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SPECTROSCOPIC ANALYSES OF THE WOLF-RAYET STARS IN NGC 3603

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RESUMEN

En base a observaciones realizadas con *HST/NICMOS* se informa sobre las medidas de intensidad de la línea He I λ10830 Å para tres estrellas WR en NGC 3603: HD 97950-A1, B y C. Combinando estas observaciones con relaciones de intensidad de líneas de H I/He II a partir de datos publicados de espectros *HST/FOS* se derivan parámetros estelares para estas estrellas WR. Comparando los resultados previos con nuestro análisis se llega a parámetros similares para HD 97950-A1 y C, pero a una temperatura considerablemente más alta y mayor luminosidad para HD 97950-B. Se confirma que las tres estrellas WR contienen gran cantidad de hidrógeno, posiblemente cercana a la relación solar de H/He, lo cual implica que estas estrellas WR están aún en una fase temprana de su evolución. Al parecer, estas tres estrellas WR en NGC 3603 son las estrellas de mayor masa que se han formado en el cúmulo. Cuando se compara con modelos de evolución estelar, la luminosidad de HD 97950-B indica que esta estrella tuvo una masa inicial mayor que 120 $M_\odot$.

ABSTRACT

We report the measurements of the He I λ10830 Å line strengths with *HST/NICMOS* for the three WR stars HD 97950-A1, B, C in NGC 3603. We combine these new observations with H I/He II line strengths from published *HST/FOS* spectra to derive the stellar parameters of the WR stars. Compared to previous results our analyses yield similar parameters for HD 97950-A1 and C but a considerably hotter temperature and higher luminosity for HD 97950-B. We confirm that all three WR stars contain a large amount of hydrogen, possibly close to a solar H/He ratio, which implies that these WR stars are still in an early phase of their evolution. It appears that the three WR stars in NGC 3603 are the most massive stars that were formed in the cluster. When compared with stellar evolution calculations the luminosity of HD 97950-B indicates that this star had an initial mass higher than 120 $M_\odot$.

Key words: **GALAXY: OPEN CLUSTERS: INDIVIDUAL: NGC 3603 METHODS: NUMERICAL — STARS: INDIVIDUAL: HD 97950 — STARS: MASS-LOSS — STARS: WOLF-RAYET**

1. INTRODUCTION

Blue compact galaxies contain knots of star formation that are estimated to comprise up to 10^5 O stars (Kunth & Sargent 1983; Arnault, Kunth, & Schild 1989). The stars in these regions are thought to be born quasi-simultaneously in an instantaneous "starburst". If these starbursts are observed 2 to 4 Myr after their formation then a large number of O stars have evolved into Wolf-Rayet (WR) stars and observable WR emission features are superimposed on the integrated light from all stars in the slit. Galaxies showing such WR star features are called WR galaxies (Conti & Vacca 1994).

There are no starburst regions of comparable dimension sufficiently close such that we could investigate the spectra of individual stars. Therefore, in order to understand the content of the WR population in massive starbursts, we have to revert to star forming regions within the local group. The best analogs are the 30 Dor region at 50 kpc in the LMC and NGC 3603 at 10 kpc in the Milky Way. Although these regions are a factor

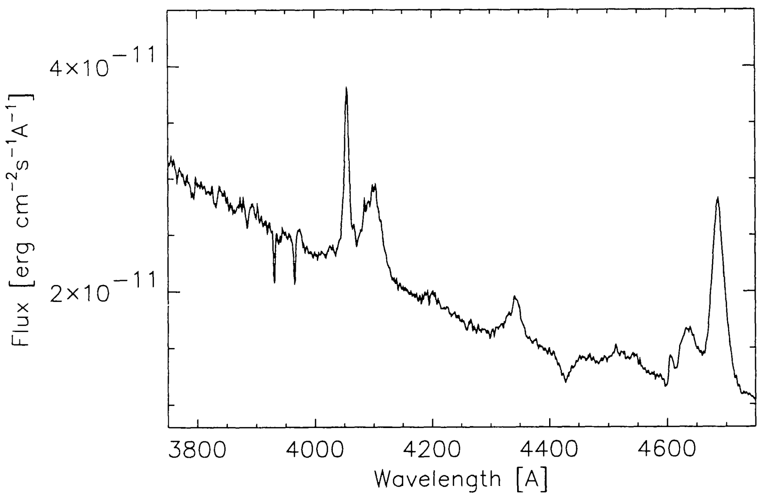

Fig. 1. Flux calibrated spectrum of HD 97950-B observed by *HST/FOS* (Drissen et al. 1995). We postulate that the enhanced flux around 4470 Å is due to the presence of a broad, flat-toped He I λ4471 emission line.

of 100 to 1000 less rich in young stars, they still are comparable in that they are extremely young containing some dozen O3 stars and a few WR stars in their core (Melnick 1985; Parker 1993; Drissen et al. 1995; Vacca et al. 1995; Walborn & Blades 1998; Massey & Hunter 1998).

The WR stars in 30 Dor have been analyzed spectroscopically by de Koter, Heap, & Hubeny (1997) and Crowther & Dessart (1998), whereas the latter paper also includes analyses of the NGC 3603 WR stars. The investigations presented here differ from the previous approaches in that our model calculations include the effects of line blanketing and the effects from the interaction of the He II λ 303 resonance line with metal transitions at the same wavelength. More importantly, because of the lack of observable He I line features, the temperature determinations in the previous analyses have been based on the ionization equilibrium of oxygen and nitrogen, respectively. Below, we present measurements of the He I λ 10830 line strengths by the *NICMOS* camera of the *HST* for the stars in NGC 3603. This allows us to base the temperature diagnostics on the better understood ionization balance of helium and therefore, we are in the position to present a robust spectroscopic analysis of the WR stars in NGC 3603.

2. OBSERVATIONS

Spectra obtained by *HST/FOS* of the NGC 3603 WR stars, HD 97950-A1, B, and C, are published in Drissen et al. (1995) and Crowther & Dessart (1998). These spectra cover the blue spectral range from 3250 Å to 4750 Å. In both publications the authors display normalized spectra and they have both decided that the flux around 4470 Å is at the continuum level in all three WR stars. This decision is crucial because the only unblended He I line in the observed spectral range would be He I λ 4471. Thus, they concluded that the He I line strengths are below the detection limit in these stars. Therefore, Crowther & Dessart (1998) did not have at their disposition the commonly used temperature diagnostic of the He I to He II line strength ratios. Instead, they based their analyses on the N III, N IV, and N V line strengths. However, an inspection of the original flux calibrated spectra reveals enhanced flux around 4470 Å; probably in all three NGC 3603 WR stars but most clearly in HD 97950-B (cf. Fig. 1).

If there are He I λ 4471 emission lines in the spectra of the NGC 3603 WR stars then the model calculations predict that there has to be an even stronger He I λ 10830 emission. For NGC 3603 there are focus test images of *HST/NICMOS* including images with the F108N filter, which is a narrow band filter centered on 10817 Å (Voit 1997). We have used one of the *HST*-archive F108N (n3tr01cor; PI D. Calzetti) images together with narrow band images taken through the F095N and F097N filters in order to derive the strengths of He I λ 10830 in the NGC 3603 stars.

In Fig. 2 we display the differences between the two filters F095N and F097N, and between the helium line filter F108N and F097N, as a function of the brightness in the F097N filter. The observational uncertainty increases for fainter stars but there is an obvious dependence for the F095N–F097N index as a function of

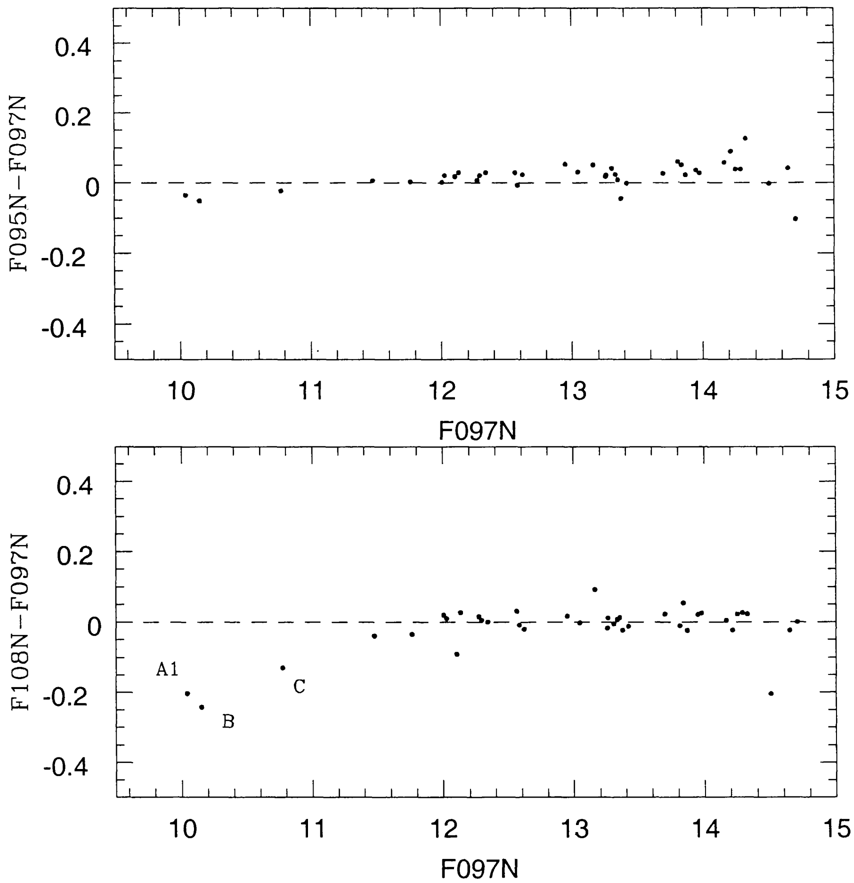

Fig. 2. Magnitude differences of stars in NGC 3603 as a function of instrumental magnitude measured from *HST/NICMOS* images. Top panel: Differences between the two "continuum" filters F095N and F097N (see § 2). Bottom panel: Differences between the He I λ10830 filter F108N and the continuum filter F097N.

brightness. For the F108N–F097N index there appears to be no trend except that there is a clear brightness difference for the three brightest stars. Based on the continuum slope of hot stars, we expect the continuum at the wavelengths of the filters to introduce differences of less than 2%. The NGC 3603 stars are highly reddened which makes the continuum slope even flatter. Therefore, the observed differences between the filter images are most probably due to line features in the stellar spectra. A line that is potentially present in the F097N filter band is He II λ 9762. The observed index F095N–F097N would indicate that the He II is in emission in the three brightest stars, and in absorption in the fainter stars. In our interpretation, the F108N–F097N index is due to the He I λ 10830 line which is in emission for the three brightest stars. If our interpretation above is correct that the F097N filter is influenced by the He II λ 9762 line, then the He I and the He II lines had approximatively equal strengths —both lines are in absorption— in the fainter stars.

The interpretation of the observed magnitude difference is not straight forward. The response in the F108N filter is a convolution of the line profile with the filter transmission. In Fig. 3 we show the predicted line of He I λ 10830 of the best fit model for HD 97950-B together with the wavelength range of the F108N filter with a transmission more than half of its maximum transmission (Voit 1997). It can be seen that the indicated wavelength range covers only the flat top of the emission line. Therefore, in a first approximation, we can interpret the F108N–F097N index simply as the peak intensity of the helium line. In Table 1 we list the peak intensities of He I λ 10830 for the three WR stars HD 97950-A1, B, and C.

These values have to be considered to be approximate because we have not taken into account the influence of the He I line's P Cygni absorption in the blue F108N filter wing and the possible contamination of the F097N observation by a spectral feature as discussed above. The accuracy of the given values are estimated to be of the order of 5% to 10% in continuum units or 20% to 100% of the line strength. We expect that we systematically underestimate the strength of the He I line.

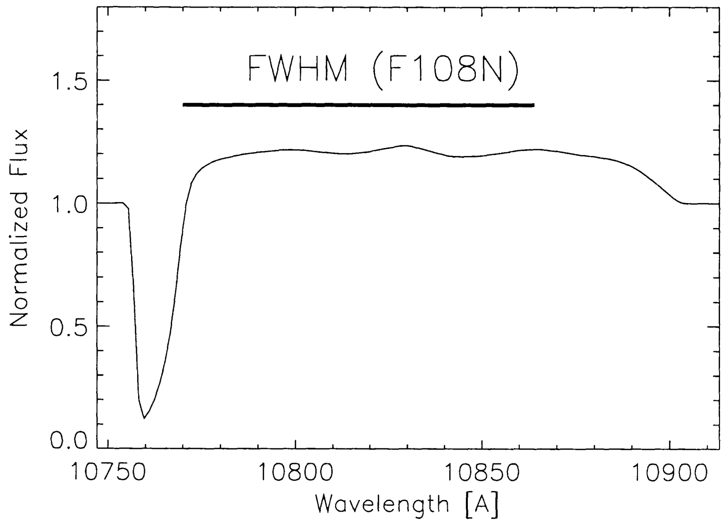

Fig. 3. Synthetic profile of He I λ 10830 compared with the *FWHM* of the *HST/NICMOS* filter F108N.

TABLE 1

EMISSION LINE PEAK INTENSITIES (CONTINUUM UNITS)

HD 97950	A1	B	C
He I λ10830	20%	24%	13%

3. MODEL CALCULATIONS

For the spectroscopic analyses presented below we have used a grid of atmosphere models. The model calculations are based on the "Kiel" code described in Hamann & Schmutz (1987) and Wessolowski, Schmutz, & Hamann (1988). The code solves the radiation transfer problem of a spherically symmetric, expanding atmosphere consistently with the non-LTE rate equations for a 11 level hydrogen atomic model and a 28 level helium model. The radiation transport of the spectral lines is computed in the comoving frame. The temperature structure is derived from the assumption of radiative equilibrium, as described in Schaerer & Schmutz (1994). The models include the effects of line blanketing with the method of Schmutz (1991) and the interaction of the He II λ 303 resonance line with metal transitions within its line profile is approximated by a loss factor of $f = 1 \times 10^{-4}$, as estimated by Schmutz (1998) for a O4 I star. The density stratification is specified by the mass-loss rate and the velocity law of the wind. The supersonic part of the velocity field $v(r)$ is given by the usual "beta law", with $\beta = 1$ and a terminal velocity $v_\infty = 2000\,\mathrm{km\,s^{-1}}$. In the subsonic regions, the velocity field is defined by a hydrostatic density stratification for $\log(g_{\mathrm{eff}}) = 3.5$. The atmosphere grid is calculated for a constant stellar radius, $R_* = 20\ R_\odot$ and hydrogen and helium abundances by number of 0.85 and 0.15, respectively. The parameters that are varied for the grid models are effective temperature and mass loss rate. The models predict the profiles of hydrogen and helium lines and the continuum energy distribution.

4. SPECTROSCOPIC ANALYSES

As pointed out by Schmutz, Hamann, & Wessolowski (1989) the predicted equivalent widths of spectral lines from a spherically expanding atmosphere depends only on two parameters: the effective temperature and the wind density, which is a combination of radius, terminal velocity, and mass-loss rate. It is therefore sufficient to vary the effective temperature and one other stellar parameter, e.g., the mass-loss rate. Therefore, we plot the observed equivalent widths as contours in the T_{eff} - $\dot{M}$ - plane. In Figs. 4 to 6 we display the fit diagrams for the three NGC 3603 WR stars.

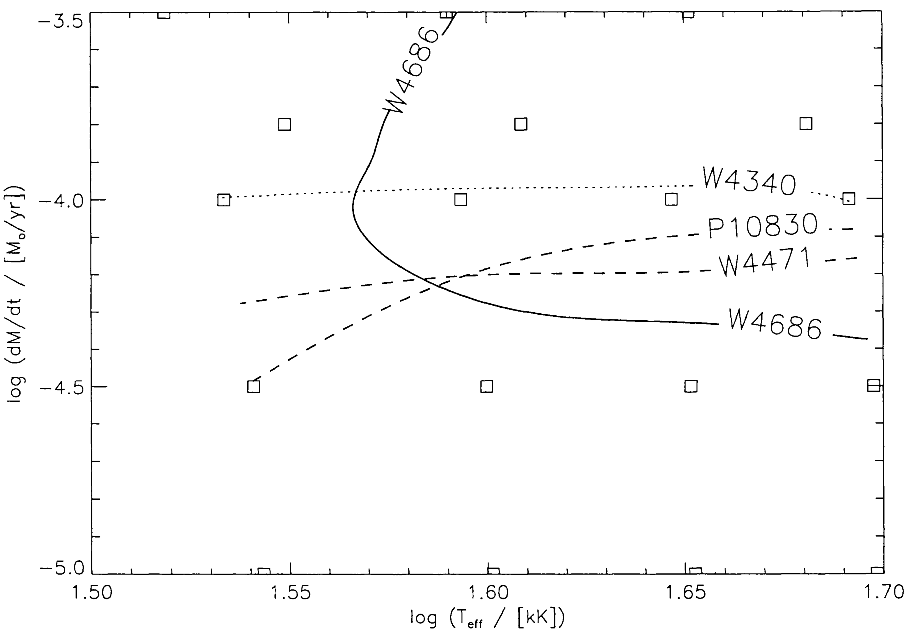

Fig. 4. Fit diagram for HD 97950-A1. The lines denote the location of the observed quantity in the T_{eff} - $\dot{M}$ -plane, i.e., of the equivalent widths for the lines H I λ 4340, He I λ 4471, and He II λ 4686, and the peak intensity in continuum units for He I λ 10830. The squares denote the calculated models.

Generally, the predicted emission line strengths increases for higher mass-loss rates and for He II lines, for higher effective temperature. The fit diagrams reveal that the effective temperature for the three WR stars is correlated with the strengths of the He II λ 4686: the stronger this line is in emission, the hotter the temperature. The strength of the other lines depends mainly on the mass loss rate. The intersection of the He I lines with the He II line determines the effective temperature and the helium mass-loss rate, scaled to $R_* = 20\ R_\odot$. If the contours for He I λ 4471 and He I λ 10830 do not agree then we assume that the He I λ 10830 is the more reliable one because the strength of He I λ 4471 depends critically on the rather uncertain rectification process. In all cases the ratio of the two He I lines agrees within the uncertainties with the predicted ratio.

In Table 2 we list the stellar parameters deduced from our analyses with a comparison to the values determined by Crowther & Dessart (1998)[1] The values of HD 97950-C are more uncertain because this star has the weakest He I λ 10830 and therefore, the highest uncertainty, up to 100%, in its line strength. The stellar radius follows from the observed absolute brightness, M_b, and the flux at 4270 Å as predicted by the atmosphere models. For the observed absolute brightness we adopt the values derived by Crowther & Dessart (1998): $M_b = -7.49$ -7.42 an -7.02 for HD 97950-A1, B, and C, respectively. The mass-loss rates then follow from scaling the value obtained from the fit diagrams with the factor $(R_*/20\ R_\odot)^{3/2}$ (see Schmutz, Hamann, & Wessolowski 1989).

In principle we should also take into account the difference between the adopted terminal velocity for the model grid and the observed terminal velocity. However, for the HD 97950 stars there are no accurately known terminal velocities and because we find that our model spectrum fits the lines of HD 97950-B (see Fig. 7), we assume that all WR stars have a terminal velocity of $v_\infty = 2000\,\mathrm{km\,s^{-1}}$. This is slightly in contradiction with the results of Crowther & Dessart (1998), who find terminal velocities between 2500 and 2700 km s^{-1}, but it has no significant influence on the derived mass loss rates within the accuracy of our results.

In the fit diagrams there is a difference between the mass loss rate indicated by helium and that deduced from the hydrogen line strength. This difference indicates that the abundance ratio of the grid models, H/He = 5.7 by number, is not correct. We note that in all three fit diagrams the H I λ 4340 line strength yields a higher value. Thus, we conclude that our model grid is based on a too low hydrogen to helium ratio. If we

[1]The parameter T_{eff} used here corresponds to T_* in Crowther & Dessart.

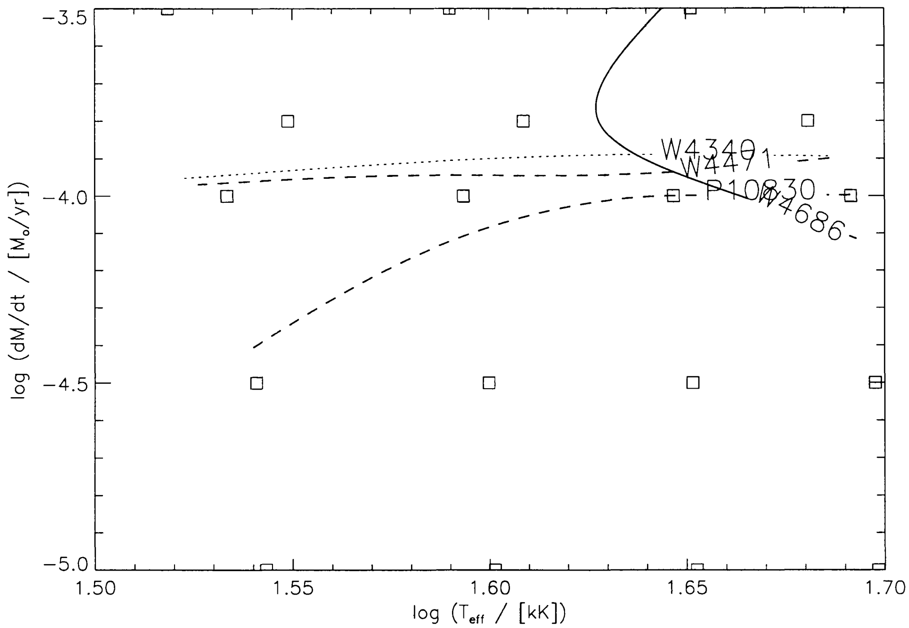

Fig. 5. As Fig. 4 but for HD 97950-B.

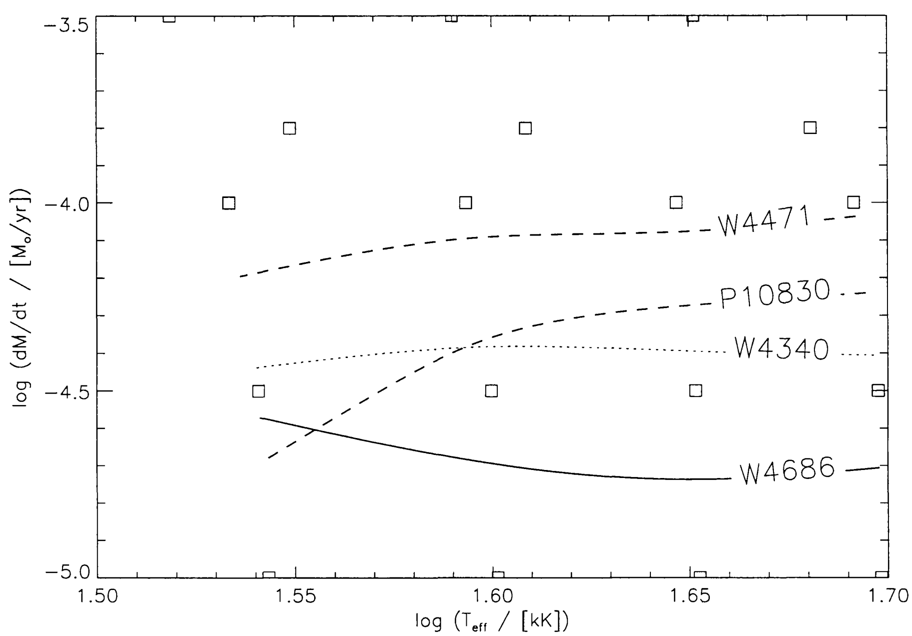

Fig. 6. As Fig. 4 but for HD 97950-C.

assume that the indicated mass-loss rates by hydrogen and helium can be used to calculate independently the fractional rates for hydrogen and helium, respectively, then we find that the abundance ratio should be close to solar. However, as mentioned above, it is likely that we have underestimated the strength of He I λ 10830, which implies that we underestimate the helium abundance. From the estimated uncertainty for the He I peak intensity, we find that the hydrogen to helium ratio could be as low as H/He = 5.

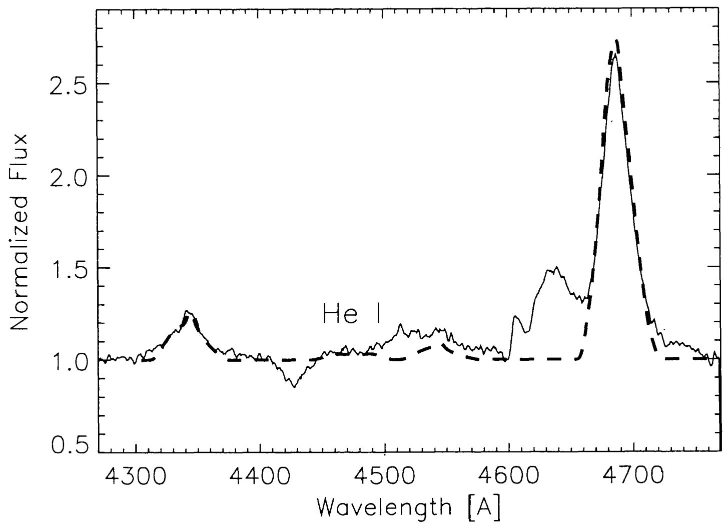

Fig. 7. Comparison of the observed normalized HST/FOS spectrum of HD 97950-B (full drawn line) with the synthetic spectrum calculated with the parameters obtained from the fit diagram (Fig 5). The model atmosphere does not include nitrogen which is responsible for the emission features around 4640 Å and the additional emission at 4520. The absorption feature at 4430 Å is a diffuse interstellar band.

TABLE 2

DERIVED STELLAR PARAMETERS

HD 97950	A1	B	C
T_{eff} (10^3 K)[a]	38	46	36
T_{eff} (10^3 K)[b]	37	35	39
R_* this work [$R_\odot$]	26	25	23
R_* C&D [$R_\odot$]	30	33	23
$\log(L/[L_\odot])$ this work	6.1	6.4	5.9
$\log(L/[L_\odot])$ C&D	6.19	6.16	6.06
$\log(\dot{M}/[M_\odot \mathrm{yr}^{-1}])$ this work	–4.0	–3.8	–4.5
$\log(\dot{M}/[M_\odot \mathrm{yr}^{-1}])$ C&D	–4.20	–4.05	–4.65

[a] This work.

[b] Crowther & Dessart.

5. DISCUSSION

The measurement of the He I λ 10830 line strengths allowed us to analyze the WR stars in NGC 3603 based on the He I/He II line ratio. In principle, we consider this procedure to be more robust than analyses based on metal line ratios. In order to synthesize reliably metal lines, like those of the nitrogen ions N III, N IV, and N V, much more complicated rate equations and additional processes with are required, like dielectronic recombination. However, the results presented here are preliminary. We need to evaluate the line strength of He I λ 10830 more accurately than done in Sect. 2. We suspect that with the values given in Table 1 we underestimate the strengths of the He I lines. With our stellar parameters the luminosities and the mass-loss rates of the three WR stars are correlated whereas previously, Crowther & Dessart (1998) derived a lower luminosity for HD 97950-B than for star A1, but star B has undoubtly the higher mass loss rate than star A1. The correlation between luminosity and mass loss rate is an expected result if the winds are driven by radiation pressure. However, for WR stars radiation pressure is not certain to be the driving force and we find values higher than unity for the wind momentum to radiation momentum ratio as is typical for WR stars. The stellar parameters given in Table 2 yield ratios of $\dot{M}v_\infty \,/\, L/c = 7$, 6, and 4 for HD 97950-A1, B, and C, respectively. This indicates that these stars are real WR stars in the sense that they have much stronger winds than predicted by the present radiation driven wind theory for their luminosities (cf. Kudritzki et al. 1992).

We confirm the result of Crowther & Dessart (1998) that the three WR stars are rich in hydrogen. Our preliminary results indicate H/He ratios between solar and H/He ≈ 5 by number. With such a high hydrogen abundance these stars are not considered to be WR stars from the point of view of stellar evolution calculations. This implies that the observed mass loss rates of these stars are much higher than used in the stellar evolution calculations during the pre-WR evolutionary phase. A similar conclusion has been stated by de Koter et al. (1997) for the R136 WR stars at the center of 30 Doradus. This leads us to suspect that it is part of normal stellar evolution for the most massive stars to enter a WR phase almost immediately after their formation. In this connection we use the term "WR phase" to denote very high mass loss-rates with $\dot{M}v_\infty/(L/c) > 1$. The WR feature observed in WR galaxies would then originate from the most massive stars still in the hydrogen burning phase. Our hypothesis implies that standard stellar evolution calculation underestimates the mass loss in the early phases of stellar evolution of massive stars. This statement agrees with the tendency of the stellar evolution theorists not to use standard mass-loss rates but rates increased by a factor of two (e.g., Meynet et al. 1994). Their argument is that they need the increased rates in order to reproduce the observed O/WR ratios (cf. Maeder 1997).

With $L = 2.5 \times 10^6\ L_\odot$ HD 97950-B is more luminous than HD 93162 and R144 (Crowther & Smith 1997). A comparison with predicted luminosities from stellar evolution calculations (e.g., Meynet et al. 1994) reveals that its luminosity indicates an initial mass in excess of 120 $M_\odot$. Thus, HD 97950-B is a candidate to be the most massive known star. However, there is indication that HD 97950-B is a binary (Drissen et al. 1995; Moffat, Seggewiss, & Shara 1985). This would reduce the intrinsic brightness of the WR star depending on the brightness of its companion. In the worst case, the two stars are of equal optical brightness which would reduce the derived luminosity by a factor of two. This correction would be sufficient for HD 97950-B to lose the status of the most massive star. On the other hand, as argued by Crowther & Dessart (1998), the influence of the companion is likely to be as little as 0.05 dex, which would be sufficient to be still on equal terms with R144.

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