Quantitative Comparisons Between Wolf-Rayet Stars in HD 97950 and R136a

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Abstract. We present quantitative analyses of Wolf-Rayet stars in the cores of two giant H II regions, HD 97950 in NGC 3603 and R136a in 30 Dor, based on archive HST spectroscopy. We confirm WN6h+abs classifications for components A1, B, and C in HD 97950 (Drissen et al. 1995), while classifications for R136a$_{1-3}$ are revised from O3 If/WN6 (de Koter et al. 1997) to WN5h. From detailed non-LTE analyses, we find that all the stars exhibit products of CNO-processed material at their surface, since they are rich in helium (H/He$\simeq$3–6) and nitrogen (N/He$\simeq$0.002–0.006). These stars are among the most luminous Wolf-Rayet stars known ($\log L/L_{\odot} = 6.0$–6.4), and are consequently very massive stars ($M_{\rm init} \geq 100 M_{\odot}$) at a relatively young age ($\sim$2 Myr), reminiscent of the WNL stars in Carina (Crowther et al. 1995a). We find that the methodology applied by Vacca & Conti (1992) to WR galaxies can account for the observed WN populations in these regions.

1. Introduction

Giant H II regions (GHRs) – nebulae photoionized by a tremendous number of Lyman photons produced by a massive-star population – are the signature of recent bursts of star formation in galaxies. Nearby GHRs can provide a wealth of information, such as the initial mass function (IMF), metallicity, star-formation rate (SFR), and age, which is valuable for the study of their more distant counterparts, starburst galaxies. They might also improve our understanding of the evolution of massive stars in different environments. Of particular interest is the distribution of O and Wolf-Rayet (WR) stars in these regions, as well as that among WR subtypes, believed to be strongly metallicity and age dependent. Our current understanding of GHRs has grown from studies of the Tarantula Nebula (30 Dor) in the LMC, ideal because of its proximity, known distance, and low reddening, and overall because it is crammed with star-forming regions. This is not the case in our Galaxy, where GHRs are scarce. NGC 3603 is the most massive GHR visually known in our Galaxy, containing the richest and densest known Galactic concentration of early, massive stars.

Studies of such regions have recently been improved through high-spatial-resolution observations provided by the Hubble Space Telescope. In particular, studies of the core of 30 Dor, R136 and its various components, as well as that of NGC 3603, i.e., HD 97950, allow the stellar content to be more accurately determined. While previous observations established that both HD 97950 and

R136 exhibit Wolf-Rayet-like spectra (Walborn 1973; Moffat et al. 1985), HST has revealed numerous components, including three WNL stars (HD 97950–A1, B, and C) and several early-O stars in HD 97950 (Drissen et al. 1995), with a similar stellar content for R136a, the brightest component of R136 (Moffat et al. 1985; Campbell et al. 1992). Of the four phases of massive young regions described by Walborn (1991), both NGC 3603 and R136 match the 'Carina Nebula' (NGC 3372) phase, with ages of between 2–3 Myr, embedded in somewhat older 7–9 Myr star-forming complexes (Melnick et al. 1989; Walborn & Blades 1997).

To date, no spectroscopic analyses of WN stars in NGC 3603 have been carried out, while de Koter et al. (1997) have conducted detailed analyses of three WN-like stars in R136 (a_1, a_3, and a_5, following the nomenclature of Weigelt & Bauer 1985), revealing high stellar luminosities and hydrogen contents which are extremely unusual for Wolf-Rayet stars. The only WR stars with properties approaching those belonging to R136 are HD 93131 and HD 93162 in the Carina Nebula, recently analysed by Crowther et al. (1995a, b). Crowther et al. and Langer et al. (1994) suggest that these stars are at an early post-main-sequence phase in their evolution, directly descended from extremely massive O stars. This view has been supported by the extreme proximity of the WN6 and O3 stars within HD 97950, which were probably formed simultaneously (Drissen et al. 1995).

In this paper, we undertake a spectroscopic analysis of the WR stars in NGC 3603 and R136, considering in parallel results obtained for the Carina WNL stars. Observations are described in Section 2, spectral classification is discussed in Section 3, while quantitative model results are shown in Section 4. Finally, we discuss the evolutionary status and ages of these H-rich WN stars in Section 5. A more complete description of this work has recently been submitted to MNRAS.

2. Observations

HST/FOS spectroscopy was obtained for the WN components in HD 97950 in September 1994 (PI Drissen) covering $\lambda\lambda$3250–4700, and in January 1996 for those in R136a (PI Heap) spanning $\lambda\lambda$3250–6700, and have been obtained from the HST archive. Ultraviolet spectroscopy of individual R136a stars was taken with the GHRS ($\lambda\lambda$1150–1750) between 1994 April (a_2 and a_5, PI Heap) and 1994 July (a_1 and a_3, PI Ebbets). Our archive spectroscopy of individual members of HD 97950 and R136a was supplemented by ground- and space-based flux-calibrated spectroscopy of the entire clusters. In the ultraviolet, SWP and LWR large-aperture exposures of HD 97950 were obtained with IUE between 1981 May and 1984 March. HST/GHRS spectroscopy of R136a was carried out in 1991 April by Heap et al. (1992), while IUE SWP and LWP small-aperture exposures were obtained between 1981 May and 1982 March. Torres-Dodgen & Massey (1988) have provided spectrophotometry for both HD 97950 and R136 in the optical covering $\lambda\lambda$3400–4800 and $\lambda\lambda$4400–6800, respectively. For comparison, we also utilize ultraviolet and optical spectroscopy of the Carina WNL stars presented by Crowther et al. (1995b), and several extreme LMC stars taken from

Crowther & Smith (1997), including the prototype O3 If/WN star Sk−67° 22 and the WN6h star R144 (Brey 89), located ~80 pc from R136a_1.

3. Spectral Classification

The core regions of R136 and NGC 3603 were classified as Wolf-Rayet stars when first spectroscopically observed. Moffat et al. (1985) suggested a WN6+O5 classification for HD 97950 while Walborn (1977) assigned a WN5+OB spectral type for R136a (subsequently supported by Moffat et al. 1985). Following HST observations, these objects were resolved into individual components. Moffat et al. (1994) confirmed the WN subtype for HD 97950A1-B-C, improved to WN6+abs by Drissen et al. (1995) using the recent Smith et al. (1996) criteria. However, some controversy has arisen for the R136a stars. Campbell et al. (1992) and Parker et al. (1995) proposed WN subtypes for a_1, a_2, a_3, and O3If/WN for a_5. On the other hand, de Koter et al. (1997) performed a detailed analysis of the R136a stars and concluded that a_1 and a_3 were not genuine Wolf-Rayet stars but instead O3 If/WN stars, due to their high hydrogen content and atypical P-Cygni profiles in the Balmer series.

Table 1. Ratios of emission equivalent widths (W_λ in Å) and of peak intensities above the continuum (P_λ) of relevant optical helium and nitrogen lines (N III λ4640, N IV λ4058, and N V λ4604–20) for HD 97950, Car OB1, and R136a stars. Present spectral classifications (following Smith et al. 1996) are compared with the standard scheme of Smith (1968, S68).

	He II λ4686 W_λ	P_λ(N V)/P_λ(N III)	P_λ(N IV)/P_λ(N III-V)	W_λ(N IV)/W_λ(N III)	– Spectral Type – S68	This work
HD 97950-A1	27.7	0.4	1.6	0.6	WN6	WN6h+abs
HD 97950-B	45.8	0.6	1.5	0.6	WN6	WN6h+abs
HD 97950-C	15.5	0.6	1.8	0.5	WN5	WN6h+abs
HD 93131	15.4	0.4	1.7	0.5	WN6	WN6ha
HD 93162	15.9	0.6	2.1	0.7	WN6	WN6ha
R136a_1	44.7	1.2	2.8	2.3	WN4.5	WN5h
R136a_2	45.3	1.3	2.6	1.7	WN4.5	WN5h
R136a_3	65.7	1.0	3.3	2.3	WN4.5	WN5h
R136a_5	10.5	1.6	2.9	0.7		O3 If/WN

Hence, using the Carina WNL stars, a typical O3 If/WN (Sk −67° 22), HD 65865 (WN5), and R144 (WN6) as prototypes, we ordered the R136a and HD 97950 stars into a smooth and consistent sequence – see Fig. 1. We refined the criteria of Smith et al. (1996), in order to account for the higher excitation of R136a_1–a_3, by assigning $0.4 \leq W_\lambda$(N IV λ4058)/W_λ(N III λ4640) ≤ 1.0 for WN6 stars. Implications of this new criterion are summarized in Table 1. We support the spectral classification by Drissen et al. (1995) for the HD 97950

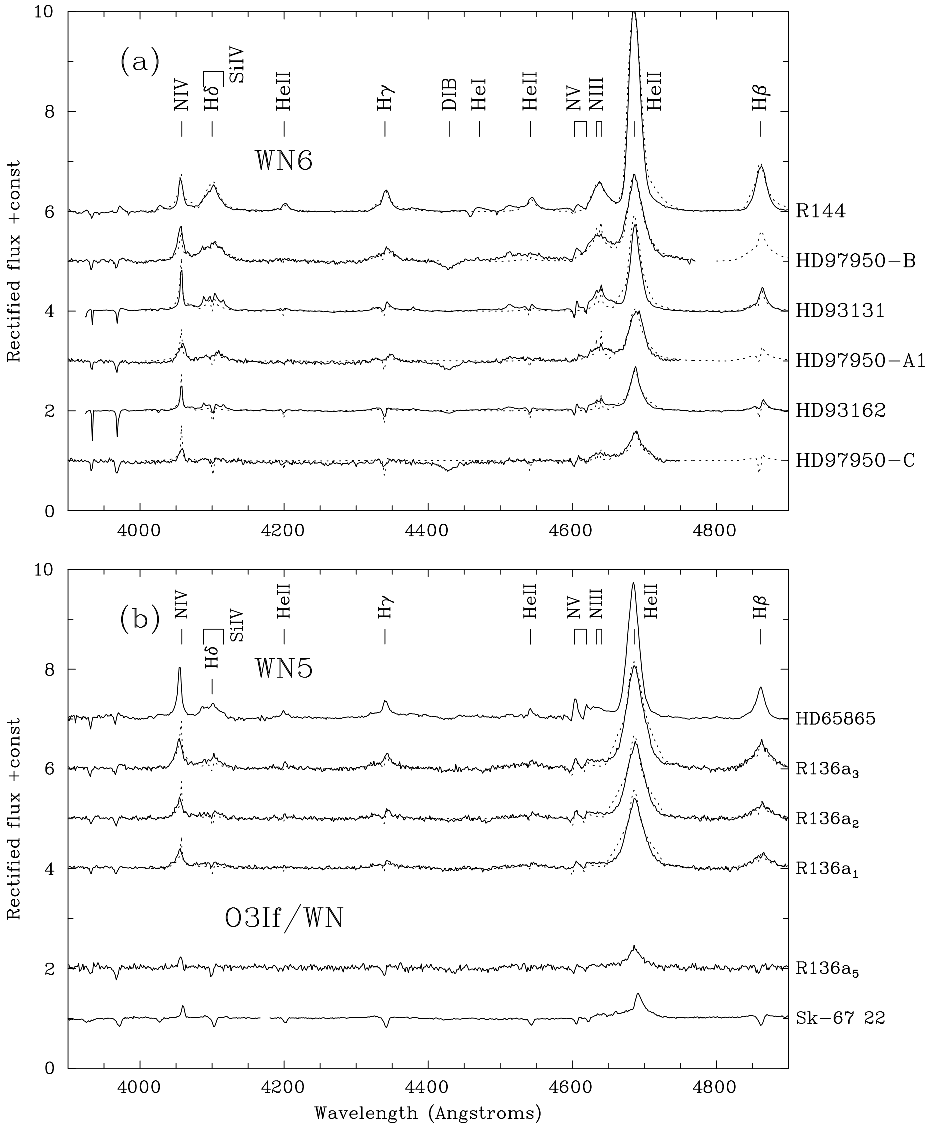

Figure 1. (a) A spectral comparison of WN6h stars in Car OB1 (HD 93131 and HD 93162) with their counterparts in HD 97950 (A1, B, and C), including the 30-Dor WN6h star R144 (Brey 89); (b) A spectral comparison of WN5h stars in R136a (a_1, a_2, and a_3) with the Galactic star HD 65865 (WR10) and R136a_5 with the prototype O3 If/WN star Sk−67° 22, showing their extremely similar spectral morphologies. Dotted lines refer to synthetic spectra discussed in Section 4.

Table 2. Derived stellar properties for the programme stars, based on analyses of their optical nitrogen-line spectra, including revised parameters for HD 93131 and HD 93162 (updated from Crowther et al. 1995a) and R144 (updated from Crowther & Smith 1997).

Star	T_* (kK)	$R_{2/3}$ ($R_\star$)	$\log L$ ($L_\odot$)	$\log \dot{M}$ ($M_\odot\,\mathrm{yr}^{-1}$)	v_∞ ($\mathrm{km\,s}^{-1}$)	H/He	$(b-v)_0$	M_b
HD 97950-A1	37	1.05	6.21	−4.19	2700	6.0	−0.29	−7.6
HD 97950-B	35	1.24	6.18	−4.03	2700	6.0	−0.26	−7.5
HD 97950-C	39	1.03	6.08	−4.63	2500	6.0	−0.30	−7.1
HD 93131	38	1.12	5.92	−4.46	2160	3.2	−0.28	−6.8
HD 93162	39	1.04	6.20	−4.43	2480	6.0	−0.30	−7.4
R144	37	1.43	6.34	−3.82	1350	1.5	−0.25	−7.9
R136a_1	45	1.12	6.42	−4.26	2650	3.5	−0.29	−7.5
R136a_2	46	1.10	6.01	−4.56	2600	2.7	−0.30	−6.5
R136a_3	44	1.22	6.06	−4.28	2700	3.2	−0.27	−6.7

stars, but differ from de Koter et al. (1997) for the R136a_1–a_3 stars and assign WN5 spectral types.

4. Properties of Individual WN Stars

In order to derive stellar parameters, we first need to obtain reddenings, distances, and line-free continuum magnitudes. We therefore investigated reddenings towards these two regions. Since results using *UBV* photometry often differ substantially from those obtained using both UV and optical determinations (compare Parker & Garmany (1993) with Fitzpatrick & Savage (1984) for 30 Dor), we followed an alternative method.

We assumed a uniform reddening along the line of sight to each core. We then compared de-reddened integrated spectra of HD 97950 and R136a with combined theoretical flux distributions of appropriate WNL and early O stars (respectively from Crowther et al. 1995b and Kurucz 1991). We obtain $E(B-V) = 1.23$ for HD 97950 ($\sim 0.2^{\mathrm{m}}$ lower than previously estimated by Moffat 1983) and $E(B-V) = 0.34$ for R136a (supporting Fitzpatrick & Savage 1984). Consequently, we revise the distance to NGC 3603, using HST photometry of 16 stars of known spectral type in this cluster, a new M_v–spectral type calibration for O stars, and the aforementioned reddening. Our result of 10.4 kpc differs substantially from previous estimates of about 7 kpc from *UBV* photometry (Melnick et al. 1989; Moffat 1983) or 8.3 kpc from dynamical techniques (Goss & Radhakrishnan 1969), but we consider our method to be more reliable.

For line-free continuum fluxes, we convolved our HST/FOS spectrophotometry with suitable *ubvr* (Smith 1968) filters. The *b*-band is chosen as our reference continuum, since the coverage of our spectra for HD 97950 stars does not extend to the *v*-band. Together with our reddening determinations, we derive absolute b magnitudes (final column of Table 2). The possible binary nature of these components would affect these magnitudes by $\leq 0.1^{\rm m}$ (assuming an O3–5 V companion with $M_b = -5.1$). We also corrected the b magnitude of R136a$_2$ since its FOS observation is contaminated by light from a$_1$ (de Koter et al. 1997).

We determined terminal wind velocities for the R136 stars from the observed UV resonance line of C IV λ1550. Since UV observations were unavailable for the HD 97950 stars, we estimated their wind velocities from an approximate correlation between FWHM(He II λ4686) and v_∞ for stars of similar spectral type with both UV and optical data.

Model calculations were made using the iterative technique of Hillier (1987, 1990), which solves the transfer equation in the comoving frame subject to statistical and radiative equilibria in an expanding, spherically symmetric, homogeneous, and steady-state atmosphere. We have performed a similar analysis to that presented in Crowther et al. (1995ab), in that we used the hydrogen, helium, and nitrogen line spectra to constrain model parameters. In Fig. 1 we compare synthetic spectra (dotted lines) with observations (solid lines) of individual stars, while in Table 2 we present the derived stellar parameters, which corroborate our expectations of very high luminosities, temperatures, and surface hydrogen abundances. The accuracy of the parameters derived for the HD 97950 stars suffers from the lack of UV and Hα–Hβ observations. Our results support the effective temperatures found by de Koter et al. (1997) for the R136a stars, despite the use of optical (N III–V) rather than UV (O IV–V) diagnostics. However, we derive a substantially higher helium content for R136a$_3$ (H/He$\simeq$3) than obtained by de Koter et al. (1997) (H/He$\simeq$10). This difference might arise from the use of the comoving frame treatment of the line transfer problem in our model, which is more costly but also more precise than the Improved Sobolev Approximation used by de Koter et al.

5. Evolutionary Status and Age of H-Rich WNL Stars

In Fig. 2, we compare the stellar luminosity and hydrogen content of WNL stars in the LMC and the Galaxy with evolutionary predictions by Langer et al. (1994) for an initial $60 M_\odot$ star. This shows clear evidence for the dichotomy between WN8–9 and WN5–6 stars, suggesting different evolutionary paths. Our results support the evolutionary scenario of Crowther et al. (1995b) that H-rich WNL stars descend directly from very massive O progenitors.

Estimates of cluster ages usually rely on evolutionary-model isochrone fits to observed colour–magnitude diagrams. Melnick et al. (1989) and De Marchi et al. (1993) used this method to determine an age of 3±1 Myr for both NGC 3603 and R136. Since surface abundances of WR stars are strongly age dependent, they can be used here to constrain the age of the cluster (we assume coeval star formation). Meynet et al. (1994) suggest a lower age limit of 2.7–3.5 Myr for the onset of WNL stars, yet the discovery of a growing number of hydrogen-rich WNL stars with H/He>2.5 (by number) questions the consistency of evolutionary and spectroscopic definitions of WNL stars (WR stars are defined to have H/He$\leq$2.5 in evolutionary models). We have therefore determined the age of these clusters by matching the surface abundances derived for the WNL stars

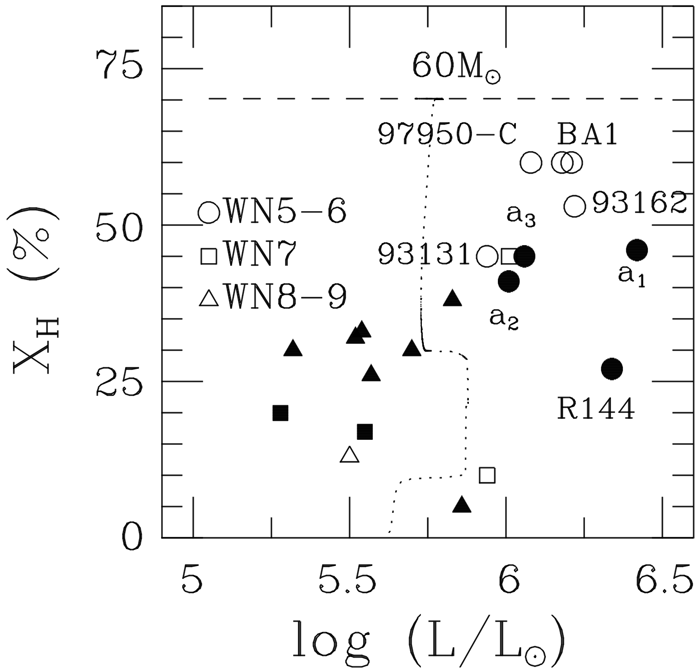

Figure 2. Comparison between luminosity and surface-hydrogen mass fraction, $X_{\rm H}$ (in %), for late WN stars in the Galaxy (open symbols) and the LMC (filled-in symbols), obtained using metal-line analyses, i.e., Crowther et al. (1995a), Crowther & Smith (1997), and this work. For comparison we include the theoretical track from Langer et al. (1994) for $M_{\rm init}$=60$M_{\odot}$ (dotted line, Z=0.02) and show the initial H-content (dashed line).

with model predictions. We find an age of about 2 Myr for both cores, in agreement with de Koter et al. (1997) for R136a.

Finally, how applicable are methods developed for WR galaxies (considered to be a subset of GHRs) to R136 and NGC 3603? Since the He II λ4686 line flux originates principally from WR stars, we should be able to infer the WR populations in these environments following the method developed by Vacca & Conti (1992). For HD 97950, the He II λ4686 line luminosity is 7.1×10^{36} erg s^{-1}, implying the presence of four WN stars, in good agreement with the observed WR population. Further studies of the WR content in nearby GHRs of different metallicity are necessary for reliable inferences of distant starburst galaxies.

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