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The distinction between O Iafpe and WNLha stars

A spectral analysis of HD 151804, HD 152408 and HDE 313846

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Abstract. From detailed atmospheric analysis of the Galactic late O supergiants, HD 151804 (O8 Iaf) and HD 152408 (O8: Iafpe) and the morphologically related Wolf-Rayet star, HDE 313846 (WR108; WN9ha) we conclude that little distinguishes the overall structure and composition of the stellar atmosphere of HD 152408 from HDE 313846, such that HD 152408 could be considered to be a W-R star equivalent to HDE 313846.

Our quantitative spectroscopic analysis uses ultraviolet (*IUE*), optical (AAT, Mt. Stromlo) and infrared (UKIRT, CTIO) spectroscopy and is based on model atmospheres obtained with the iterative scheme of Hillier (1990). Stellar properties for all three stars are quite similar: log $L_*/L_\odot \approx 5.8$, $R_*/R_\odot \approx 35$, $-4.9 \leq \log\ \dot{M}/M_\odot \mathrm{yr}^{-1} \leq -4.5$, $955 \leq v_\infty \leq 1445\,\mathrm{km\,s}^{-1}$. Spectroscopic mass-loss rates are in excellent agreement with radio methods and are more representative of late WN (WNL) stars than O-type supergiants.

From this comparison we find that the O and WNL spectral classifications are distinguished principally by surface mass flux ($\dot{M}/4\pi R_*^2$), with stellar temperature and surface helium content secondary effects. Since surface chemical abundances do not necessarily define the core energy production mechanism – a commonly used distinction between O and WR types – we argue caution when comparing observed O:WNL ratios with theoretical predictions and inferring stellar evolution in various galaxies.

The increasing helium content of the programme stars – O8 Iaf (y=N(He)/[N(H)+N(He)]=0.20), O8: Iafpe (y=0.40) and WN9ha (y=0.45) – is strongly indicative of a direct evolutionary connection from O8 If⇒WN9ha without passage through an intermediate Luminous Blue Variable phase, contrary to current evolutionary theory, and suggestive of additional processes (e.g. rotation) bringing processed material to the surface. The high helium content of HD 151804 confirms previous findings that Of stars are helium enriched by core processed material.

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1. Introduction

Conti (1976) suggested that the observed continuity in spectral morphology from Of to WN-sequence Wolf-Rayet (W-R) stars represented evidence for the evolution of massive stars from spectral type Of to WN. However, direct evolution from Of to WN stages is not considered to be feasible, except for the most massive ($M_{\rm initial} \gtrsim 120\ M_\odot$) stars (Maeder 1982) where mass loss rates are sufficiently high to peel away the required mass. For stars with $M_{\rm initial} \gtrsim 50\ M_\odot$, observed mass loss rates appear to be so low that these stars must pass through a Luminous Blue Variable (LBV) phase to lose enough mass so that they can enter the W-R sequence at the late WN (WNL) stage.

The evolutionary path between Of and WN stars is crucial to understanding massive star evolution since these distinct spectral types have been identified with quite different core nuclear processes. Of stars are assumed to be core hydrogen burning while those stars with WN classifications have long been identified as core helium burning objects with very little hydrogen in their atmospheres (Smith 1973). This definition has been used essentially unchanged to relate stages in the theoretical modelling of the evolution of massive stars (e.g. Maeder & Meynet 1987) to observed spectral types. While *evolutionary* models readily distinguish core helium-burning 'stars' from their core hydrogen-burning precursors, purely *morphological* techniques do not enable a clear distinction. For those W-R stars containing significant *surface* hydrogen, typically WNL, the identification of the end of *core hydrogen* burning can only be obtained by resorting to comparison of accurate spectroscopic analysis with detailed models of stellar interiors.

Lamers & Leitherer (1993) found a continuous progression in wind density from normal O stars, through Of stars to the WNL types. The FWHM and equivalent width of He II λ4686 –

an indicator of the wind strength in Of and WN stars and common criteria to define the classes – show a blending between Of and WN stars instead of a clear separation (Bohannan 1990). It is hardly surprising that no distinct separation has been agreed upon at the extrema of the Of and WN classifications. Indeed, the distinction between the 'least extreme' Wolf-Rayet star from the 'most extreme' Of star is often in the eye of the beholder (Conti & Bohannan 1989). For example, Walborn (1982) was not able to readily distinguish HDE 313846 (WR108), then classified as WN9 (van der Hucht et al. 1981; now classified WN9ha[1] by Crowther et al. 1995a, hereafter Paper I) from HD 152408 (O8: Iafpe; Walborn 1972), with both objects showing composite Of and WN characteristics.

Recently, in our studies of WNL stars (Paper I; Crowther et al. 1995c, hereafter Paper III) we concluded that the least extreme Wolf-Rayet stars, those classified as WNLha have evolved *directly* from Of stars. Specifically we proposed in Paper I that HDE 313846 (WN9ha) has evolved directly from a massive, late-type Of ancestor. Because of morphological similarity, HD 152408 (O8: Iafpe) was identified as a possible prototype of the precursor to the current state of HDE 313846.

In this paper we present detailed atmospheric analyses of HDE 313846, HD152408 and a less extreme Of star, HD 151804 (O8 Iaf; Walborn 1972) in order (i) to investigate the physical differences between stars with Of and WN classifications, and (ii) to test our evolutionary scenario in light of the recent calculations by Langer et al. (1994) and suggestions by Nota et al. (1996) on the evolution of massive stars. In Sect. 2 we present our ultraviolet, optical and infrared observations of the programme stars. In Sect. 3 our analysis technique is introduced, spectroscopic analysis performed and results discussed. In Sect. 4 we consider the proper classification of HD 152408 (OIafpe or WN9ha), compare our results with previous studies of Of and WN stars and discuss the broader evolutionary implications of our findings.

2. Observations

We first discuss the ultraviolet, optical and infrared spectroscopy, photometry used in this study.

2.1. Optical spectroscopy

New optical observations of HD 152408 and HD 151804 have been obtained using the 3.9m Anglo-Australian Telescope (AAT), New South Wales, Australia and 74″ (1.9m) telescope at Mount Stromlo Observatory (MSO), Canberra, Australia.

In 1995 April we have obtained AAT−UCL echelle spectrograph (UCLES) observations using the 31.6 l/mm grating and a Tektronix CCD (1024×1024, 24 μm pixels). Complete spectral coverage between $\lambda\lambda$3820–7330 required three echelle settings. A slit width of 1.5″ yielded a spectral resolution in the extracted spectra of 0.10–0.19 Å, as measured from the widths of Th-Ar arc lines. The CCD frames were bias-subtracted, and the echelle orders were then optimally extracted using the software package ECHOMOP (Mills & Webb 1994). Subsequent analysis was performed using the DIPSO (Howarth et al. 1995) package. Optical observations of HDE 313846 have previously been obtained at the AAT−UCLES with an identical setup (except a slit width of 2″) in 1993 May and have been described in Paper I.

Table 1. Measured equivalent widths (W_λ in Å) and mean systemic radial velocities (in km s^{-1}) for selected optical profiles in our programme stars based on AAT−UCLES observations

HD(E)		151804		152408		313846	
λ	ident.	W_λ em.	abs.	em.	abs.	em.	abs.
3889	He I(2)+H I	0.24	0.43	1.12	0.52	2.09	0.29
4088–4116	Si IV(1)	0.15	0.60	0.83	0.25	0.88	0.28
4097–4103	N III(1)+Hδ	0.29	1.38	1.85	1.41	1.97	0.92
4340	Hγ+He II	0.07	0.81	0.87	0.35	0.73	0.27
4378	N III(18)	...	0.09	0.15	0.04	0.40	...
4472	He I(14)	0.05	0.73	0.56	0.96	0.66	0.61
4485–4504	?	0.50	...	0.70	...	0.54	...
4634–4641	N III(2)	1.69	...	3.48	...	6.05	...
4647–4651	C III(1)	0.10	0.03	0.60	...	1.55	...
4686	He II	0.68	...	3.08	...	5.81	...
4860	Hβ+He II	0.84	0.16	3.70	...	2.77	...
4921	He I(48)	0.02	0.13	0.28	0.03	0.25	...
5320–5327	N III(21)	0.17	...	0.62	...	0.93	...
5412	He II	...	0.55	...	0.40	0.53	0.27
5696	C III(2)	0.90	...	0.65	...	0.94	...
5876	He I(11)	0.25	1.30	3.26	1.85	3.96	1.50
6562	Hα+He II	11.20	...	25.07	...	23.35	...
6667–6700	Si IV(3.02)	0.41	...	0.73	...	0.75	...
6678	He I(46)	0.05	0.13	1.31	...	1.38	...
	$v_{\rm rad}$ (σ)	+30 (14)		+33 (8)		−2 (11)	

Our MSO observations of HD 151804, HD 152408 and HDE 313846 were obtained in 1995 June with the coudé spectrograph, 32″ camera, Tektronix CCD (2048×2048, 24μm pixels) and 600 l mm^{-1} grating. This setup resulted in a dispersion of 0.49Å pixel^{-1} and a spectral resolution of 1.1–1.3Å, as measured from the widths of Cu-Ar arc lines, using a 300μm slit. Three grating settings for each star allowed near complete spectral coverage between $\lambda\lambda$3860–6640. The CCD data were bias-corrected, flat-fielded and then optimally extracted using the PAMELA (Horne 1986) routines within FIGARO (Meyerdierks 1993). A spectrophotometric standard (HD 60573, Walsh 1993) was used to calibrate the stellar spectra. Once calibrated, the spectra were rectified using low order polynomials and provided a valuable check on the reliability of our echelle data reduction.

Our new AAT and MSO observations are in good agreement with high resolution optical observations from the intensive monitoring campaign on HD 152408 by Prinja & Fullerton (1994) and on HD 151804 by Prinja et al. (1996) obtained in 1992 July at the 1.5m CTIO telescope and echelle spectrograph. Overall, our spectra compare reasonably well with those presented by Nota et al. (1996). However, where the two datasets are

[1] We follow the latest WN spectral classification scheme of Smith et al. (1996) for the WNL+abs (= WNLha) stars, and follow the nomenclature of Crowther & Smith (1996b) for the WN9–11 sequence

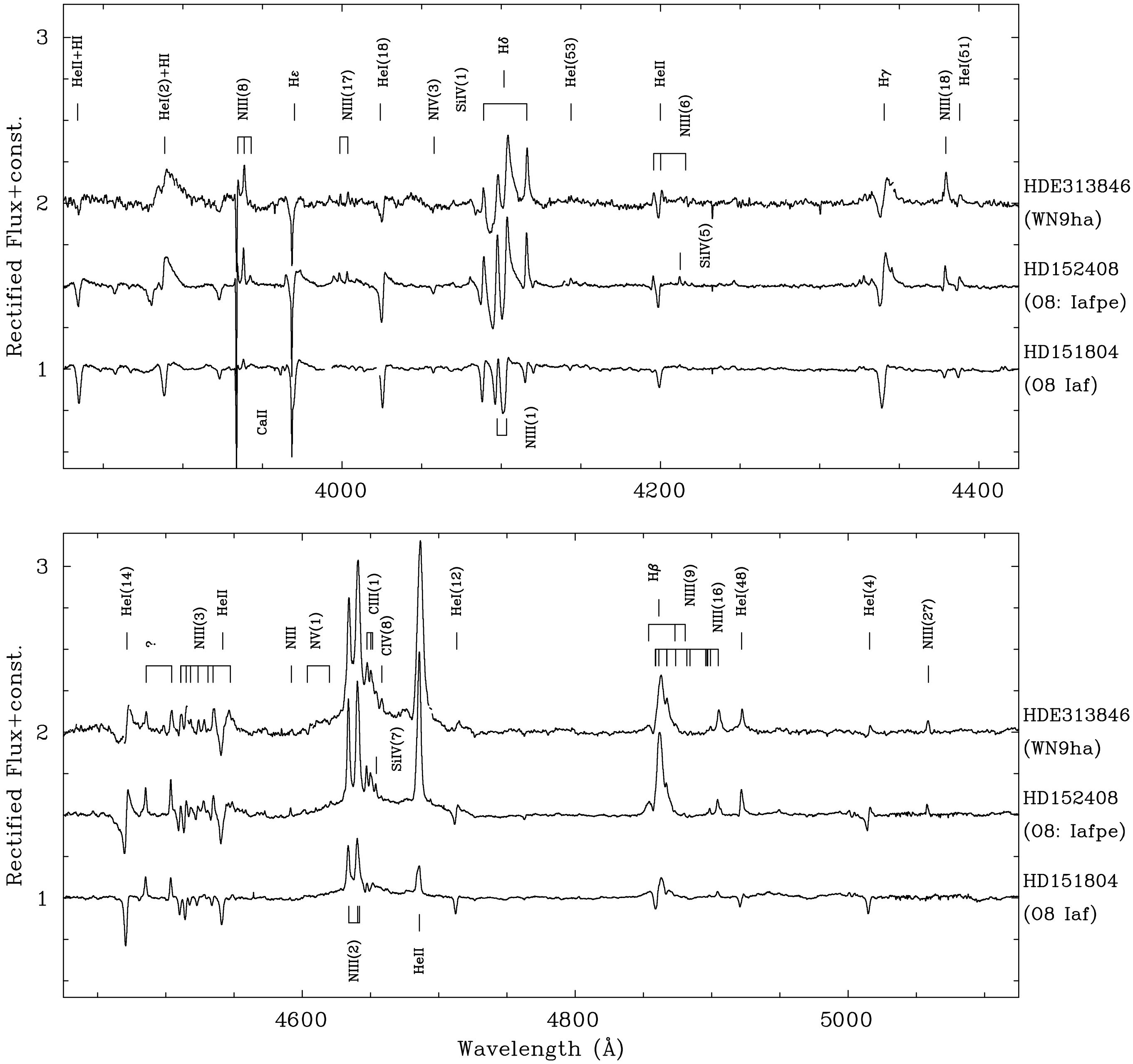

Fig. 1a. Comparison of AAT−UCLES optical spectra HD 151804 (O8 Iaf), HD 152408 (O8: Iafpe) and HDE 313846 (WN9ha). Multiplet numbers are shown in parenthesis. Successive stars are shifted vertically by 0.5 continuum units for clarity

discrepant, we have greater confidence in our method of recovering the true spectral shape through use of flux calibrated spectra. For example, Nota et al. (1996) obtain Hα emission equivalent widths of 12.0Å and 9.1Å for HD 152408 and HD 151804, respectively, in contrast to 25.1Å and 11.2Å measured here, 23.6Å and 11.8Å from Prinja & Fullerton (1994) and Prinja et al. (1996), and 34.7Å and 13.2Å from Conti (1974).

AAT−UCLES spectra of HD 151804, HD 152408 and HDE 313846 covering $\lambda\lambda$3825–6825 are presented in Fig. 1a(parts a and b). In addition to the usual hydrogen and helium profiles, many metal lines are also observed, the strongest of which are familiar in Of stars, such as N III $\lambda\lambda$4097–4103, $\lambda\lambda$4634–41, C III λ4647–51, λ5696, $\lambda\lambda$6727–6762 and Si IV $\lambda\lambda$4088–4116, $\lambda\lambda$6667–6701. Numerous weak profiles are observed both in emission (e.g. N III λ4379, $\lambda\lambda$5320–5324, λ6395, C IV λ4658 in HDE 313846) and absorption (e.g. N IV λ4058 and N V $\lambda\lambda$4603–20 in HDE 313846).

The familiar 'unidentified' features observed in O6–O9.7 supergiants (and WN9–11 stars as well) at 4485.65±0.14Å and 4504.27±0.20Å (corrected air wavelengths) are prominent in our programme stars These features have been tentatively identified with C III from their correlation with λ5696 emission

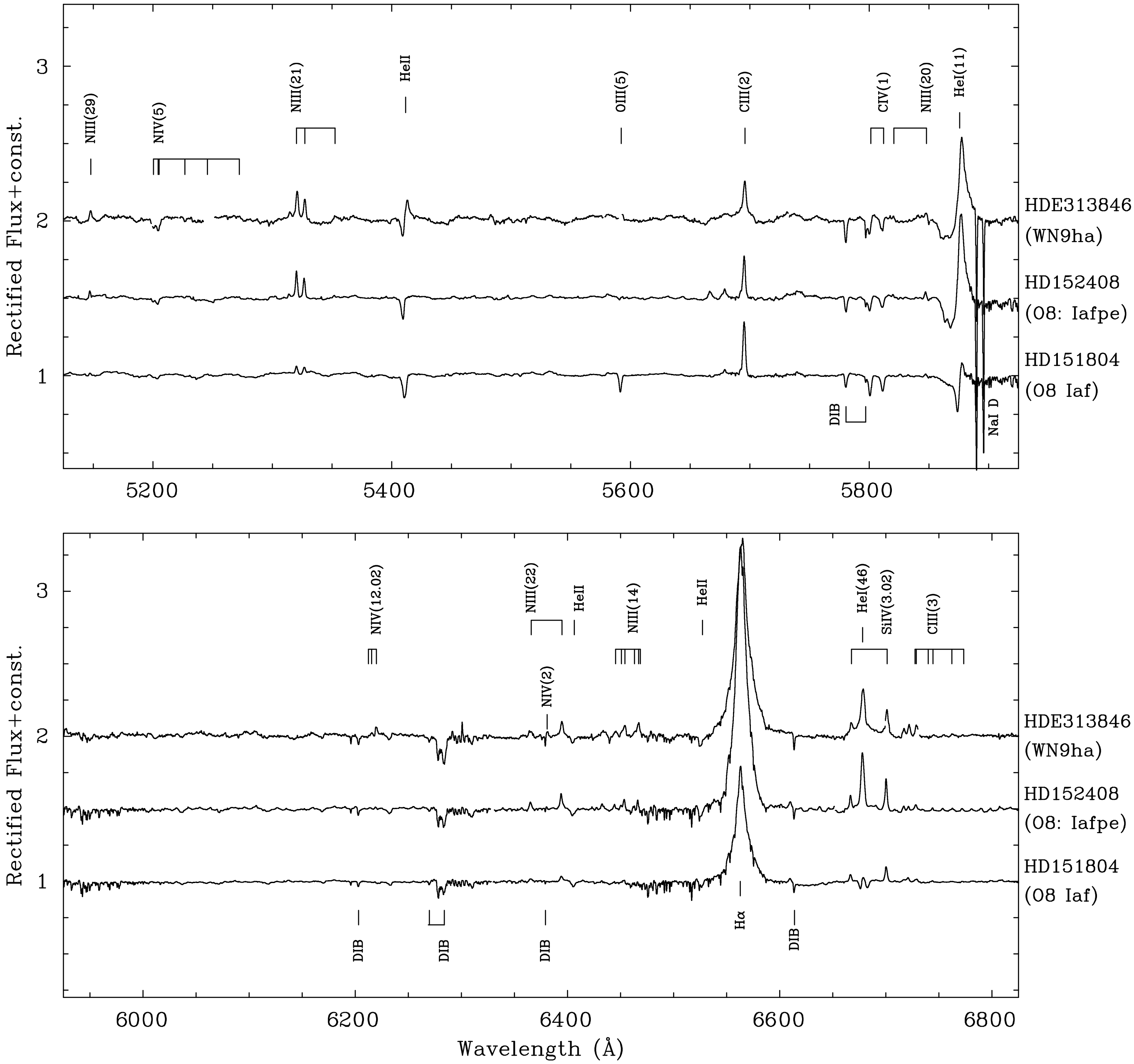

Fig. 1b. Comparison of AAT−UCLES optical spectra of HD 151804, HD 152408 and HDE 313846 (continued)

(Conti 1973), although this has remained unsubstantiated. More recently, Underhill & Gilroy (1990) proposed their identity as dielectronic transitions of N III, for which many experimentally identified lines lie close to these wavelengths, such as $5g'^4F_{3/2}$–$4f'^4D_{1/2}$ (λ4486.34) and $5g'^4F_{7/2}$–$4f'^2D_{5/2}$ (λ4503.87) from Hallin et al. (1976). However, a mechanism that would allow two such dielectronic transitions to be preferentially observed is not currently known, so that a convincing identification for these features remain uncertain.

Mean systemic radial velocities, $v_{\rm rad}$, are given in Table 1, based on sharp, metal emission features arising from regions close to the stellar photosphere, together with line equivalent widths (W_λ) for selected profiles. These mean radial velocities are essentially that measured by Prinja & Fullerton (1994) and Prinja et al. (1996) for HD 152408 (+40.3 km s^{-1}) and HD 151804 (+30 km s^{-1}), respectively.

Fig. 2 shows selected wind profiles for HD 151804, HD 152408 and HDE 313846. The extreme nature of their stellar winds are emphasised by the significant emission observed at He II λ4686, He I λ5876 and Hα. Of these, He II λ4686 is very sensitive to the stellar temperature, while He I λ5876 and Hα are the principal optical indicators of mass-loss. The usual O star diagnostics, He I λ4471 (Fig. 1aa) and He II λ4542 (Fig. 2) are so affected by wind contamination that the spectral classifica-

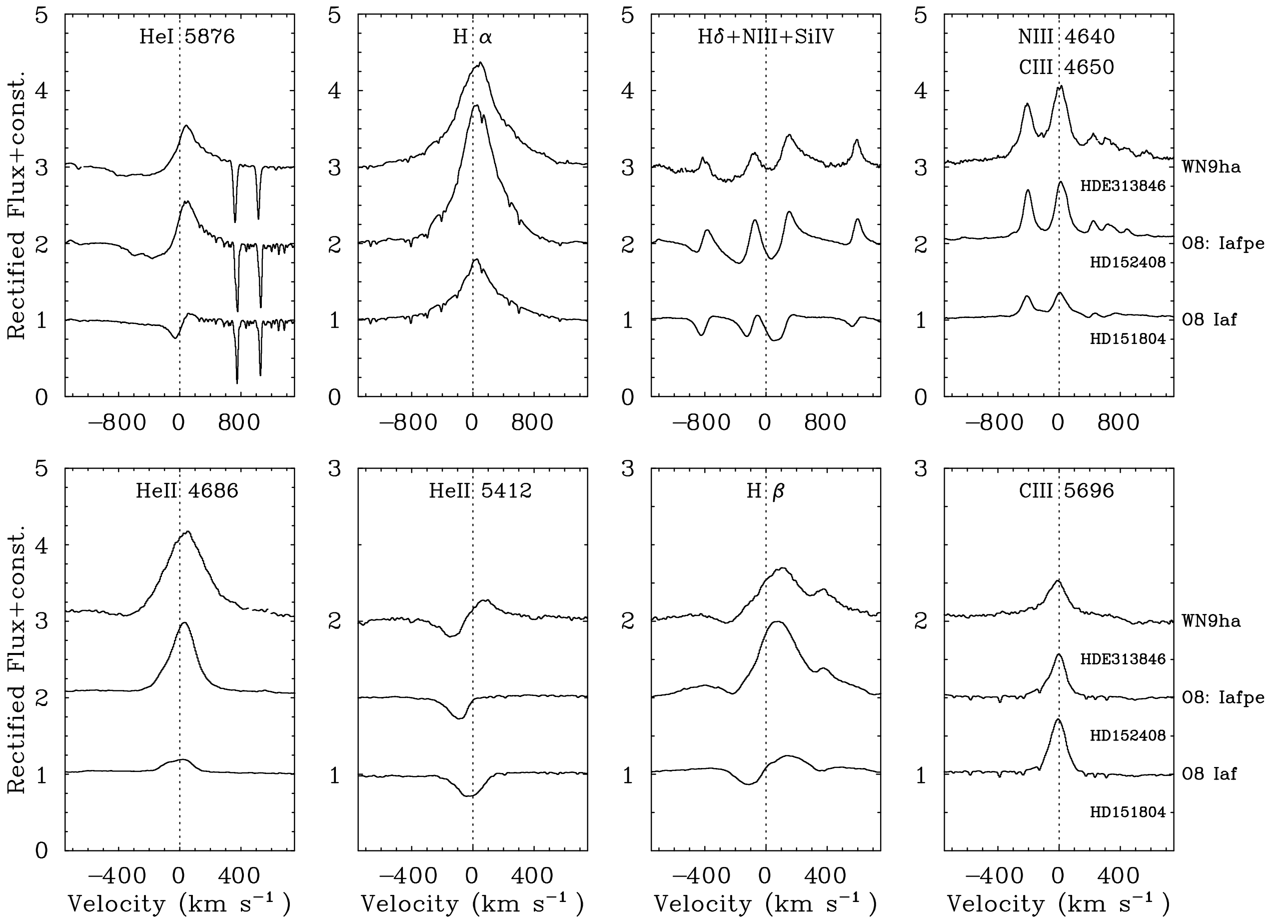

Fig. 2. A comparison of selected AAT−UCLES profiles (radial velocity corrected) for HD 151804 (O8 Iaf), HD 152408 (O8: Iafpe) and HDE 313846 (WN9ha). He II λ5412 (absorption or P Cygni) differentiates between Of and Wolf-Rayet spectroscopic classifications, although significant wind contaminations to this profile are observed in the Ofpe star. We identify the feature at λ4867 on the red wing of Hβ as a component of multiplet No. 9 of N III ($\lambda\lambda$4859–4897) – compare with the closely related behaviour of Si IV λ4116

tion of these stars should only be considered as morphological indicators of their spectra, not of their stellar properties. The difficulty in the spectral classification of stars close to the Of–WN 'boundary' has previously been discussed by Walborn (1982), Conti & Bohannan (1989) and in Paper I. In particular, we found in Paper I that a subtle, though significant morphological difference between these stars was that He II λ5412 is observed as a P Cygni wind profile for HDE 313846, justifying a WN9ha classification. In contrast, He II λ5412 in HD 152408 is in absorption, consistent with an OIafpe classification. This feature in HD 152408 is though clearly contaminated by the wind since the minimum of the absorption profile is blue shifted by $\sim$120 km s^{-1} from the systemic velocity defined by sharp emission features arising close to the photosphere.

2.2. Infrared spectroscopy

Infrared spectroscopic observations allow direct measurements of Wolf-Rayet terminal wind velocities and provide tight constraints on surface chemistries (e.g. Crowther & Smith 1996a). For our analysis of HD 152408 and HD 151804 we have used K-band infrared spectroscopy (2.02–2.23μm) from the CTIO 4-m + Ohio State Infrared Imager/spectrometer (OSIRIS) ($\lambda/\Delta\lambda\sim$1300), observed in 1993 September by Hanson & Conti (1994) and kindly made available to us. New observations of HD 152408 from the AAT in 1994 April covering λ9600–11200 have also been obtained, using the RGO spectrograph with a 600H grating in first order and Tektronix CCD resulting in a spectral resolution of 3.8Å as measured from arc lines. Previous I-band data of HDE 313846 of Howarth & Schmutz (1992) used in Paper I have been combined with new U.K. Infrared Telescope (UKIRT) cooled grating spectrograph (CGS4) data obtained in 1994 August using the 300mm camera, a 75 l/mm grating (1.03–2.21μm, $\lambda/\Delta\lambda$=600–850) and a 62$\times$58 InSb array. The reduction technique of these spectra is identical to that discussed by Crowther & Smith (1996a).

The K-band spectra (Fig. 3) clearly show that the morphological similarities amongst these objects seen in the visible is also apparent in the infrared. HD 151804 again has the weakest wind signature and only minor differences are observed

Table 2. Optical and IR photometry and absolute magnitudes of the programme stars. All values are shown in magnitudes with the true distance modulus denoted by $m-M$. The absolute magnitude was calculated with R=A_V/E_{B-V}=3.2. Interstellar reddenings are derived from fitting of theoretical energy distributions with observed spectrophotometry or broad-band photometry

HD(E)	V	B−V	J	H	K	L	M	8.7μm	N	Ref.	E_{B-V}	$m-M$	Ref.	M_V
151804	5.22	0.07	5.06	4.92	4.86	4.71	4.72	–	4.38	b,c	0.32	11.4	a	−7.19
152408	5.77	0.16	5.21	5.02	4.92	4.65	4.59	4.15	4.14	b,f	0.42	11.4	a	−6.97
313846	10.16	0.68	7.75	7.40	7.13	6.76	6.67	6.45	–	d,f	1.15	13.5	e	−7.02

(a) Humphreys 1978; (b) Leitherer & Wolf 1984; (c) Abbott et al. 1984; (d) Williams et al. 1987; (e) Paper I; (f) Barlow & Cohen 1995

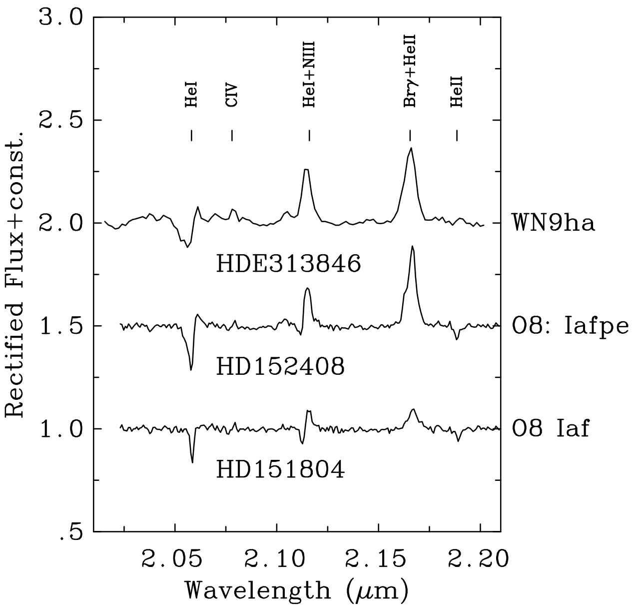

Fig. 3. K-band spectra of HD 151804, HD 152408 (both CTIO–OSIRIS observations from Hanson & Conti 1994) and HDE 313846 (from UKIRT–CGS4 data taken in 1994 August). The principal – though minor – morphological difference between these stars is that He II λ2.1885 (10–7) is observed weakly in absorption in the Of and Ofpe stars and is apparently a weak P Cygni line in HDE 313846

between HDE 313846 and HD 152408. Weak He II 2.189μm (10–7) absorption profiles are observed for HD 151804 and HD 152408, while HDE 313846 shows a shallow P Cygni profile. Also, the He I–N III 2.116μm blend shows a P Cygni profile for HD 151804 and HD 152408, with pure emission in HDE 313846.

2.3. Ultraviolet spectroscopy

The stellar winds of hot, massive stars are most readily observed in the ultraviolet through numerous resonance lines with P Cygni profiles located between $\lambda\lambda$1000–1600 (e.g. Si IV, C IV and N V). Since both of the Of stars are bright and only moderately reddened, *Copernicus* OAO (Hutchings 1976) and *International Ultraviolet Explorer (IUE)* high resolution (HIRES, Walborn et al. 1985) spectra are available. Archive HIRES *IUE* observations for both HD 152408 (SWP15219) and HD 151804 (SWP9269) have been kindly provided by Dr R.K. Prinja. HDE 313846, on the other hand, is faint and heavily reddened. Low-resolution (LORES) *IUE* spectrophotometric observations were obtained from the *IUE* archive at the World Data Centre at the Rutherford Appleton Laboratory for HDE 313846 (and for the O stars as well), which are useful for interstellar reddening determinations and reduced using the IUEDR software (Giddings et al. 1994).

The selected P Cygni profiles for HD 151804 and HD 152408 plotted in Fig. 4 well illustrate the extreme nature of their stellar winds relative to normal O stars. The intense wind (and probable nitrogen enrichment) of HD 152408 is further indicated by strong N IV λ1486] and λ1719 emission (cf. Walborn et al. 1985).

2.4. Photometry and absolute magnitudes

Extensive wide-band optical and infrared photometry for all three programme stars can be gleaned from various sources. We present photometric measurements in Table 2 together with distance moduli, absolute magnitudes and interstellar reddenings. The interstellar redding is measured from theoretical continuum fits to observed UV and optical spectrophotometry and IR photometry (Fig. 5). Typical uncertainties in E_{B-V} for this method are $\pm$0.03 mag with resultant errors of $\pm$0.1 mag in derived absolute magnitudes. While the distance to Sco OB1 (containing HD 151804 and HD 152408) is fairly well known (Humphreys 1978), that to HDE 313846 is more uncertain (Paper I). Previous reddening estimates of E_{B-V}=0.47 for HD 152408 and E_{B-V}=0.35 for HD 151804 by van Genderen et al. (1984) are in reasonable agreement with our derived values.

3. Spectroscopic analysis

3.1. Method

The calculations used here are based on the iterative technique of Hillier (1987, 1990) which solves the transfer equation in the co-moving frame subject to statistical and radiative equilibrium in an expanding, spherically-symmetric, homogeneous, steady-state atmosphere. Further details of the model atmospheres and the method applied to obtain line profile matches are given in Paper I, although we now use a stark broadening profile, instead of a gaussian, for suitable absorption lines. Our adopted model atom has a total of 108 levels (523 non-LTE transitions) with hydrogen (H I n=1–10) and helium (He I n=1–10, He II n=1–

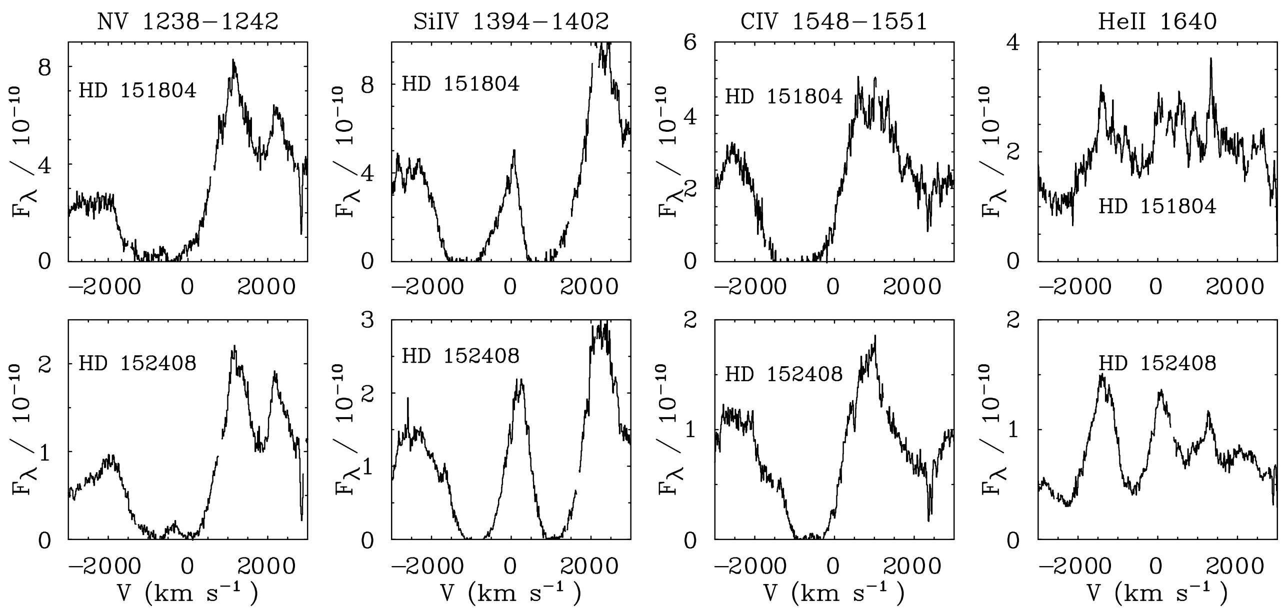

Fig. 4. Selected ultraviolet *IUE* P Cygni profiles for HD 151084 and HD 152408 (N V $\lambda\lambda$1238–42, Si IV $\lambda\lambda$1394–1402, C IV λ1548–51 and He II λ1640) demonstrate the extreme nature of the winds of these objects. As in the optical region the He II signature in HD 152408 is clearly much more prominent than in HD 151804

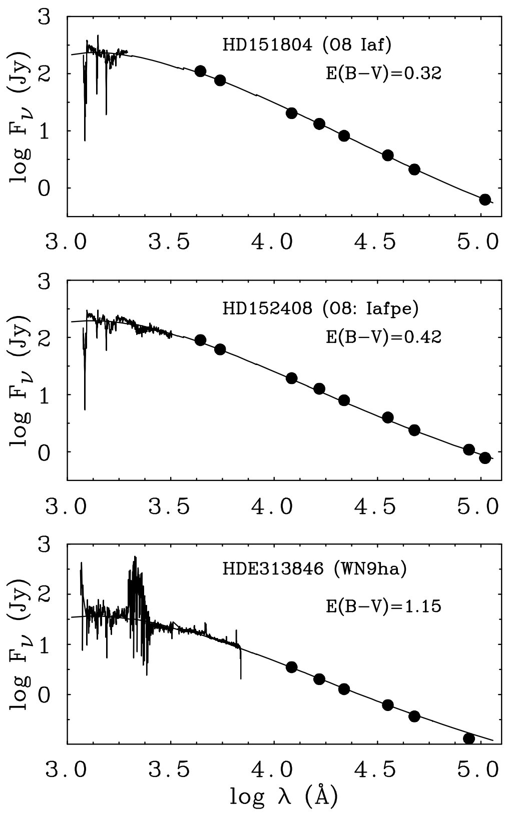

Fig. 5. Theoretical continuum fits to observed UV (LORES *IUE*) and optical (Torres-Dodgen & Massey 1988) spectrophotometry and wide-band photometry for our programme stars

16) treated in detail, with individual states of He I considered up to n=7 (individual levels for $l \geq$3 are grouped together), above which they are combined into singlets and triplets.

Stellar parameters are determined by fitting theoretical profiles of hydrogen (Hα), He I (λ5876) and He II (λ4686, λ10124) to the observed profiles. Estimates of the accuracy of the stellar parameters obtained here have been discussed in Paper I: log $T_{\rm eff}$, log $L/\dot{M}$ and H/He ratios are reliable to ±0.05 dex, ±0.1 dex and ±0.5 (by number), respectively.

The stellar radius (R_*) – defined as the inner boundary of the model atmosphere – is located at a Rosseland optical depth of 20. The stellar temperature (T_*) is related to (R_*) by the Stefan-Boltzmann relation. Similarly, the effective temperature ($T_{\rm eff}$) is determined at the radius ($R_{2/3}$) at which the Rosseland optical depth equals 2/3.

Terminal wind velocities for HD 151804 and HD 152408 were measured by Prinja et al. (1990) from the blueward edge of the ‘black’ absorption trough in the ultraviolet P Cygni resonance profiles of Si IV and C IV to be 1445 km s^{-1} and 955 km s^{-1}, respectively. Due to the large interstellar extinction towards HDE 313846, high resolution *IUE* spectroscopy is not available; we used the terminal velocity measured by Howarth & Schmutz (1992) from the infrared metastable He I λ10830 profile, 1170 km s^{-1}.

Carbon (C III-IV) and nitrogen (N II-V) are included in these model atmospheres to allow for their effect on wind cooling (Hillier 1988), though metal abundances are not explicitly determined. We have previously estimated nitrogen and carbon abundances for HDE 313846 (Paper I). From morphological similarities we assume an identical nitrogen enrichment of HD 152408 and HDE 313846 (N/He=0.005 and C/N=0.1 by number). This assumption was supported by our detailed modelling, when corrected for the lower metallicity of Sco OB1. As our analysis implies, HD 151804 possesses a somewhat lower surface helium content, so we assume a 50% lower nitrogen enrichment (N/He=0.0025, C/N=0.2) for this star.

As was the situation in Paper I all of observed line profiles of HDE 313846 could not be reproduced simultaneously using either a standard (β=1) or a slow (β=2) velocity law (Eqn.[1] from Hillier 1988). We have found that using a velocity law described by a standard β=1 and slow β=2.5 law, weighted towards the latter, and a turbulent velocity of 50 km s^{-1} yield improved fits to the observations. Fig. 6(a) shows the adopted velocity distribution for HD 152408 compared to the standard laws as a function of Rosseland optical depth ($\tau_{\rm R}$). The derived temperature distribution is compared with a grey distribution in Fig. 6(b) and line formation regions of He II λ4686, He I λ5876 and Hα are shown in Fig. 6(c). These lines are typically formed between 1.5–3 R_* and at log (N_e/cm^{-3})=11$\pm$0.5. Similar quantities for HD 151804 are presented by Prinja et al. (1996). In addition, when using λ4686 (4–3) as our He II diagnostic, we could not reproduce the strength of λ10124 (5–4), which casts unknown uncertainty on the use of λ5412 (7–4) profile as a diagnostic. The origin of this defect in the model line profiles remains unknown, though to investigate the effect on the resulting stellar parameters of the differing diagnostics we have calculated two distinct models based on the two profiles, Model A using λ4686, and Model B with λ10124. We do not present this analysis for HD 151804 as we do not yet have observations of He II λ10124.

As is the case with other W-R spectroscopic analyses, our wind models do not account for absorption components of some He I and He II lines arising from the underlying hydrostatic photosphere. In particular, we have not attempted to model absorption lines such as He II λ4542, the critical O-star classification feature. Conti et al. (1977) found that all absorption lines for both of the Of stars studied here were moving outward with non-negligible velocities ($\approx$10 km s^{-1}), a result which suggests that these lines are affected by the dense stellar winds flowing outward from these stars. Since our chosen optical and infrared diagnostics are dominated by the stellar wind we are confident that this inadequacy is not crucial to our conclusion, although is an interesting topic to be addressed in future work.

Our present models do not include line blanketing. In our studies of W-R stars (e.g. Paper II) we have identified problems with simultaneously reproducing high (N V) and low (He I) excitation features, an effect attributed to the neglect of line blanketing. Blanketing will lead to a higher ionization in the inner part of the atmosphere and a lower wind ionization in the outer regions (Hillier 1995). Since the effect of blanketing increases with higher excitation and mass-loss rates, the neglect of blanketing is less critical for late Of and WNLha stars than for normal W-R stars, an assumption consistent with the small effect of line blanketing found in the LMC WN9–10 stars (Paper I) which have similar excitation and mass loss rates. Indeed, we have found excellent consistency between observed helium and metal ionization stages, with those that are predicted.

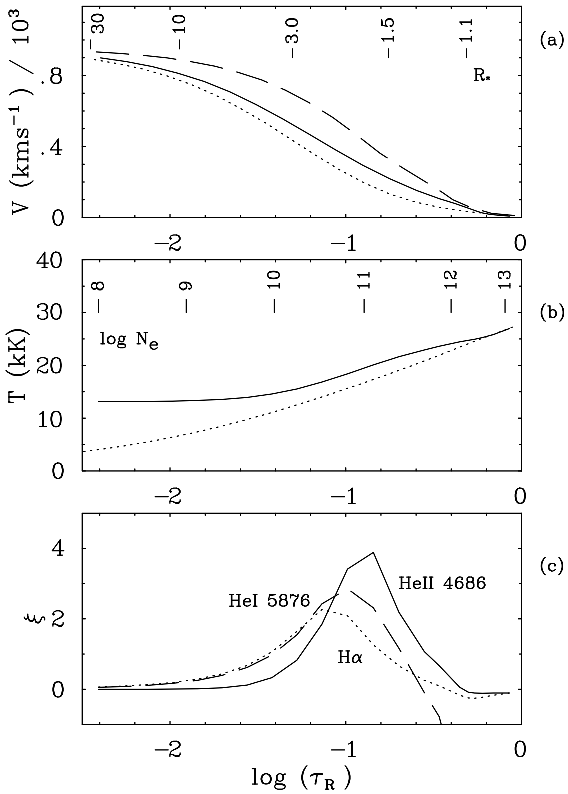

Fig. 6a–c. Various wind properties for HD 152408 (Model A) as a function of Rosseland optical depth ($\tau_{\rm R}$); **a** Assumed velocity distribution (solid line), with standard β=1 (dashed-line) and β=2.5 (dotted-line) laws also indicated, as is the radius scale (in R_*); **b** Theoretical temperature distribution (solid) compared with the grey distribution (dashed line) including the electron density scale (N_e in cm^{-3}); **c** Line formation regions for principal wind diagnostic lines – He II λ4686 (solid), He I λ5876 (dashed) and Hα (dotted)

3.2. Results from line profile fits

The overall quality of line profile fits to the wide variety of ultraviolet, optical and infrared profiles shown in Fig. 7 indicates that our model solutions are accurate for determination of ‘global’ stellar properties. In all cases the synthetic profiles reproduce the strength and shape of the wind emission features, including non-diagnostic lines such as Hβ and Hγ. Although important discrepancies remain for some wind contaminated photospheric lines such as He II λ5412 (7–4) and λ21885 (10–7), other ‘photospheric’ features (e.g. Hγ in HD 151804) are surprisingly well matched.

All three stars have significantly extended atmospheres with very similar stellar radii, luminosities, and mass-loss rates (Table 3). Stellar parameters obtained from Models A and B, using alternative He II lines, are in close agreement (Table 3), suggesting the exact choice of diagnostic does not have a major effect on the resulting wind properties or surface abundances. The derived effective temperatures and bolometric corrections are $\approx$8 000K and 0.7 mag lower than those of normal O8-type supergiants (Vacca et al. 1996), a difference resulting from the geometrical extension of the outer layers of the stellar atmosphere (e.g.

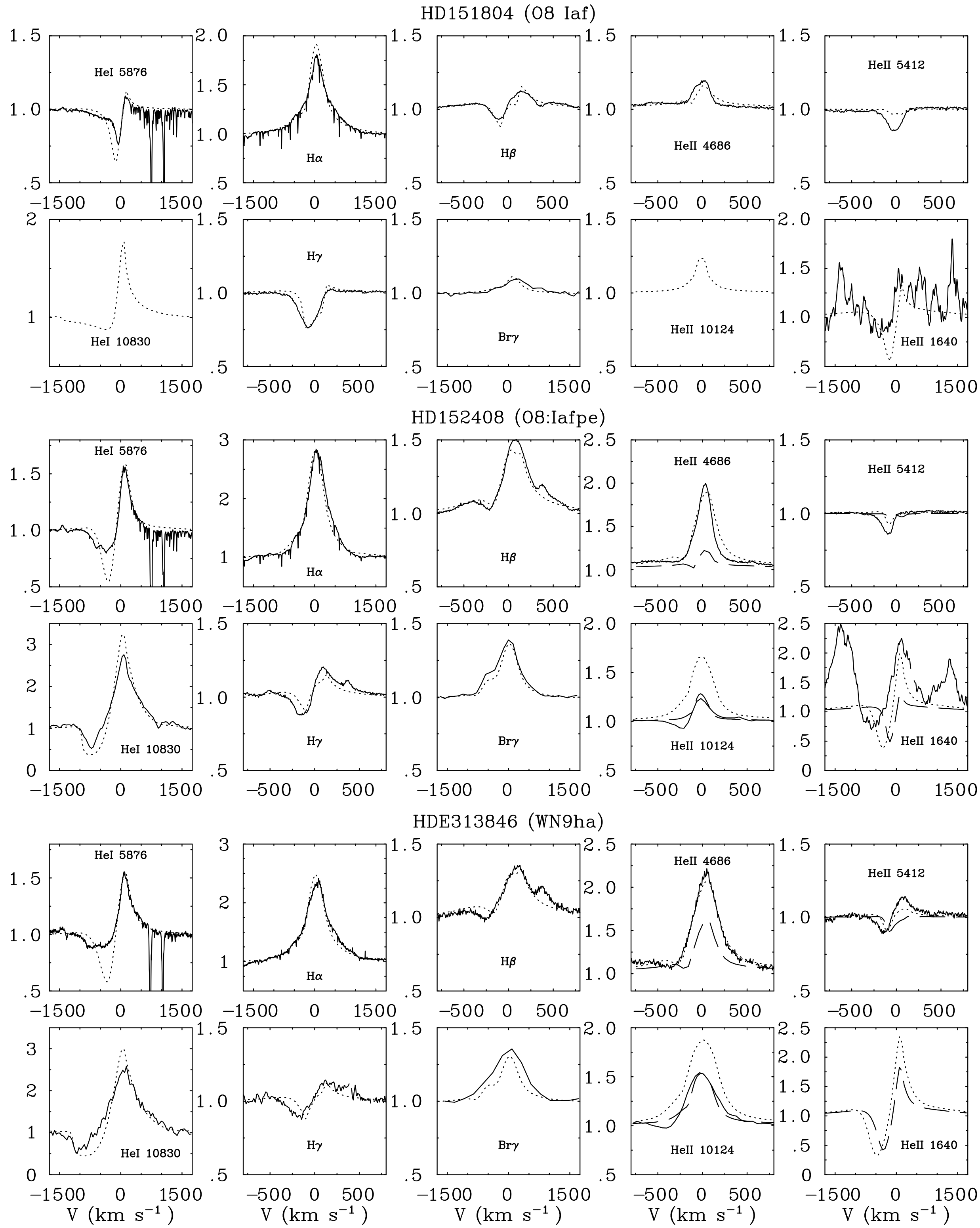

Fig. 7. Selected profile fits to UV (*IUE*), optical (AAT) and infrared (CTIO and UKIRT) observations (solid line) of HD 152408, HD 151804 and HDE 313846 for Model A (dotted line) based on the λ4686 He II diagnostic, and Model B (dashed line) based on λ10124 He II, using stellar parameters given in Table 1. The blend of N III $\lambda\lambda$4859–4896, $\lambda\lambda$4318–4351 with Hβ and Hγ, particularly evident in HDE 313846, is not modelled here

Table 3. Stellar parameters of the programme stars derived from the following diagnostics – He I λ5876, Hα and He II λ4686 (Model A), λ10124 (Model B). $\dot{M}/(4\pi R_*^2)$ is the surface mass flux; $\dot{M}v_\infty/(L_*/c)$ the wind performance number; y(=N(He)/[N(H)+N(He)]), the helium content by number; and log Q_0, the flux of Lyman continuum ionising photons

HD	Model	T_*	R_*	$T_{\rm eff}$	$R_{2/3}$	log L	log $\dot{M}$	v_∞	log($\frac{\dot{M}}{4\pi R_*^2}$)	$\frac{\dot{M}v_\infty}{}$	y	log Q_0	$(B-V)_0$	$M_{\rm V}$
		kK	$R_\odot$	kK	R_*	$L_\odot$	$M_\odot {\rm yr}^{-1}$	km s^{-1}	$M_\odot {\rm yr}^{-1} R_\odot^{-2}$	(L_*/c)		s^{-1}	mag	mag
151804	A	27.3	37.0	26.7	1.05	5.84	−4.92	1445	−9.15	1.24	0.20	49.24	−0.32	−7.2
152408	A	28.5	32.4	27.6	1.07	5.80	−4.62	955	−8.74	1.79	0.40	49.32	−0.33	−7.0
	B	27.6	33.1	26.7	1.07	5.76	−4.65	955	−8.79	1.83	0.40	49.24	−0.32	−7.0
E313846	A	28.6	33.1	27.7	1.07	5.82	−4.53	1170	−8.67	2.57	0.45	49.37	−0.33	−7.0
	B	28.0	32.9	27.2	1.06	5.78	−4.57	1170	−8.70	2.58	0.45	49.32	−0.32	−7.0

Table 4. Mass-loss rates for HD 151804 and HD 152408 from radio (2cm and 6cm) fluxes (Bieging et al. 1989), ($\dot{M}_{\rm radio}$, and from spectroscopic analysis presented here, $\dot{M}_{\rm spect}$. Quoted errors are those formally resulting from uncertainties in radio fluxes; additional (uniform) errors result from uncertainties in assumed distances

HD	ν (GHz)	S_ν (mJy)	μ	Z	γ	log $\dot{M}_{\rm radio}$	log $\dot{M}_{\rm spect}$ ($M_\odot {\rm yr}^{-1}$)
151804	5	0.40	2.560	1.008	1.005	−4.81±0.08	−4.92
	15	0.40				−5.02±0.08	−4.92
152408	5	1.05	3.327	1.020	1.014	−4.57±0.03	−4.62
	15	2.40				−4.51±0.02	−4.62

Note: ν is the frequency, S_ν is the flux, and μ, Z, γ are the mean molecular weight per ion, r.m.s. ionic charge and the mean number of electrons per ion.

Kunasz et al. 1975). Stellar luminosities are, however, comparable with normal O8-type supergiants, with the Lyman ionising flux of HDE 313846 similar to α Cam (O9.5 Ia; Voels et al. 1989). Our derived stellar parameters for HDE 313846 are in good agreement with those obtained in Paper I, although a slightly lower (≈1 000K) stellar temperature results from the use of an improved velocity distribution.

We confirm the conclusions of previous spectroscopic studies that chemically processed material is revealed at the surfaces of O supergiants (e.g. Herrero et al. 1992)[2]. Remarkable helium enrichment is found for all three programme stars. HD 151804 shows significant enrichment (H/He=4.0 by number, $X_{\rm He}$=50% by mass) while the surface helium abundance in HD 152408 (H/He=1.5, $X_{\rm He}$=70%) is unprecedented for an O-type star[3] and is more typical of a WNL star (e.g. Paper III; Hamann et al. 1995).

The spectroscopic mass loss rates derived from line profile fits in the UV, optical and near-IR, $\dot{M}_{\rm spect}$, are in excellent agreement with those predicted by applying the formulation of Wright & Barlow (1975) to the radio observations of Bieging et al. (1989), $\dot{M}_{\rm radio}$, (Table 4). The radio continuum is formed in the outer part of the extended atmosphere (150 to 300 R_*) where H^+, He^+ (and C^{2+}, N^{2+}) are the dominant ionization stages and, consequently, mass loss rates determined from radio observations are quite sensitive to the adopted chemical composition and ionization. The agreement we find between the spectroscopic and radio mass loss rates arises from the use of appropriate chemical element abundances and ionizations from our spectroscopic results. Previous radio mass-loss determinations for HD 151804 and HD 152408 by Lamers & Leitherer (1993) were 0.1–0.25 dex lower as they assumed lower helium abundances.

Since one would not expect that similar clumping factors would be present in both the inner and outer parts of the atmosphere (Puls et al. 1996), The agreement between the optical mass loss rates – arising from lines formed at a few stellar radii – and the radio suggests that the degree of density inhomogeneities in these stars is small. However, the relatively weak winds of our programme stars do not produce strong electron scattering wings (except He II λ4686 which is also sensitive to assumed velocity distributions), which are used in strong-lined WNE stars to constrain the degree of wind clumping (c.f. Schmutz 1996). Clumping, while small, must be present as the mass loss rate of these stars are known to be variable. Intensive time series observations of HD 151804 by Prinja et al. (1996) has revealed variations in Hα emission which is consistent with variations of ±5% in mass-loss on very short (hourly) time scales. Similar variations are probably present for both HD 152408 (see Prinja & Fullerton 1994) and HDE 313846.

The ratio of the stellar wind momentum to the photon momentum ($\dot{M}v_\infty/[L_*/c]$), the wind performance number, is significantly higher in HD 151804 and HD 152408 than in normal late O-type stars (∼0.5, Lamers & Leitherer 1993). For these stars and for HDE 313846 the wind performance number (Table 3) exceeds unity, numbers which can likely be explained by current radiation-driven wind theory through multiple scattering (Springmann 1994; Gayley et al. 1995). We shall return to this point in Sect. 4.

[2] However, Schaerer & Schmutz (1994) emphasise that analysis based – as Herrerro et al. and others have done – on plane-parallel models for stars with extended atmospheres can lead to significant, systematic errors in, amongst other parameters, abundances

[3] The O star most enriched in helium prior to our analysis was HD 193682 (O5 III(f)) for which Herrero et al. (1992) obtained H/He=2.3 ($X_{\rm He}$=63%) – though see also previous footnote

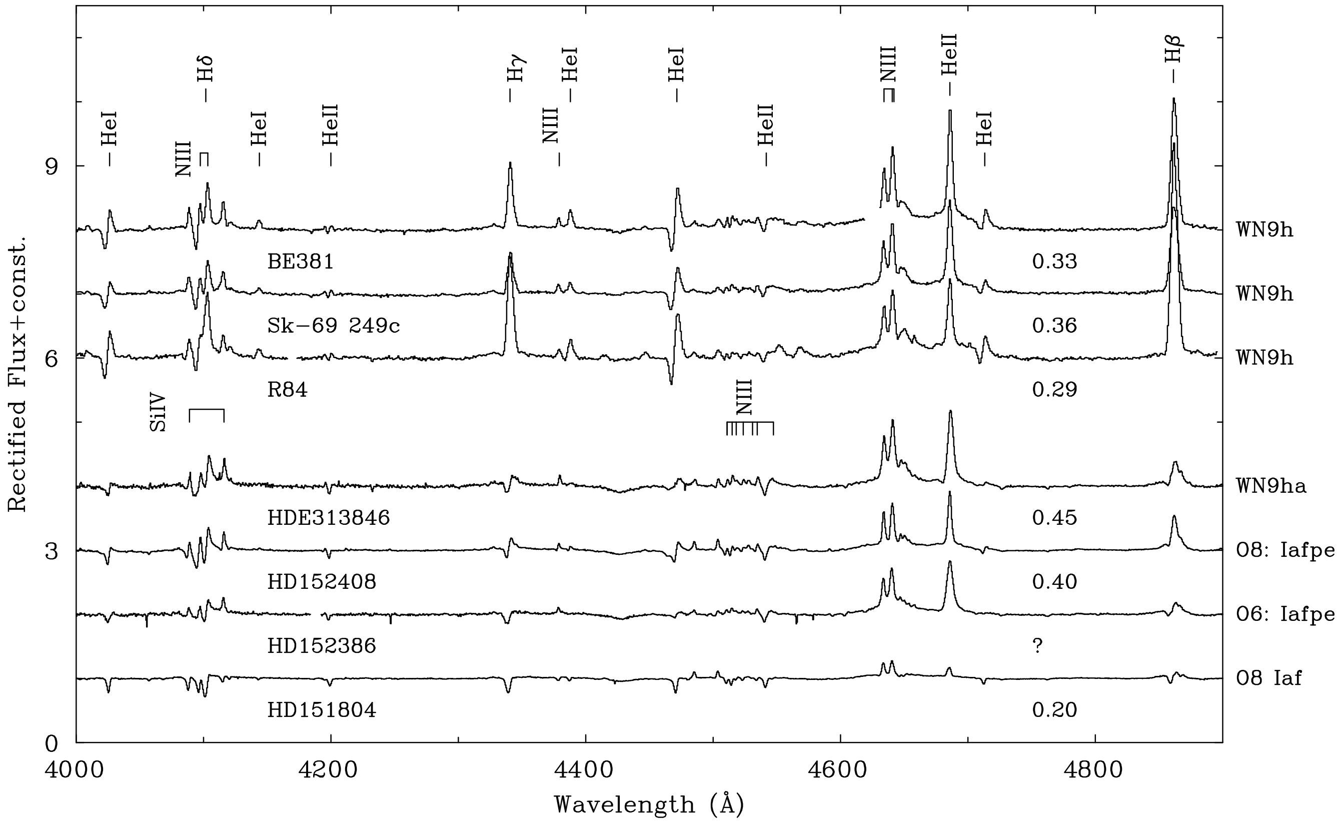

Fig. 8. A spectral comparison of our programme stars with the other known Ofpe star, HD 152386, and the LMC WN9 stars R84, Sk−69° 249c and BE381 between λλ4000–4900. LMC spectra, taken from Paper I and Crowther & Smith (1996b) are radial velocity corrected for the purpose of comparison, while new spectroscopy of HD 152386 is from AAT−UCLES in 1995 April. All data are plotted to the same scale, shifted vertically for clarity by relative constants of either 1 or 2 continuum units

4. Of–WN: a morphological or evolutionary distinction?

The continuity of physical properties suggested by the similar spectral morphology of HD 151804 (O8 Iaf), HD 152408 (O8: Iafpe) and HDE 313846 (WR108, WN9ha) is confirmed by our spectroscopic analysis. Moreover, the smooth trend of surface chemical abundances strongly suggests that these three stars share a common evolutionary path, O8 Iaf⇒O8: Iafpe⇒WN9ha, with no intervening LBV phase of very high mass loss (first propsed in Paper I). In this section we compare the stellar parameters of these stars with other O supergiants and WNL stars to investigate the fine line separating stars classified as extreme Of and those with WNL spectral types. We discuss in detail the evolutionary connection between Of and WN stars, as revealed by chemical abundance analysis.

4.1. Could HD 152408 be considered a Wolf-Rayet star from its optical spectrum?

For the stellar morphologist the distinction between extreme Of types and low-excitation, relatively weak emission WNL types is often a judgement call. The problem is well illustrated by the shifting classification of HDE 313846. The earliest spectral classification was Wolf-Rayet (Cannon & Mayall 1938). More recently, HDE 313846 has been variously designated as O7: Iafpe (Hutchings 1979) and WN9 (van der Hucht et al. 1981). Walborn (1982) argued that two other Galactic O Iafpe stars, HD 152408 and HD 152386, should also be labelled as WN9 if HDE 313846 were so classified. The type we have adopted here for HDE 313846, WN9ha, indicates that the upper Balmer series show P Cygni profiles and that hydrogen is abundant in the atmosphere (Paper I). As our analysis both here and in Paper I well illustrate, a W-R classification for HDE 313846 is appropriate from the physics of its stellar atmosphere.

The question then concerns HD 152408: should it too be given a W-R designation? We will examine this question based on four criteria: 1) the blue shift of certain absorption lines relative to the star's systemic radial velocity, 2) the strength and width of the He II emission lines, 3) the overall spectral appearance, and 4) the density and speed of the expanding atmosphere (in Sect. 4.2)

The classical distinction between Of and WN stars lies in the dominance of the WN spectrum by strong emission lines. Conti (1973) distinguishes the Wolf-Rayet classification as follows: "the *only* absorption lines seen (in W-R types) are *violet shifted* (P Cygni type). Although in some cases emission lines appear which are similar to to those found in some Of stars, the latter types *always* have some *unshifted* absorption lines present." As defined in Paper I, if the O-type classification line He II λ4542 has a P Cygni profile or has an obvious blue shifted central ab-

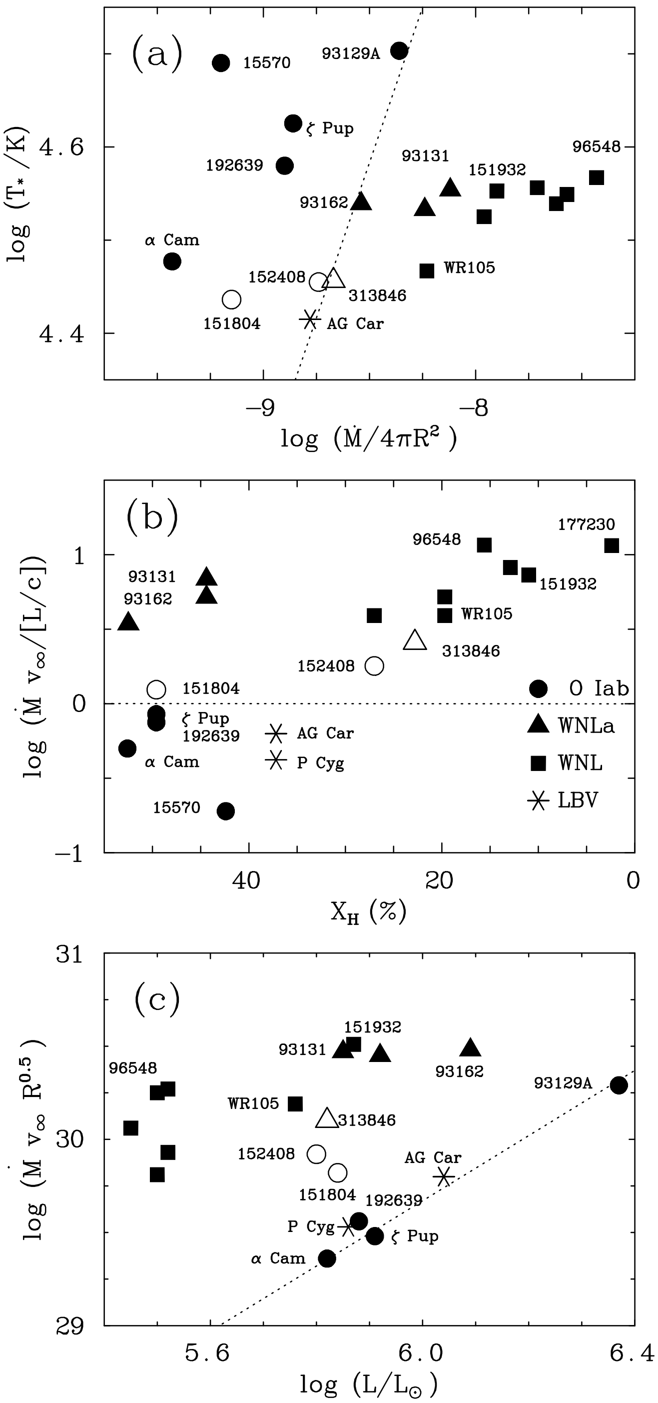

Fig. 9. a Stellar temperature (log K) versus surface mass flux ($M_{\odot}\mathrm{yr}^{-1}R_{\odot}^{-2}$) for the programme stars (open symbols) compared to other Galactic WNL, O supergiants and LBVs (filled-in symbols) from Table 5 and Paper III. The approximate division between spectroscopic O and W-R stars is shown (dotted line); **b** Wind performance numbers versus surface hydrogen mass fraction (in %), with the single scattering limit indicated as a dotted line; **c** A comparison of the wind momentum–luminosity relation ($\dot{M}v_{\infty}$ in cgs-units, and R_{*} in $R_{\odot}$) from Puls et al. (1996) (dotted-line) with observations, indicating significant differences for those O and WN stars showing wind momentum factors greater than unity

sorption with weak or even negligible emission, the appropriate classification is W-R. The critical physical difference then is the nature of the stellar wind in the two types. In W-R stars, all of the classical classification absorption lines are formed in a dense, outwardly flowing stellar atmosphere; while in Of stars, they are formed in an essentially static photosphere.

As discussed in Sect. 2.1, He II λ4542 in both HDE 313846 and HD 152408 show asymmetric absorption profiles centred at $\sim$110 km s^{-1} and $\sim$80 km s^{-1}, respectively, relative to the systemic radial velocity of each star. In contrast, HD 151804 shows a symmetric profile for both lines centred at a blueward radial velocity shift of only $\sim$20 km s^{-1}. He II λ5412 in HDE 313846 shows a weak P Cygni profile with blue absorption minimum at $\sim$150 km s^{-1}, relative to the systemic velocity, while HD 152408 shows a pure absorption profile with a minimum blue shifted velocity $\sim$120 km s^{-1} (Fig. 2). HDE 313846 clearly meets the blue shifted or P Cygni profile criterion. For HD 152408 to retain a O8: Iafpe classification on the basis of no 'obvious' blue shifted absorption lines, one would have to set a limit of $\sim$100 km s^{-1} for He II λ4542 and slightly higher for He II λ5412.

Another often invoked distinction between Of and WNL types is the width of He II λ4686 (e.g. Conti & Bohannan 1989). However, this criterion has to be carefully applied as some 'normal' Of supergiants, such as ζ Pup (O4 I(n)f) have broader He II λ4686 than some 'normal' WNL stars, such as WR156 (WN8h, Paper III). The use of FWHM *and* equivalent widths of He II λ4686 for Of and WNL stars show a smooth trend in the correlation of these two quantities with limited overlap between Of and WNL types (Bohannan 1990; Crowther & Smith 1996b). Single WNL stars are distinguished from Of types (at intermediate dispersion spectroscopy) through the following criteria (from Crowther & Smith 1996b): WN6–8 types have $W_{\lambda}(\lambda4686)\geq$10 Å and FWHM($\lambda$4686)$\gtrsim$ 7Å, while WN9–11 stars have $0<W_{\lambda}(\lambda4686)\leq$10 Å, FWHM($\lambda$4686) $\approx$5 Å plus $W_{\lambda}(\lambda5876)\geq$3.5 Å. The additional He I λ5876 diagnostic is required to discriminate low excitation WNL stars from the extreme Of stars. Adopting a lower limit of $W_{\lambda}(\lambda5876)\geq$1.0 Å, HD 152408 (and HD 152386 as well) could be considered as a WNL-type W-R star, with a spectral class of WN9 based on its He I-II line strengths.

In Fig. 8 we contrast blue spectra of HD 151804, HD 152408 and HDE 313846 with the other known Ofpe star, HD 152386 (O6: Iafpe), and three of the prototype Ofpe/WN9 stars (Bohannan & Walborn 1989) which are now classified as WN9h (Paper I), R84 (HDE 269227), Sk$-69°$ 249c (HDE 269927c) and BE 381. The overall spectroscopic appearance of HD 152408 is essentially identical to HDE 313846 and and very similar to HD 152386 (the latter shows broader He II λ4686 emission and weaker He I λ4471 and Hβ emission components). Lines formed in the low velocity region of their stellar winds (e.g. He II λ4686, N III $\lambda\lambda$4634–41) are comparable in strength and width to the LMC WN9h stars, implying similar excitation. However, features formed further out in their winds (He I and H I) show contrasting morphologies due to differences in the outer atmospheres. Because of the P Cygni-like profiles of Hγ in HDE 313846, the spectral type of this star was revised to WN9ha (Paper I). Should a W-R classification be considered for HD 152408, the same type would be appropriate for it as well.

4.2. Physical comparison with other Of and WN stars

We now turn to the wider implications of our spectroscopic analyses through a comparison of the stellar parameters of the three programme stars with those of a sample of O-type supergiants and WNL stars (Table 5). The similarities in physical and chemical properties of HD 152408 with HDE 313846 argue for similar spectral classification of these stars, either Ofpe or WNL. In contrast, the properties of HD 151804, though extreme, are not inconsistent with a late Of designation. As we discussed earlier, the critical distinction between Of and WNL classifications lies in the presence or absence of blue shifted absorption lines, particularly the Pickering He II series (Sect. 4.1). The Pickering lines are strongly dependent on the density of He^{2+}, a quantity which depends on a combination of the wind ionization, density, and helium content. Simply put, a W-R classification results when the stellar wind density ($\dot{M}/v_\infty 4\pi R_*^2$) or the surface mass flux ($\dot{M}/4\pi R_*^2$) is high close to the photosphere.

To demonstrate this effect we plot in Fig. 9(a) the surface mass flux ($\dot{M}/4\pi R_*^2$) with stellar temperature for Galactic LBVs, Of and WNL stars. Differences in surface mass flux and to a lesser degree stellar temperature and helium content readily explain the observed He II λ5412 profiles. In Of stars such as ζ Pup and HD 151804, He II λ5412 shows a symmetric absorption profile with weak wind contamination. A modest increase in surface mass flux leads first to an asymmetric blue shifted profile (e.g. HD 152408), then a fully developed P Cygni profile (e.g. HDE 313846), and finally an emission profile, showing negligible absorption (see e.g. Fig. 1 in Paper I for HD 86161). This trend broadly confirms the earlier study of Lamers & Leitherer (1993) who found a smooth progression in increasing wind density ($\dot{M}/v_\infty 4\pi R_*^2$) from normal O stars, through Of supergiants, to the WNL sequence.

Crowther & Smith (1996b) have recently identified a broad correlation between increasing helium content and wind performance – the ratio of wind momentum to the single scattering limit – for Galactic and LMC WNL stars. In Fig. 9(b) we show that this trend is also true for Of stars. In addition, we find that the degree of helium enrichment is inversely proportional to wind velocity (Table 5), a relationship which can be attributed to the increase in surface mass flux from Of to WNL types. Indeed, the terminal wind velocities of HD 151804 and HD 152408 are, respectively, 75% and 50% of the mean terminal velocity (1915 km s^{-1}) for the 17 O7–9 supergiants measured by Prinja et al. (1990). Spectral morphological differences between HDE 313846 and the LMC WN9 stars plotted in Fig. 8 result principally from dramatically different terminal wind velocities (Paper I).

Puls et al. (1996) have recently identified a tight relation between 'reduced wind momentum' ($\dot{M} v_\infty R_*^{0.5}$) and luminosity for Galactic O supergiants (their Fig. 22b). In Fig. 9(c) we compare these parameters for our sample of stars, revealing higher wind momenta for our programme stars (and all WNL stars), in contrast with normal O supergiants, further demonstrating the extreme velocity and mass-loss properties of the exteme Of and WNL stars.

The rate of mass-loss is reflected in the spectral classification of Of supergiants; the definition of OIafpe requires both Hα and Hβ be observed in emission (also true for WNL stars). Since Balmer emission is directly related to mass-loss rate (e.g. Puls et al. 1996), a high mass loss rate is implicit for emission to be seen at both Hα and Hβ. From the 77 O stars studied by Conti (1974), the largest Hα emission equivalent width (by far) was for HD 152408, the only OIafpe star in his sample. Other late Of stars which show relatively strong emission components in the Balmer series and at He I λ5876 include HD 150958 (O6.5 Ia(n)f$^+$) and the massive X-ray binary HD 153919 (O6.5 Iaf$^+$); these represent further candidates for high mass-loss rates and helium enrichment.

Finally, let us return to the question of the classification of HD 152408 as a WNL Wolf-Rayet type. In Sect 4.1, we argued against a WN9ha classification because of the blue shift of He II λ5412 and the strength of He I λ5876 were less than predetermined limits. In contrast, in this section we have found that the wind properties and chemical abundances of HD 152408 are quite consistent with a Wolf-Rayet character. To resolve this dichotomy we will in a future paper compare HD 152408 and HDE 313846 to the third known OIafpe star, HD 152386. Spectroscopically this star closely resembles both HDE 313846 and HD 152408 (Fig. 8), with weak P Cygni profiles at He II λ5412 and Hγ, and a mass loss rate (log $\dot{M}/M_\odot$yr$^{-1}\lesssim-4.47$, Leitherer et al. 1995) that is comparable to HDE 313846.

4.3. Evolutionary status of Of–WN stars

The smooth continuity of the spectroscopic, physical and chemical properties of HD 151804, HD 152408 and HDE 313846 suggests an evolutionary connection between some OIaf stars and WNL types, without the need for an intermediate LBV phase. However, the rarity of stars classified as OIafpe suggests that only massive stars in a narrow range of initial stellar mass, metallicity and, perhaps, rotational velocity will advance through this spectral type and evolve to exhibit WNL characteristics. In this section we will discuss the effect that stellar rotation may play in changing the surface chemical composition and stellar evolution of the O-type stars, consider what might be the core energy source of the OIafpe and WN9ha stars and conclude with some thoughts on classification of the OIafpe stars and on interpreting the O:WN ratios of galaxies.

Metallicity plays a key role both in mass loss and in stellar evolution (Maeder & Meynet 1994). HD 151804 and HD 152408 are members of Sco OB1, located at a Galactocentric distance, similar to our local environment and likely formed from similar material to that in the solar neighborhood. The initial metallicity of HDE 313846 was estimated to be Z=0.04 in Paper I. Since all of the known OIafpe and WN9ha stars are located in the Galaxy, solar metallicity or greater is probably

Table 5. Stellar parameters of selected hot, massive stars, sorted by wind performance number (column 12). He II λ4686 equivalent width (W_λ) and FWHM (both in Å) measurements are from our own observations. The stellar parameters for Galactic WN6–8 stars given here (and in subsequent figures) are from the *arithmetic* mean of the helium and nitrogen analyses of Paper II

HD	Alias	Sp. Type	He II λ4686 W_λ	FWHM	T_* kK	R_* $R_\odot$	$\log \dot{M}$ $M_\odot \mathrm{yr}^{-1}$	$\log L_*$ $L_\odot$	v_∞ km s^{-1}	$\log(\frac{\dot{M}}{4\pi R_*^2})$ $M_\odot \mathrm{yr}^{-1} R_\odot^{-2}$	$\frac{\dot{M} v_\infty}{(L_*/c)}$	y	$\log Q_0$ s^{-1}	Ref.
15570		O4 If$^+$	2.1	8.3	49.0	24.3	−5.33	6.49	2605	−9.2	0.2	0.25	..	3,4,5
193237	P Cyg	B1 Ia$^+$	0.0	0.0	19.3	75.0	−4.47	5.86	185	−9.3	0.4	0.29	..	8
30614	α Cam	O9.5 Ia	0.0	0.0	30.0	30.0	−5.38	5.80	1590	−9.4	0.5	0.18	49.36	1,3,4
94910	AG Car	WN11h	0.6	3.1	26.0	51.7	−4.25	6.04	250	−8.8	0.6	0.29	49.35	7
66811	ζ Pup	O4 I(n)f	2.5	6.2	42.2	17.0	−5.30	5.91	2485	−8.9	0.7	0.20	49.71	2,3,4
192639		O7 Ib(f)	0.0	0.0	38.5	19.5	−5.22	5.88	2180	−8.9	0.8	0.20	..	3,10
151804		O8 Iaf	0.7	3.6	27.3	37.0	−4.92	5.84	1445	−9.1	1.2	0.20	49.25	11
93129A		O3 If*	1.7	11.9	50.5	20.0	−4.66	6.37	3150	−8.4	1.5	0.09	..	3,10
152408		O8: Iafpe	3.1	3.3	28.5	32.4	−4.62	5.80	955	−8.8	1.8	0.40	49.32	11
E313846	WR108	WN9ha	5.8	5.2	28.6	33.1	−4.53	5.82	1170	−8.7	2.6	0.45	49.37	11
93162	WR25	WN6ha	10.5	16.4	34.6	30.9	−4.46	6.10	2480	−8.5	3.4	0.18	49.75	6
	WR105	WN9h	9.7	6.4	29.3	29.4	−4.19	5.76	700	−8.2	3.9	0.50	49.26	9
92740	WR22	WN7ha	20.0	11.8	34.1	26.1	−4.31	5.93	1785	−8.2	5.2	0.24	49.59	6
93131	WR24	WN6ha	21.0	15.5	35.8	21.9	−4.34	5.86	2160	−8.1	6.9	0.24	49.55	6
151932	WR78	WN7h	41.8	12.8	35.7	22.4	−4.10	5.88	1385	−7.9	7.3	0.67	49.58	6
177230	WR123	WN8h	33.8	11.8	35.4	14.9	−4.12	5.51	970	−7.6	11.5	0.91	49.16	6
96548	WR40	WN8h	56.0	12.5	36.9	14.1	−4.03	5.52	840	−7.4	11.6	0.57	49.18	6

References: (1) Voels et al. 1989; (2) Bohannan et al. 1990; (3) Prinja et al. 1990; (4) Lamers & Leitherer 1993; (5) Herrero 1994; (6) Paper II; (7) Smith et al. 1994; (8) Langer et al. 1994; (9) Smith et al. 1995; (10) Puls et al. 1996; (11) this work

required for the OIaf ⇒ OIafpe ⇒ WN9ha path. For environments with lower metallicity, such as the LMC where no OIafpe stars resembling HD 152408 are known, progenitors with masses similar to HD151804 would follow a quite different path to the WN stage due to lower mass-loss rates in the O-star stage. If so, this scenario would explain the large number of WN9–11h stars found in the LMC, some members of which may be quiescent LBVs or the products of an LBV phase (Paper I; Crowther & Smith 1996b).

The scenario sketched above is quite different from the conclusion from spectral morphology considerations by Nota et al. (1996) that HD 152408 and HDE 313846 represent a point of transition from Of to WN9–11h. This difference is moot if both of these stars are classified as WN9ha. However, other key arguments counter to their conclusion are that OIafpe stars are only found in solar metallicity environments, while the WN9–11h types are found exclusively in low metallicity environments like the LMC, and that WN9–11h stars exhibit a lower degree of surface helium enrichment (typically H/He≥2; Crowther & Smith 1996b) than OIafpe and WN9ha stars (H/He≤1.5). The WN9h and WN9ha types appear to have taken quite different paths from their O-type progenitors.

We have previously suggested that direct evolution from Of⇒WNL is not restricted to stars of the spectral types studied here. In Paper III we argued that the Carina WN6–7ha stars (e.g. HD 93162) are directly descended from very massive progenitors. Recently, Crowther & Smith (1996b) have proposed that some LMC WN6–7 stars, specifically those in 30 Doradus, have also evolved directly from massive O stars, despite their lower initial metallicity. O3 If/WN6 stars, unique to the Magellanic Clouds (Walborn 1994), probably represent an intermediate stage in this evolution, equivalent to the WN6–7ha stars observed our Galaxy (e.g. NGC 3603, Drissen et al. 1995). Indeed, the WN6–7ha and O3 If/WN6 stars are probably still hydrogen burning, a conclusion reached from determinations of very high stellar mass at the present evolutionary stage of these stars. Rauw et al. (1996) have recently obtained an estimate of $\geq 72 M_\odot$ for the present mass of the WN7ha component of the eclipsing binary system HD 92740 (WR22). The initial mass of this star would certainly have been in excess of 100 $M_\odot$.

The core nuclear process in extreme Of and WNL stars with atmospheric hydrogen cannot be determined without resorting to interior evolutionary calculations. Recent models of 50 $M_\odot$ stars – a good estimate of the initial mass of our programme stars – by Langer et al. (1994) predict that core hydrogen burning is extinguished at a surface composition of $y \gtrsim 0.36$ and He-burning commences at a surface composition of $y \gtrsim 0.67$. An LBV stage is linked to a short (1.5 10^4yr) intermediate phase of H-shell burning between core hydrogen and core helium burning. The observed surface helium abundances of HD 152408 and HDE 313846 correspond with this H-shell burning phase of Langer et al. (1994). However, neither star shows observational evidence of LBV-type activity, such as light and spectroscopic variations or dramatic mass ejection. In addition, this range of surface helium content is also common to most WNL stars (Paper III; Crowther & Smith 1996b). If one assumes that

He-burning commences at y=0.40 – approximately the surface helium abundance where core hydrogen stops in the Langer et al. models – then HD 152408 and HDE 313846 may be core He-burning, while HD 151804 is probably not.

Stellar rotation, while known to be important, has not been included in detailed models of the structure and evolution of massive stars. Zahn (1994) has summarised the role of mixing processes in massive stars, and speculated that rotation probably plays a major role in mixing outside the convective core. Recent calculations by Fliegner & Langer (1995) and Langer (1995) indicate that surface compositions in stars more massive than 60 $M_\odot$ are significantly modified during early post-main sequence stages by rotational mixing at rotational velocities commonly found in early-type stars. The measured $v \sin i$ rotational velocities of the stars considered here, which range from 100 km s^{-1} to 155 km s^{-1} (Uesugi & Fukuda 1982), are typical of the rotational velocities measured for O-type supergiants (Conti & Ebbets 1977). If rotational mixing has changed the overall stellar structure and played a major role in the defining the evolution of massive stars, surface chemical abundances may be so altered that it may not be possible to distinguish between core hydrogen burning and core helium burning conditions for those evolved stars with significant hydrogen in their atmospheres.

The assumption from stellar interior models that *all* W-R stars are core-helium burning is inconsistent with the interpretation from atmospheric analysis that WNL W-R types appear to have hydrogen-burning cores. The core nuclear process of WNL stars is critical to the determination of properties of galaxies from comparison of observed O:WNL ratios to stellar evolution calculations with different initial chemical compositions. Further, since massive O supergiants and W-R stars play a key role in the dynamics and evolution of galaxies at certain phases of galaxian evolution – e.g. starburst galaxies – detailed understanding of the distinction between extreme Of types and WN stars is relevant for reliable determination of star formation rates, nucleosynthesis yields, initial mass functions, etc.

In summary, the detailed analysis presented here demonstrates that the WN spectroscopic classification results from a high surface mass flux, with stellar temperature and helium abundance as secondary effects. Based on our detailed atmospheric analysis little distinguishes HD 152408 from HDE 313846, a conclusion reached some time ago by Walborn (1982) on purely morphological grounds. Since HDE 313846 is classified as WN9ha, perhaps so should HD 152408 and the remaining OIafpe star HD 152386, a conclusion we leave to a later analysis.

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