances in the two objects are similar.

3.3.2 Carbon
The carbon abundances are based on a single weak feature (the 4267-Å doublet) which is of similar strength in each star. MLD have commented on the fact that the line appears difficult to model properly with the non-LTE techniques that we use here. Even in B-type dwarfs, calculation of this transition is problematic in both LTE and non-LTE. Hence while the absolute abundance estimates should be treated with considerable caution, the similarity in line strength points to both stars having similar C photospheric abundances.

3.3.3 Nitrogen
This element is particularly important as it provides an excellent diagnostic for the mixing of nucleosynthetically processed material from the stellar core to the surface. Hence, a search was made for lines of both N II and N III in the spectrum of OB 10-64. Unfortunately all the detections were marginal and the corresponding line strengths should be treated with caution. The single N II line imply that the two stars have similar nitrogen abundances while the four N III lines implies that OB 10-64 is depleted by approximately 0.2 dex. However, it should be noted that the theoretical N III line strengths are very sensitive to the adopted effective temperature, which coupled with the observational uncertainties, implies that this difference is probably not significant.

3.3.4 Oxygen
This is the best observed species, with 13 lines being analysed. The oxygen abundances in the two stars are very similar as can be seen 10-64 would make reliable profile fitting of the helium diffuse lines difficult. However in Fig. 3, selected diffuse helium lines are shown for the two stellar spectra. In general, agreement is excellent and we conclude that within the observational uncertainties, the helium abundances in the two objects are similar.

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3.3.4 Oxygen
This is the best observed species, with 13 lines being analysed. The oxygen abundances in the two stars are very similar as can be seen
from the absolute abundance estimates. It is encouraging that the standard error for the differential abundance is significantly smaller, implying that the use of a differential method is indeed removing some sources of systematic error. Assuming that the remaining errors are distributed normally, the estimated uncertainty in the mean differential abundance would be reduced to approximately $0.02$ and hence there is marginal evidence for a slight enhancement in OB 10-64.

### 3.3.5 Magnesium

The estimates are again based on a single feature but the two stars appear to have similar abundances.

### 3.3.6 Silicon

The $\text{Si}^{\text{III}}$ lines were analysed using both non-LTE and LTE methods. The former leads to higher absolute estimates but a similar differential abundance as for the LTE calculations. As discussed by MLD, the non-LTE profiles of the $\text{Si}^{\text{III}}$ lines show some emission in their wings in this temperature regime; this is probably an artefact of the lack of line blanketing in the calculations. Hence in Table 5 the LTE results are summarized, but the absolute abundance estimates should be treated with caution. The differential abundance implies a small silicon enhancement in OB 10-64 in contrast to that found from the two $\text{Si}^{\text{IV}}$ lines. The latter result should also be treated with some caution as the analysis of one of the $\text{Si}^{\text{IV}}$ lines was undertaken in LTE (it was not included in the non-LTE model ion), which will make the absolute abundance estimates particularly unreliable. Additionally, the theoretical line strengths are extremely sensitive to the adopted effective temperature with, for example, a change of less than 1000 K being sufficient to eliminate the discrepancy. Hence we believe that the $\text{Si}^{\text{III}}$ differential abundance is the more reliable.

Despite the difficulties for individual ions discussed above, we believe that the differential abundance estimates should be generally reliable. This reflects the similar atmospheric parameters and metal-line equivalent widths for the two stars. The former ensures that the method of analysis (LTE or non-LTE) is relatively unimportant and indeed we confirmed this by re-analysing the $\text{O}^{\text{II}}$ equivalent widths using LTE methods. Additionally, the similarity in line strengths makes the choice of the microturbulent velocity relatively unimportant provided it is the same in both stars; for example, re-analysing the metal-line spectra with a microturbulent velocity of 15 km s$^{-1}$ changed the differential estimates by less than 0.05 dex.

### 3.4 Wind analysis and stellar wind momentum

OB 10-64 is an ideal object to test the validity of the concept of the wind momentum – luminosity relationship. It has a well-determined chemical composition comparable to the solar neighbourhood and an equally well-determined effective temperature and gravity. The reddening is moderate and the absolute magnitude follows from the distance to M31 (see Table 1). Using a non-LTE model atmosphere code with the corresponding effective temperature and gravity, we can calculate the emergent stellar flux and determine the stellar radius from the absolute $V$-band magnitude (see Kudritzki 1980). We obtain a radius of

![Figure 3](https://academic.oup.com/mnras/article-abstract/325/1/257/958440/2001-RAS-MNRAS-325-257-272)
This means that OB 10-64 has stellar parameters very similar to the galactic object HD 37128 (e Ori), which has been investigated recently by Kudritzki et al. (1999) in their study of the wind momentum – luminosity relationship of galactic A- and B-supergiants. We therefore expect both objects to have comparable wind momenta. HD167264, the Galactic comparison object for the abundance study in this paper, has a very uncertain distance (and, therefore, radius and luminosity). From the similarity of the spectra we can only assume that its luminosity must be comparable to OB 10-64 and HD 37128.

An inspection of Fig. 4 immediately indicates (albeit in a qualitative manner) that the stellar wind properties of the three objects cannot be very different. For the quantitative wind analysis

Figure 4. A compilation of galactic IUE spectra of two B0 Ia Galactic stars and the STIS spectra of OB 10-64.

Figure 5. The wind analysis fit (dotted line) for $v_\infty$ shown for the C IV line only. OB 10-64 is the solid line and HD167264 is the dashed. The HD167264 high-resolution IUE spectra has been degraded to the STIS resolution. A $v_\infty = 1650$ km s$^{-1}$ is found.

$R = 34 R_\odot$. This means that OB 10-64 has stellar parameters very similar to the galactic object HD 37128 (e Ori), which has been investigated recently by Kudritzki et al. (1999) in their study of the wind momentum – luminosity relationship of galactic A- and B-supergiants. We therefore expect both objects to have comparable wind momenta. HD167264, the Galactic comparison object for the abundance study in this paper, has a very uncertain distance (and, therefore, radius and luminosity). From the similarity of the spectra we can only assume that its luminosity must be comparable to OB 10-64 and HD 37128.

An inspection of Fig. 4 immediately indicates (albeit in a qualitative manner) that the stellar wind properties of the three objects cannot be very different. For the quantitative wind analysis
of OB 10-64 we proceed exactly in the same way as described by Kudritzki et al. (1999). First, we measure the terminal velocity \(v_\text{w}\) of the stellar wind from radiative transfer fits of the strong UV resonance lines of N V, C IV and Si IV using the method developed by Haser (1995) (see also Haser et al. 1995, 1998; Lamers et al. 1999). This is similar to the technique applied by Howarth et al. (1997). The fit yields \(v_\text{w} = 1650\, \text{km}\, s^{-1}\) for both OB 10-64 and HD167264 (see Fig. 5), which is very close to the value of 1600 km s\(^{-1}\) found for HD 37128.

Subsequently, the mass-loss rate \(M\) can be obtained from a fit of the observed line profile of H\(\alpha\), and Fig. 6 shows a comparison of the OB 10-64 line profile with those of two Galactic B0 Ia stars. This requires a non-LTE unified model atmosphere analysis incorporating the stellar wind and spherical extension (Kudritzki et al. 1999). Assuming a radius of 34 R\(_{\odot}\) and a terminal velocity of \(v_\text{w} = 1650\, \text{km}\, s^{-1}\), we calculated a sequence of unified models with different mass-loss rates. Fig. 7 gives an idea of the accuracy of the line profile fit, which is somewhat restricted due to the central contamination by the H\(\alpha\)-region emission. Despite this, a reasonable determination of the mass-loss rate is certainly possible. Values as low as \(1.0 \times 10^{-6}\, M_\odot\, \text{yr}^{-1}\) can clearly be ruled out together with values above \(1.75 \times 10^{-6}\, M_\odot\, \text{yr}^{-1}\). We adopt \(1.6 \times 10^{-6}\, M_\odot\, \text{yr}^{-1}\) as the model which gives the best compromise fit in Fig. 7. This means that OB 10-64 has a slightly lower mass-loss rate than HD 37128 (2.5 \(\times\)10^{-6}\, M\(_\odot\), \(v_\text{w}\)=1650 km s\(^{-1}\)) (Kudritzki et al. 1999). The modified stellar wind momentum \(M v_\text{w}(R/R_\odot)^{0.5}\), which is expected to be a function of luminosity only, is 28.98 (in cgs units) compared to 29.15 for HD 37128. Fig. 8 compares the modified wind momenta of OB 10-64 and of all the galactic early B-supergiants studied by Kudritzki et al. (1999). Within the intrinsic scatter of the wind momentum–luminosity relationship the agreement is excellent. This is the first direct demonstration that the concept of the WLR works for objects of this spectral type (i.e. early B-types) outside our own Galaxy.

## 4 WOLF–RAYET ANALYSIS

### 4.1 Technique

We use the non-LTE code of Hillier & Miller (1998) which iteratively solves the transfer equation in the co-moving frame subject to statistical and radiative equilibria in an expanding, spherically symmetric and steady-state atmosphere. Relative to earlier versions of this code (Hillier 1987, 1990), two major enhancements have been incorporated, of particular relevance to WC-type stars, specifically (i) line blanketing and (ii) clumping.

Our analysis of OB 10-WR1 follows a method similar to that recently applied to Galactic WC stars by Hillier & Miller (1999). Specific details of the (extremely complex) model atoms used here for our quantitative analysis are provided in Dessart et al. (2000), together with information on the source of atomic data used for He I–II, C II–IV, O II–VI, Si IV and Fe IV–VI. We use an identical (slow) form of the velocity law, such that acceleration is modest at small radii, but continues to large distances. We assume that the wind is clumped with a volume filling factor, \(f\), and that there is no inter-clump material. Since radiation instabilities are not expected to be important in the inner wind, we parametrize the filling factor so that it approaches unity at small velocities. Clumped and non-clumped spectra are very similar, except that line profiles are slightly narrower with weaker electron scattering wings in the former. Although non-clumped models can be easily rejected (Hillier & Miller 1999), because of the severe line blending in WC winds \(M v_\text{w}(R/c)^{0.5}\) is derived by our spectroscopic analysis, rather than \(M\) and \(f\) independently.

### 4.2 Spectroscopic analysis of OB 10-WR1

As usual, a series of models was calculated in which stellar parameters \((T_\text{e}, \log L/L_\odot, v_\text{w}M v_\text{w}/\sqrt{f}, \text{C/He, O/He})\) were adjusted until the observed ionization balance, line strengths, widths, and absolute \(\approx\)-band flux were reproduced. Because of the (substantial) effect that differing mass-loss rates, temperatures and elemental abundances have on the emergent spectrum, this was an iterative process.

The wind ionization balance is ideally selected on the basis of isolated optical lines from adjacent ionization stages of carbon (e.g. C III \(\lambda 6740/C IV \lambda 7700\)) and/or helium (He I \(\lambda 5876/\text{He II} \lambda 5412\)). In practice, this was difficult to achieve because of the severe blending in WC winds, so our derived temperature should be treated as approximate. Current spectroscopic models fail to reproduce the absolute and relative strengths of the WC classification lines at C III \(\lambda\lambda 5696, 5801–12\) (see Hillier & Miller 1998; Dessart et al. 2000). As in other recent spectroscopic studies of WC stars, He II \(\lambda 5412/C IV \lambda 5471\) were selected as the principal C/He diagnostic since the relative strengths of these features are insensitive to differences of temperature or mass-loss rate. Oxygen abundances were impossible to constrain, since the principal diagnostic region spans \(\lambda\lambda 2900–3500\) (Hillier & Miller 1999). Consequently, we adopt \(\text{C/O} \approx 4\) by number as predicted by stellar evolutionary models (Schaller et al. 1992). Based on results obtained for OB 10-64 in Section 3, we shall adopt solar abundances for Si and Fe.

As discussed by Hillier & Miller (1998), many weak spectral features sit upon the continuum so that ideally one would wish to compare synthetic models with fluxed spectroscopy. Since absolute fluxes are unavailable for OB 10-WR1, we have instead rectified the data set, taking care to use as few ‘continuum’ regions as possible.

Our ISIS spectroscopic data of OB 10-WR1 is shown in Fig. 9. Overall, the spectrum is reasonably well reproduced by our model, except that C III \(\lambda\lambda 5696\) and C IV \(\lambda\lambda 5801–12\) are too weak. Nebular emission lines are prominent in the observed spectrum, and contaminate the He II \(\lambda 6560\) and C III \(\lambda\lambda 6740\) stellar lines. We find \(v_\text{w} = 75\, \text{K}\), \(\log L/L_\odot = 5.68 \pm 0.16, v_\text{w} = 3000\, \text{km}\, \text{s}^{-1}\) and \(M v_\text{w} = 10^{-4}\, M_\odot\, \text{yr}^{-1}\), with \(\text{C/He} \approx 0.1\) by number, from He II \(\lambda 5412/C IV \lambda 5471\), despite the low S/N achieved in this region from a single 30-min ISIS exposure. The wind performance number of OB 10-WR1 is \(M v_\text{w}/(L/c) \approx 14\) for our assumed \(f = 0.1\). In order to better constrain the stellar parameters of OB 10-WR1, one would require UV spectroscopy with HST/STIS to permit a reliable reddening determination (the chief source of uncertainty in \(\log L/L_\odot\)), \(v_\text{w}\) via P Cyg resonance lines, and oxygen abundances from the near-IR diagnostics. For \(E(B-V) = 0.18\), the expected UV continuum flux from OB 10-WR1 is \(2 \times 10^{-16}\, \text{erg cm}^{-2}\, \text{s}^{-1}\, \text{Å}^{-1}\) at 3000 Å, or \(1 \times 10^{-15}\, \text{erg cm}^{-2}\, \text{s}^{-1}\, \text{Å}^{-1}\) at 1500 Å, assuming a standard Galactic extinction towards OB 10 (though see Section 2.4).

### 4.3 Quantitative comparison with HD 92809 (WC6)

How do the parameters of OB 10-WR1 compare with WCE counterparts in other galaxies? Amongst Galactic WC6 stars, only HD 92809 (WR23) and HD 76536 (WR14) are moderately...
reddened and lie at established distances (Koesterke & Hamann 1995). Since high-quality flux-calibrated spectroscopy of HD 92809 is available to us (Section 2), we now carry out an identical analysis of it, permitting a quantitative comparison to be carried out. Although numerous Galactic WCE stars have been studied by Koesterke & Hamann (1995), including HD 92809, the inclusion of line blanketing and clumping into models has a major effect on the stellar luminosity and wind density, justifying the need for a re-evaluation of its properties (Dessart et al. 2000).

HD 92809 lies in the Car OB1 association, at a distance of 2.63 kpc, with a narrow v-band Smith magnitude of 9.71 mag. Our spectral synthesis of HD 92809, using methods identical to those described above, indicates a reddening of $E(B-V) = 0.50$ mag [Koesterke & Hamann (1995) obtained $E(B-V) = 0.38$], such that $M_V = -4.08$ mag, substantially lower than OB 10-WR1 ($M_V = -5.4 \pm 0.4$ mag). We adopt $v_w = 2280 \text{ km s}^{-1}$ for HD 92809 following the UV analysis by Prinja, Barlow & Howarth (1990), also somewhat lower than OB 10-WR1. The measured emission equivalent widths of selected lines in the optical spectra of OB 10-WR1 and HD 92809 are listed in Table 6. In general, HD 92809 has similar line equivalent widths to OB 10-WR1, except that the He II $\lambda 5412$/C IV $\lambda 5471$ ratio is much smaller, suggesting a higher carbon abundance. Single WC stars appear to show remarkably uniform emission equivalent widths at each spectral type, oblivious of their stellar parameters or chemistry. For example, Conti & Massey (1989) measured C IV $\lambda 5801$–12 equivalent widths in the range 440–1150 Å for (apparently) single Galactic WC6 stars. Therefore, we can have confidence that OB 10-WR1 is also single.

Our spectroscopic analysis was repeated for HD 92809, with our final UV and optical synthetic spectrum compared with observations of HD 92809 in Fig. 10 [de-reddened by $E(B-V) = 0.50$ mag following the reddening law of Seaton (1979)]. Overall, the comparison is excellent for line strengths and shapes, as is the match to the continuum distribution throughout the spectrum. The number of line features that are poorly reproduced is small, and again includes C III $\lambda 5696$ and C IV $\lambda 5801$–12.

For HD 92089, we derive the following stellar parameters:

<table>
<thead>
<tr>
<th>Factor</th>
<th>Parameter</th>
<th>Value</th>
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</table>
| $T_*$   | $75 \text{ kK}$ | $5.3$, and $M/L \sim 10^{-4.8} \text{ M}_\odot \text{ yr}^{-1}$.
| Fits to | He II $\lambda 5412$ | C IV $\lambda 5471$ imply C/He $\sim 0.3$ by number.
| $M/L$   | $5.3$, and $M/L \sim 10^{-4.8} \text{ M}_\odot \text{ yr}^{-1}$.
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| Fits to | He II $\lambda 5412$ | C IV $\lambda 5471$ imply C/He $\sim 0.3$ by number.
| $M/L$   | $5.3$, and $M/L \sim 10^{-4.8} \text{ M}_\odot \text{ yr}^{-1}$.
5 DISCUSSION

5.1 Comparison of the Galactic and M31 B-supergiants

The differential analysis of the B-types implies that the two stars appear to have very similar chemical compositions. There is some marginal evidence for a small metal enhancement in OB 10-64 but this could, for example, just be an artefact of an overestimation of its equivalent widths from the lower quality spectroscopic data. We believe the differential oxygen abundance to be particularly sound given the 13 features used in the analysis and the relatively small spread in their results. As these are luminous supergiants one must qualify the use of absolute abundance values in any external comparison. For oxygen, magnesium and silicon, however, the abundances derived in HD167264 (distance from Sun, \(1.7 \text{kpc}\); Hill, Walker & Yang 1986) are similar to the absolute values derived in solar-neighbourhood B-type main-sequence stars. The analysis and absolute abundance determination of the dwarfs is more reliable and has been shown to be in excellent agreement with HII regions and the ISM within \(500 \text{pc}\) of the Sun (Gies & Lambert 1992; Rolleston et al. 2000) Hence we can be reasonably confident that the designations of MLD are valid, we conclude that OB 10-64 should also be classified as ‘processed’ and hence at least its carbon and nitrogen abundances may not be representative of its natal composition.

In Section 2.4 we have assumed a distance to M31 of 783 kpc and hence have an estimate of \(M_V = -6.93 \pm 0.4\). The model atmosphere analysis produces a flux distribution for the stellar parameters shown in Table 4, which provides a bolometric correction of \(-2.9\). Hence we determine an \(M_{bol} = -9.83 \pm 0.6\), and \(L/L_\odot = 5.85 \pm 0.24\). This is typical of B-type supergiants (and their possible A-type descendants) as found by Kudritzki et al. (1999), and as illustrated in Fig. 8. A comparison with evolutionary models (see Fig. 13; also Schaller et al. 1992) implies an initial main-sequence mass for the star of approximately \(55\ M_\odot\). Whether the star has just come directly from the main-sequence or is a blue-loop star with a previous history as a red supergiant is unclear. The Schaller et al. models predict that the surface CNO abundances should be drastically altered if the star has been a red supergiant and is in a blue-loop. While we suggest that it may show some

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Figure 10. Comparison between de-reddened \((E(B - V) = 0.50\text{mag})\) IUE/HIRES and MSSSO/DBS spectroscopy of HD 92809 (solid) with our synthetic model (dotted).
evidence of CNO processing, the quantitative values we derive do not appear to support the star having highly processed core material at its surface indicative of a red supergiant origin (where the nitrogen abundance is predicted to be approximately $+1.0\text{ dex}$ higher than normal). Whatever its history, its lifetime is likely to have been of the order $3.5\pm 0.9\text{ Myr}$ (from Schaller et al. 1992), in excellent agreement with the age of the more evolved WR1 star (with age $3.6\pm 0.9\text{ Myr}$, see Section 5.2) suggesting coeval formation in the OB 10 association.

5.2 Comparison between Galactic, LMC and M31 WC stars

Table 7 reveals that the stellar and chemical properties of OB 10-WR1 and HD 92809 differ substantially, despite originating from very similar environments. Following the mass–luminosity relation for hydrogen-free WR stars of Schaerer & Maeder (1992), a present mass of $18\pm 4M_{\odot}$ is implied. In contrast, the stellar luminosity of HD 92809 is typical of Galactic WCE stars with a present mass of $11M_{\odot}$. Depending on the choice of evolutionary model, an age within the range $2.7-4.5\text{ Myr}$ is implied for OB 10-WR1.

Since OB 10-WR1 is visually the brightest (apparently single) WCE star in M31 (Massey & Johnson 1998), it is valid to question whether photometry/spectroscopy of this star is contaminated by bright stars along similar sight lines, particularly since 1 arcsec corresponds to a physical scale of $5\text{ pc}$ at the distance of M31. Excess continuum light would serve to dilute the equivalent widths of the WC emission line spectrum, yet from Table 6, the emission-line strengths of OB 10-WR1 are consistent with the single WC6 star HD 92809. Therefore, in the absence of high spatial-resolution imaging, we can have confidence that the observed continuum flux is principally that of the WC star, such that its stellar luminosity has not been artificially enhanced.

Galactic WCE stars are known to span a range of carbon abundances and luminosity — according to Koesterke & Hamann (1995) $0.1\leq \text{ C/He} \leq 0.5$, and $5.0 \leq \log L/L_{\odot} \leq 5.4$ for stars higher than normal). Whatever its history, its lifetime is likely to have been of the order $3.5\pm 1\text{ Myr}$ (from Schaller et al. 1992), in excellent agreement with the age of the more evolved WR1 star (with age $3.6\pm 0.9\text{ Myr}$, see Section 5.2) suggesting coeval formation in the OB 10 association.

Figure 11. A mosaic of DSS images of M31 tiled together (hence the apparent break in the background), with the position of the OB 10 association labelled as the square. For comparison, the positions of three A–F type supergiants analysed by Venn et al. (2000) are shown, with their other star A-207 lying off this field-of-view in the outer south west corner of M31. North is up, east to the left and the size of the image is $115\times 90\text{ arcmin}$. The three crosses indicate the positions of the three inner disk H II regions analysed by Blair et al. (1982; regions BA75, BA423 and BA289). The length of the double arrow shows $5\text{ kpc}$ at the distance of M31, along the major axis. The projected galactocentric radius of the OB 10 association is $5.9\text{ kpc}$.

Figure 12. Oxygen abundances as a function of distance from the galaxy centre derived in a study of H II regions and the stars so far analysed in M31. The open diamonds are the nebular H II region abundances from Blair et al. (1982), and the line shows the least-squares-fit to these results, giving a gradient of $-0.03\pm 0.01\text{ dex kpc}^{-1}$. We have recalculated the projected galactocentric distances to the H II regions using an updated distance to M31 of 783 kpc. The solid circles are the oxygen results from Venn et al. (2000), from the three A–F type supergiants shown in Fig. 11. The solid star is our photospheric result from OB 10-64, with the error bar representing the standard error in the mean.

Figure 13. The evolutionary tracks from Schaller et al. (1992) are plotted for 15–60$M_{\odot}$ stars, as labelled. The positions of OB 10-64, and WR1 are shown. OB 10-64 appears to have evolved from $\sim 55M_{\odot}$ star, whereas WR1 probably evolved from a more massive object. Given the existence of an evolved star of lower mass than WR1, we can infer limits on the time duration of massive star formation in this cluster.
with established distances, and applying a global scaling of 0.3 dex to account for blanketing (see Section 4.3). Therefore, OB 10-WR1 is amongst the least enriched in carbon, with the highest luminosity. These characteristics are reminiscent of the nearby WC5+OB binary WR146, recently analysed by Dessart et al. (2000) who derived log $L/L_\odot = 5.7$ and C/He = 0.08 by number. Extending the comparison to the LMC WCE stars (all WC4 spectral type), reveals quite different conclusions. In contrast with the Galactic sample, the luminosity of OB 10-WR1 is fairly typical of LMC WC4 stars, spanning $5.4 \leq \log L/L_\odot \leq 6.0$, with comparable C/He abundances established for Brey 10 and Brey 50 (see fig. 4 in Crowther et al. 2000). Therefore, OB 10-WR1 is more typical of WCE stars at relatively low metallicity. A twice-solar metallicity for OB 10 – inferred from H II studies (Blair et al. 1982) – would be very difficult to reconcile with our derived properties of OB 10-WR1.

### 5.3 Probing the chemical composition and evolution of M31

In Fig. 12 we have plotted the oxygen H II region abundances from Blair et al. (1982) showing the abundance gradient they derive, and the position of OB 10-64. We have recalculated the de-projected galactocentric distances of all the objects in this plot by assuming a distance of 783 kpc, an inclination angle of 77.5°, major axis angle of 37.5°, and centre of M31 to be RA(2000) = $00^h$42$m$00$s$, Dec. (2000) = $+41^\circ16^\prime08^\prime07"$ (the latter from Hjellming & Smartt 1982). The galactocentric distance of OB 10 is 5.9 kpc, and the Blair et al. results suggest that the gas metallicity at this position should be significantly above solar ($\approx 9.1$ dex). Our absolute abundance of 8.7 dex is well below this value, and while we acknowledge the difficulty in comparing absolute abundances from different methods we are confident that OB 10-64 does not have a metallicity significantly higher than this value – the star has metal-line strengths and atmospheric parameters very similar to those of the Galactic standard HD 167264 as discussed in Section 5.1.

Venn et al. (2000) have presented an analysis of three other stars in M31 (A–F supergiants) and the oxygen abundances for these are also plotted in Fig. 12. Fig. 11 also shows the spatial positions of the A-type supergiants and OB10 in the M31 disc. We see that the present results strengthen the suggestion of Venn et al. that the abundance gradient of oxygen is quite flat, extending the stellar results into the supposedly metal-rich region interior to $R_g = 10$ kpc. As noted by Venn et al., neglecting the innermost H II regions results in good agreement between the nebular and stellar results, albeit with a negligible gradient, so it is important to try to understand the current discrepancy in the inner region. In the work concerning the H II regions, the observed quantity used to derive [O/H] is $R_{23}$, the ratio $([\text{OIII}]3727+\text{[OII]}\lambda\lambda 4959,5007)/\text{H}\beta$, which is observed to increase with $R_g$. This ratio has been calibrated as a function of [O/H] by a number of authors, and indeed as Venn et al. pointed out, using the calibration of Zaritsky, Kennicutt & Huchra (1994) instead of Pagel et al. (1979), reduces the [O/H] abundance gradient from Blair et al.’s value of $-0.03$ dex kpc$^{-1}$ to $-0.02$ dex kpc$^{-1}$. Indeed, within the range of $R_{23}$ defined by the H II regions in question, 0.0 \leq R_{23} \leq 0.8, there are significant differences between the slopes and absolute values of the various $R_{23}$ versus [O/H] relations (see fig. 11 of McGaugh 1991). In fact McGaugh’s own calibration results in an even flatter gradient than that of Zaritsky et al. (1994), and systematically lower oxygen abundances by 0.1 to 0.2 dex, with the largest difference being at higher metallicities (see Kobulnicky, Kennicutt & Pizagno 1999, equations 9 and 10 for the parametrization). For metallicities above solar there are almost no H II regions for which there are independent estimates of the electron temperature because of the weakness of the [OIII] $\lambda\lambda 4363$ line. Thus the various calibrations in use depend either upon extrapolated empirical relationships, or upon models for which one must make certain assumptions (for example concerning abundances, abundance ratios, model atmosphere fluxes and dust).

Fortunately, Galarza, Walterbos & Braun (1999) have presented new results for M31 H II regions between 5–15 kpc, and three of these are very close to the OB association OB 10 (regions designated K310, K314 and K315). K315 is spatially coincident with OB 10 and we assume that it is sampling the nebula excited by its OB stars. Interestingly, Galarza et al. (1999) discuss their H II regions by morphological type; centre-bright, ring, complex and diffuse, but only those regions defined as centre-bright exhibit a significant gradient in $R_{23}$. Of the regions mentioned above, only K314 is a centre-bright region, it is about 1.5 arcmin away from OB 10-64, and McGaugh’s calibration gives $12 + \log([\text{O/H}] = 8.98$, whereas Zaritzky’s gives 9.17. We can apply these calibrations to all three H II regions mentioned above, plus the five subapertures centred on K315 for which Galarza et al. (1999) also give data, which results in oxygen abundances ranging from approximately 8.7 to 9.0 dex using McGaugh’s calibration, or from 8.9 to 9.2 dex using Zaritzky’s (see Table 8). The former calibration appears to give absolute results in better agreement with the stellar results, indeed our absolute abundance of 8.69 $\pm$ 0.1 agrees within the errors with the McGaugh calibration of 8.7–9.0 dex. We therefore use this relationship to re-derive oxygen abundances using the published H II data from Blair et al. (1982), Dennefeld & Kunth (1981) and Galarza et al. (1999) (centre-bright regions only). A discussion of which calibration is more physically reliable is outside the scope of this paper, however it seems consistent to homogeneously re-derive the abundances from the full observational data set using a single relation. We have chosen the McGaugh calibration simply because it provides better agreement with the OB10 stellar results, but would caution against using any one of these calibrations blindly before more work is carried out on their reliability and the reasons for discrepancies.

These results are shown in Fig. 14 together with the stellar results and the least-squares fit to the nebular results which gives an oxygen abundance gradient of $-0.018 \pm 0.01$ dex kpc$^{-1}$, with an intercept at $R_g = 0.0$ of 9.02 dex. Note that the corresponding values using Zaritsky’s calibration are $-0.025$ dex kpc$^{-1}$ and 9.22 dex, however the gradient determined from H II regions in the inner, possibly metal-rich regions, still depends critically upon the functional form of the calibration used. Clearly this problem can only be resolved by more detailed observations and modelling of these inner regions. The stellar results imply that the [O/H] gradient is extremely flat in the range 5 to 25 kpc. We have not fitted a gradient to the four stars as they are not a homogenous data
spectral data of two massive stars in the young OB 10 association in M31. This represents the most detailed study of hot, massive stars in this galaxy to date, and shows that quantitative extragalactic stellar astrophysics is not only possible with these objects, but is a powerful diagnostic tool advancing our knowledge in several related areas.

Our analyses allows us to probe massive stellar evolution, mass loss and stellar wind characteristics in the most massive, luminous stars in the local Universe. We show that we can determine accurate chemical abundances in B-type supergiants which are probes of the current metallicity of the ISM. Our stellar analysis indicates that the empirical calibration of the $R_{23}$ ratio in H II regions at metallicities of solar and above is not well constrained. Hence when discussing stellar evolution from characteristics of evolved massive stars (WR stars, LBVs, blue and red supergiants) one should be careful to use direct metallicity determinations of the star-forming region – photospheric abundance estimates in massive B-type (and A-type, see Venn et al. 2000) supergiants provide an excellent means of doing so.

We have demonstrated that it is possible to analyse the physical and chemical properties of individual WC stars in M31 using 4-m-class telescopes, although more precise luminosities and abundances await UV spectroscopy. Comparison between OB 10-WR1 and WCE stars in other galaxies, particularly HD 92809 in our Galaxy, reveals that its high luminosity and low C/He ratio is more typical of WCE stars in metal-poor environments, in spite of the low-number statistics. Since OB 10 is in the inner region of the M31 disc ($R_g = 5.9\, kpc$), we would have wrongly concluded that WR1 originated in a very metal-rich region, had we assumed a metallicity from the previous H II region analysis.

We have carried out a detailed wind analysis of the B-type supergiant and (assuming previously determined distances to M31) find its wind momentum–luminosity relationship to be in excellent agreement with similar Galactic early B-type stars. This is a further indication (cf. Kudritzki et al. 1999) that a properly calibrated wind momentum–luminosity relationship within the Local Group may allow accurate distance moduli to be determined to the most luminous stars in galaxies within $\sim 20\, Mpc$. In further papers we will analyse a larger set of M31 A and B-type supergiants, extending the radial baseline from the central to regions to $R_g \geq 20\, kpc$.

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**Table 8. H II regions observed by Galarza et al. (1999) in the vicinity of OB 10; note that K315 is coincident with the position of OB 10-64 for which we obtain an oxygen abundance of 8.7 dex. Derived abundances [O/H]_Z and [O/H]_M refer to the use of the calibrations of Zaritsky et al. (1994) and McGaugh (1991) respectively.**

<table>
<thead>
<tr>
<th>H II region identifier</th>
<th>Morphological type</th>
<th>log($R_{23}$)</th>
<th>[O/H]_Z</th>
<th>[O/H]_M</th>
</tr>
</thead>
<tbody>
<tr>
<td>K310</td>
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<td>9.00</td>
<td>8.85</td>
</tr>
<tr>
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<td>9.17</td>
<td>8.98</td>
</tr>
<tr>
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<td>8.90</td>
</tr>
<tr>
<td>K315a</td>
<td>diffuse</td>
<td>&lt;0.23</td>
<td>&gt;9.16</td>
<td>&gt;8.98</td>
</tr>
<tr>
<td>K315b</td>
<td>diffuse</td>
<td>0.23</td>
<td>9.16</td>
<td>8.98</td>
</tr>
<tr>
<td>K315c</td>
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<td>K315e</td>
<td>ring</td>
<td>0.63</td>
<td>8.84</td>
<td>8.69</td>
</tr>
</tbody>
</table>

**Figure 14. All H II region results from Blair et al. (1982; diamonds); Dennefeld & Kunth (1981; triangles); Galarza et al. (1999; crosses) using the calibration of McGaugh (1991). Stellar points are represented by filled symbols as in Fig. 12. The straight line represents a least squares fit to the nebular data giving a gradient of $-0.018 \pm 0.01$ dex kpc$^{-1}$.**

6 CONCLUSIONS

We have carried out detailed, quantitative analyses of high-quality set in terms of their atmospheric parameters and analysis methods; the star analysed here is a B-type supergiant, while that at 12 kpc are A-type supergiants, while that at 22 kpc is an F-type supergiant. Certainly, more stellar observations are clearly required, as any gradient which does exist may be masked by statistical scatter or real variations at any particular $R_g$.

Without the analysis presented here for OB 10-64, we would have assumed that the initial metallicity of OB 10-WR1 was much higher than solar, and that the wind analysis and stellar evolution discussion would have been based on quite different parameters. This indicates that one must be careful in assuming an initial metallicity determined from global galactic properties when characterizing the evolution of single evolved stars, especially WR stars. It is necessary to use more direct methods to determine the state of the natal gas in the environment of the cluster formation.

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