

Progress in model atmosphere studies of Wolf-Rayet stars

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Abstract. Recent progress in the quantitative analysis of Wolf-Rayet stars is reviewed, emphasising the role played by choice of spectral diagnostics, clumping and line-blanketing on derived stellar properties. The ionizing properties of WR stars are discussed, based on clumped, line-blanketed models for WN and WC stars. The role of metallicity and mass-loss is assessed, and the role of H II regions as probes of predicted Lyman continuum distributions. Suggestions are made for differences in observed properties of WCE and WO subtypes.

1. Introduction

It is only through understanding the physics of massive stars, their atmospheres, radiation, and evolution, that we will be able to make progress in many aspects of astrophysics. Particularly important is the quantitative study of young starbursts, which are dominated by the effects of O-type and Wolf-Rayet stars. WR stars comprise only 10% of the massive stellar content in the Galactic mini-starburst, NGC 3603, yet they contribute 20% of the total ionizing flux and 60% of the total kinetic energy injected into the ISM (Crowther & Dessart 1998). In order that young starbursts can be properly studied, both nearby, and at high-redshift, it is crucial that the properties and evolution of O-type and WR stars spanning a range of initial metallicities are determined. In this review, I will consider recent theoretical progress in WR analyses that has been made towards this goal, focusing especially on spectroscopic and ionizing properties.

2. Quantitative spectroscopy of WR stars

Quantitative analysis of WR stars represents a formidable challenge, since their stellar winds are so dense that their photospheres are invisible, so that the usual assumptions of plane-parallel geometry and local thermodynamic equilibrium (LTE) are wholly inadequate. A minimum requirement is to consider non-LTE in an extended, expanding atmosphere for multi-level atoms. At present, four independent model atmosphere codes are capable of routinely analysing the spectra of WR stars, considering complex model atoms of hydrogen, helium, nitrogen, carbon and oxygen, developed by D.J. Hillier (Pittsburgh), W.-R. Hamann (Potsdam), W. Schmutz (Zürich) and A. de Koter (Amsterdam), the former also implemented by P.A. Crowther (London) and F. Najarro (Madrid). Each code solves the non-LTE radiative transfer problem, with line blanketing, electron scattering, radiative equilibrium and clumping also accounted for in most cases. Individual calculations are generally computationally demanding, so that a large parameter space can not be readily explored. The solution is to solve

the transfer problem in the Sobolev approximation, rather than the co-moving frame (*e.g.*, de Koter *et al.* 1993; Machado, these Proceedings). Overall, consistency between results from these codes is generally very good (see however De Marco *et al.*, these Proceedings).

3. Progress in the determination of stellar properties

In the simplest case, the stellar properties of WR stars are derived from the following diagnostics: two spectral lines from adjacent ionization stages of helium (He II $\lambda 5412$ and He I $\lambda 5876$ most commonly), plus the absolute magnitude in a standard filter (typically M_v) and the terminal wind velocity (v_∞), often measured from UV resonance lines. The default number of model parameters available is therefore four, R_* , T_* , \dot{M} and v_∞ . Stellar temperatures for extended atmospheres are related to the inner boundary of the model atmosphere (generally around Rosseland optical depth $\tau_{\text{Ross}} \simeq 20$), which often deviates significantly from the ‘effective’ temperature, at $\tau_{\text{Ross}} = 2/3$ (Hamann 1994). Schmutz *et al.* (1989) identified the so-called transformed radius (R_t), a measure of wind density, which relates R_* , \dot{M} and v_∞ so that almost identical spectra are produced for fixed R_t , reducing the number of free parameters. In this way, a large number of WR stars in the Galaxy and Magellanic Clouds have been analysed by Hamann and co-workers, comparing observed line equivalent widths to interpolations of large model grids (see Hamann, these Proceedings). However, actual WR stars are not pure helium stars, so that the contribution of other elements is necessary, except in very metal-deficient regions.

3.1. The effect of including metals

It was soon established that the wind properties of WR stars were affected by the presence of metals, notably carbon and nitrogen (Hillier 1988; 1989). For WN stars, metals are trace elements ($\sim 1\%$ in nitrogen by mass), so pure He analyses compare relatively well with those additionally including carbon and nitrogen, which control the outer wind properties. In late-type WN (WNL) stars hydrogen contributes significantly (up to $\sim 50\%$ in extreme cases). Determination of atmospheric contents requires detailed analysis of individual stars through a comparison between theoretical line profiles (*e.g.*, H α for hydrogen) and spectroscopic observations (*e.g.*, Crowther *et al.* 1995a). In WC stars, it was soon realised that pure He studies were inadequate to obtain reliable stellar properties, since carbon mass fractions are $\sim 40\text{--}50\%$ (Hillier 1989). WC analyses need to use He and C diagnostics simultaneously in order that the stellar and chemical properties may be determined. The degree of complexity in atomic data handled for carbon has a great influence on predicted line strengths (Hillier & Miller 1999).

This technique has a major disadvantage in that it is time consuming and computationally expensive. Nevertheless, derived stellar properties can be considered robust, while model deficiencies may be readily identified. Studies of individual stars have now been performed for Galactic, Magellanic Cloud and other Local Group WR stars using 4m class ground-based telescopes (*e.g.*, Smith *et al.* 1995 in M 33). Source confusion becomes problematic at large distances from ground-based observations ($0.''8$ corresponds to a scale of 3 parsec at the modest distance of M 33).

3.2. Choice of spectral diagnostics

Although helium and carbon diagnostics are combined to derive the properties of WC stars, the majority of WN studies use solely helium. Early results for weak-lined, early-type WN (WNE) stars led to surprisingly low stellar temperatures (*e.g.*, Hamann *et al.* 1995), which were comparable with WNL stars instead of strong-lined WNE stars. Crowther *et al.* (1995b) demonstrated that the stellar temperatures of weak-lined WNE stars are in line with strong-lined examples, if nitrogen diagnostics (*e.g.*, N IV $\lambda 4058$, N V $\lambda 4603-20$) are used instead of helium. Results from helium are more straightforward, since the availability and quality of its atomic data is superior to nitrogen. However, He I lines are typically formed at large radii from the core, and are extremely weak in hot WR stars, with the exception of 10830\AA that is observationally challenging. In contrast, N IV-V lines originate from the inner wind and are readily observed. Consequently, nitrogen may serve as a more sensitive diagnostic of the stellar temperature.

Hamann & Koesterke (1998a) have recently re-analysed a large sample of Galactic WN stars and arrived at similar conclusions to Crowther *et al.* (1995b). In Fig. 1, the stellar temperatures and luminosities of WN stars obtained by alternative helium and nitrogen diagnostics are compared. Consistent results are obtained for WNL stars, while higher temperatures and luminosities are obtained from nitrogen diagnostics for WNE stars, especially weak-lined stars. Differences in derived temperatures may be large, increasing by a factor of up to two (from 36 kK to 71 kK for the WN5(h) star WR 49). The change in luminosity is greater still – increasing by a factor of six in this star because of the sensitive dependence of bolometric correction (BC) with temperature. Parameters derived from helium or nitrogen lines should be fully consistent, so that discrepancies indicate that something is missing in current models. Perhaps clumps in the wind affect the ionization balance in the He I line forming region of WNE stars – this may also be relevant to the (poorly predicted) strength of He I P-Cygni absorption

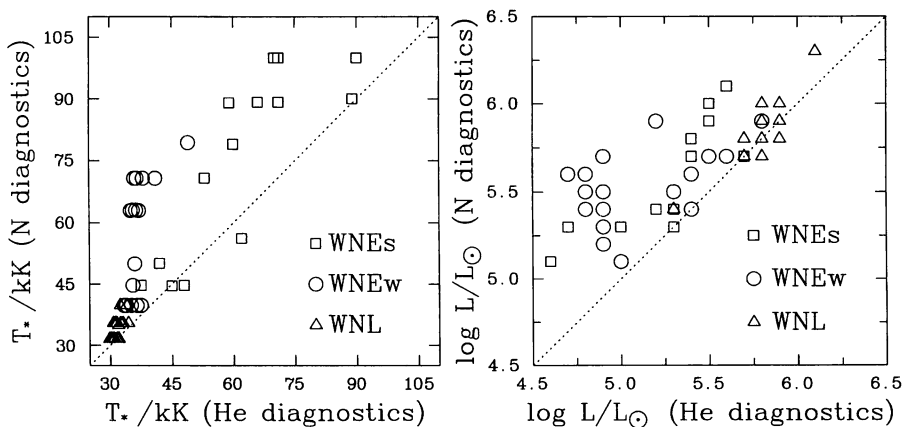


Figure 1. Comparison between stellar temperatures and luminosities of Galactic WN stars obtained from optical helium diagnostics (Hamann *et al.* 1995) and nitrogen diagnostics (Hamann & Koesterke 1998a), adjusted for the assumed absolute magnitudes of the latter work. Larger stellar temperatures imply dramatically higher luminosities for weak lined WNE stars.

components. *Whatever the cause, care should be taken when comparing results obtained from different spectral diagnostics.* Schmutz (priv. comm.) suggests that photon loss at He II $\lambda 303\text{\AA}$ resolves these differences.

Detailed analyses of WC-type stars have also been carried out (*e.g.*, Koesterke & Hamann 1995; Gräfener *et al.* 1998) using helium, carbon and occasionally oxygen diagnostics. However, the additional number of free parameters (C/He, O/He) has restricted the sample analysed to date, and oxygen diagnostics lie in the near-UV, requiring space based observations (Hillier & Miller 1999). Since the UV and optical spectra of WC stars are dominated by overlapping broad emission lines, it is difficult to assign suitable continuum windows. Analyses typically consider the continuum and line spectra in isolation, namely that interstellar extinctions are obtained by matching continua to de-reddened observations, while theoretical line profiles are compared to normalized spectra. A less error-prone approach is the comparison between de-reddened fluxed observations and synthetic spectra, accounting for line overlap. In this way, erroneously defined continuum windows (*e.g.*, at He II $\lambda 5412$, Hillier & Miller 1999), and unusual UV extinction laws, may be identified.

3.3. IR analyses

Studies discussed above rely exclusively on optical (or occasionally UV) spectral diagnostics. The first infra-red (IR) spectroscopy of WR stars was obtained by Williams (1982), although recent advances mean that this wavelength region can now be used to observe a large sample of WR stars, particularly those obscured at shorter wavelengths. Crowther & Smith (1996) have assessed the reliability of IR analyses of WR stars by studying two WNE stars for which UV and optical data sets were also available. They found that results from exclusively near-IR observations were in good agreement with optical studies, and later with *ISO* spectroscopy for WR 136 (R. Ignace, priv. comm.). Bohannan & Crowther (1999) have recently compared optical and IR analyses of Of and WNL stars.

Quantitative IR studies of WN-like stars at our Galactic Centre have recently been presented (*e.g.*, Najarro *et al.* 1997a). Unfortunately, the majority of these stars are relatively cool, so that the sole *K*-band He II diagnostic at $2.189\mu\text{m}$ is unavailable. Without a second ionization stage, a unique temperature may not be obtained, so that mass-loss rates and abundances are uncertain. Dessart *et al.* (these Proceedings) attempt to solve this by using the stronger He II $3.09\mu\text{m}$ line in the thermal IR as a temperature diagnostic. Another limitation with the *K*-band is that the prominent He I line at $\lambda 2.058\mu\text{m}$ is strongly affected by (metallicity dependent) line blanketing effects, as shown by Crowther *et al.* (1995a, 1998). Problems with the quantitative analysis of low temperature stars are neatly summarised by Hillier *et al.* (1998) for the Galactic early B-type supergiant HDE 316285. They obtained a wide range of possible mass-loss rates and surface H/He abundances for this star, despite the availability of high quality optical and near-IR spectroscopy.

4. Relaxing the standard assumptions

Model calculations so far discussed use R_* , T_* , \dot{M} and v_∞ , plus elemental abundances as free parameters. However, observational evidence suggests that presently assumed quantities, such as the velocity law and homogeneity may be inappropriate. In addition, it is well known that line-blanketing by thousands

of transitions in the ultraviolet (UV) and extreme ultraviolet (EUV) need to be incorporated into calculations. Each additional relaxation adds (at least) one new variable parameter to the existing set. Consequently, of the several hundred WR stars thus far analysed quantitatively, to date studies of only two have included assorted elements, a variety of velocity laws, clumping and line-blanketing (Schmutz 1997; Hillier & Miller 1999).

4.1. Variations in velocity law

Generally, a uniform form of the radial velocity field $v \propto v_{\infty}(1-R/r)^{\beta}$ is assumed, of exponent $\beta = 1$. Tailored analysis are required to test alternative laws. Unfortunately, different velocity forms are frequently able to reproduce the observed spectrum equally well (Hillier 1991). In some cases, specific exponents produce optimum agreement, provided with a suitably large range of spectroscopic observations. From a careful comparison of the optical and far-red appearance of the LBV P Cygni, Najarro *et al.* (1997b) found that a $\beta = 4.5$ law provided the best match. Including mid-IR *ISO* observations led to a revision to $\beta = 2.5$ (Najarro *et al.* 1998). Unfortunately, a long wavelength observational baseline is rarely available. Schmutz (1997) went a stage further by *deriving* the form of the velocity law in WR 6 from hydrodynamics, which deviated significantly from a standard law, although $\beta \simeq 3$ in the outer wind. As an indication of the reliability of this approach, the emission profile of He I $\lambda 10830$ was reproduced better than in previous studies.

4.2. Wind inhomogeneities and departures from spherical symmetry

WR winds are known to be inhomogeneous, from both observational and theoretical arguments (Willis, these Proceedings). However, homogeneity has been assumed by the majority of atmosphere studies to date. Consideration of electron scattering – causing a frequency redistribution of line photons – provides the key to spectral synthesis (Hillier 1984; 1991b). Homogeneous models often overestimate the strength of electron scattering wings relative to the overall emission line intensity. Since free-free emission and radiative recombination both scale as the square of the density, whereas the electron scattering opacity scales linearly with density, estimates of wind inhomogeneities may be estimated by varying volume filling factors and mass-loss rates so that line profiles and electron scattering wings are simultaneously reproduced. In line transfer calculations performed to date, several simplifying assumptions are made, namely that models are composed of radial shells of material, with no inter-clump medium. The variation of clumping factor with radius is taken into consideration in some cases since radiative instabilities are not expected to be important in the inner wind.

Schmutz (1997) and Hillier & Miller (1999) have estimated mass-loss rates of WR 6 and WR 111 which are a factor of 3–4 lower than those resulting from homogeneous models. Hamann & Koesterke (1998b) have also applied an identical approach to a sample of four WR stars, with similar results obtained. Substantially lower mass-loss rates of WR stars has importance in evolutionary model calculations and in reducing the momentum (alternatively opacity) problem of driving WR winds (Gayley *et al.* 1995).

To date, all spectroscopic studies have assumed spherical symmetry. Evidence from spectropolarimetry indicates that this is appropriate for $\sim 85\%$ of cases (Harries *et al.* 1998). For the remaining stars, density ratios of 2–3 are implied from observations. Future calculations will need to consider departures

from spherical symmetry. Indeed, the wind of the prototypical WNE star WR 6 is grossly asymmetric.

4.3. Influence of line-blanketing

Observations of the forest of iron lines in the UV spectra of WR stars, demonstrate the large influence that line-blanketing by Fe-group elements has on the emergent spectrum. The neglect of blanketing reveals itself through inconsistencies of model fits, and results from comparison with ionized nebulae. The principal problem in accounting for line-blanketing is being able to handle the effect of tens of thousands of line transitions in the radiative transfer calculations. To date, Schmutz, de Koter and Hillier have made allowance for blanketing, albeit using different techniques, each with their own advantages and disadvantages. Monte Carlo sampling by Schmutz (1994, 1997) allows the opacity of a huge number of lines to be considered, although spectral synthesis of individual features in the UV is not possible, while the reverse is true for Hillier & Miller (1998) who use a 'super-level' approach, treating the transfer problem correctly. In Fig. 2 models for a WCE star are compared, in which increasing number of elements are included, He, C, O, and Fe. Carbon and oxygen have a considerable effect on the UV and optical energy distribution of the models, with Fe modifying the emergent UV flux distribution (Hillier & Miller 1998, 1999). What effect does allowing for clumping and line-blanketing have on the resulting stellar properties? In Table 1 the results of Schmutz (1997) and Hillier & Miller (1999) for WR 6 (WN4b) and WR 111 (WC5) are compared with earlier studies. Stellar temperatures and bolometric luminosities of the blanketed analyses are considerably greater than those from unblanketed models, with a significant EUV excess (and corresponding increase of BC), while mass-loss rates are significantly lower, as a result of considering clumped winds. For the case of WNL stars, Crowther *et al.* (1998) and Herald *et al.* (these Proceedings) find that blanketing has a minor influence on stellar temperatures (though the EUV energy distribution is affected). This result is in apparent contradiction

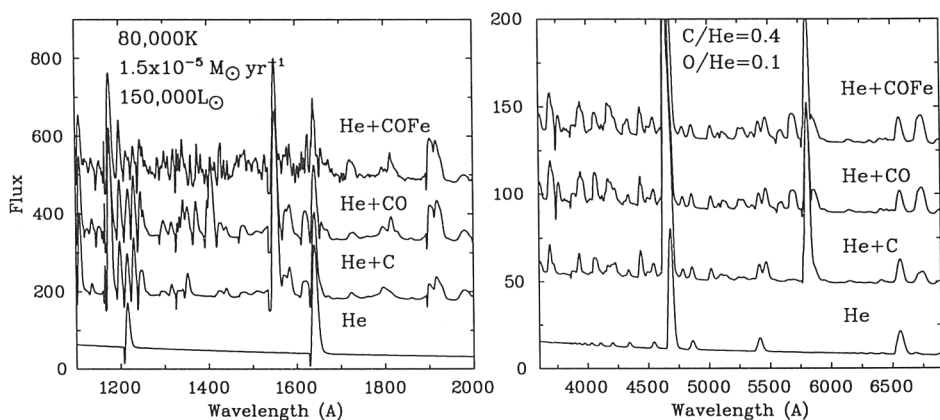


Figure 2. Comparison between a WC model at fixed stellar parameters, including He, He+C, He+C+O and finally He, C, O and Fe using the Hillier & Miller (1998) code.

Table 1. Comparison of WR stellar properties derived from recent spectroscopic analyses including blanketing and clumping (Schmutz 1997 S97; Hillier & Miller 1999, HM99) relative to earlier studies not accounting for these effects (Schmutz *et al.* 1989 SHW89; Koesterke & Hamann 1995 KH95; Hamann *et al.* 1995 HKW95)

T_* (kK)	$\log L$ (L_\odot)	$\log \dot{M}$ ($M_\odot \text{yr}^{-1}$)	BC (mag)	$\frac{\dot{M}v_\infty}{L/c}$	diagnostics	ref.
WR 6 = HD 50896 (WN5 or WN4b)						
71	5.2	-4.1	-3.7	37	He	HKW95
84	5.7	-4.5 (cl)	-4.9	6	He	S97
WR 111 = HD 165763 (WC5)						
35	4.6	-4.6	-3.2	90	He	SHW89
62	5.0	-4.3	-4.0	50	He+C	KH95
90	5.3	-4.8 (cl)	-4.7	10	He+C+O	HM99

with the analysis of LMC WN9–11 stars by Pasquali *et al.* (1997) using *grids* of line-blanketed models. Pasquali *et al.* revealed considerably higher temperatures relative to earlier unblanketed tailored analyses (Crowther *et al.* 1995a; Crowther & Smith 1997). Subsequent *tailored* spectroscopic analyses including blanketing by Pasquali (priv. comm.), agree well with the parameters obtained by Crowther & Smith.

Our ability to synthesize individual and groups of Fe lines in the spectrum of WR stars suggests that they can be used to derive Fe-group abundances. UV spectra of O-types (Haser *et al.* 1998) and optical spectra of A supergiants (McCarthy *et al.* 1995) have previously been used to determine Fe-contents in extra-galactic environments, though few detailed attempts have been made using WR stars (see Hillier & Miller 1999). As an indication of the potential for the future, Crowther *et al.* (1999) have recently used *HST* spectroscopy of the erupting LBV V 1 in the giant H II region NGC 2363, within the Magellanic irregular galaxy NGC 2366 (3.5 Mpc) to determine its Fe-abundance.

5. What are the ionizing spectra of Wolf-Rayet stars?

The ionizing flux distribution of WR stars has importance in the study of extra-galactic regions containing young massive stars (giant H II regions, WR galaxies etc.). Recent results for O-types incorporating non-LTE and wind effects have resulted in improved agreement with observations of associated H II regions (*e.g.*, Stasińska & Schaerer 1997). It is equally important that suitable ionizing distributions for WR stars are used, which affect determinations of IMFs and ages. Since the Lyman continuum distributions of WR stars is not directly visible (due to absorption by intervening hydrogen), indirect methods need to be used to verify current models (*e.g.* Schmutz 1996).

5.1. Nebulae as probes of the Lyman continuum flux distribution

The principal work in this field was that of Esteban *et al.* (1993) who combined pure helium, unblanketed WR model fluxes (Schmutz *et al.* 1992) with observed properties of WR ring nebulae, to investigate the properties of the central stars. Esteban *et al.* varied stellar temperatures until agreement was reached between the observed and predicted nebular properties. Comparisons with (independent)

stellar analyses of the central stars was found to be reasonable, except that lower temperatures were required from the photo-ionization models for WNL stars.

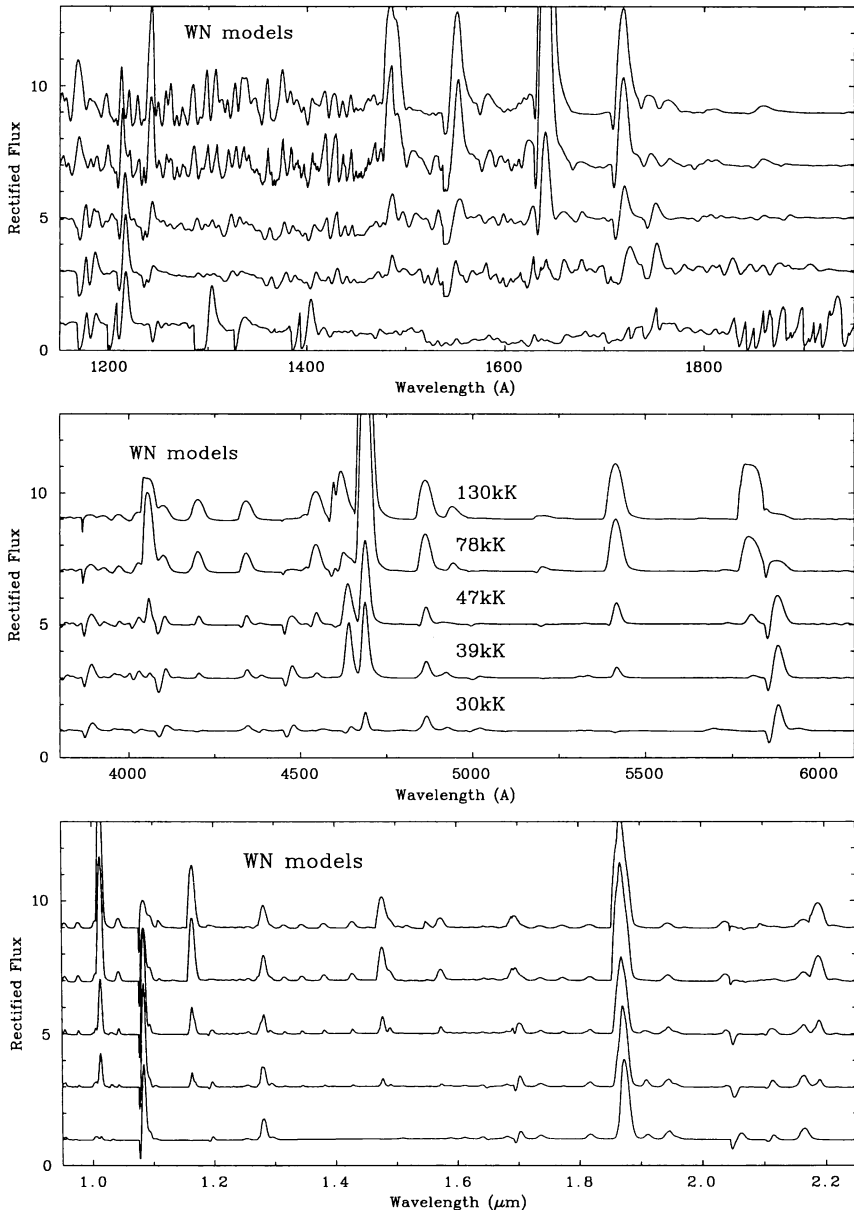


Figure 3. Synthetic UV, optical and near-IR spectra of WN stars for a variety of temperatures using the Hillier & Miller (1998) line-blanketing code, spanning WN4 to WN9. Assumed parameters are $\log(\dot{M}/M_{\odot}\text{yr}^{-1}) = -4.6$, $\log(L_{*}/L_{\odot}) = 5.5$, $v_{\infty} = 2000 \text{ km s}^{-1}$, plus H : He : C : N : Si : Fe mass-fractions (in %) of 0.2 : 98 : 0.03 : 1.4 : 0.09 : 0.15 and a filling factor of 0.1.

Recently, Crowther *et al.* (1998) and Pasquali *et al.* (these Proceedings) have returned to this technique, newly considering the influence of line-blanketing using the Hillier and Schmutz codes. They depart from Esteban *et al.* in that ionizing flux distributions *obtained* from a stellar analysis of the central star are used in the photo-ionization modelling.

Crowther *et al.* (1998) compared line-blanketed and unblanketed flux distributions resulting from stellar analyses of the WN8 star WR 124, with observations of its associated nebula, M1-67. They found that the blanketed model predicted the nebular temperature and ionization balance much better than the unblanketed case. Allowance for improved nebular properties of M1-67 from Grosdidier *et al.* (1998), particularly the radial density distribution, leads to even better agreement with observations. Pasquali *et al.* (these Proceedings) find good agreement between the predicted and observed nebular properties of NGC 3199, using stellar flux distributions from analyses of its central WNE star WR 18 with the Schmutz and Hillier codes. Unfortunately, the observed properties (T_e , N_e , ΔR , abundances etc.) of most WR nebulae at present are insufficiently well determined to use as tests of stellar models.

5.2. The effect of blanketing on ionizing fluxes

Overall, spectral synthesis and photo-ionization modelling results give us confidence in the validity of current line blanketed Wolf-Rayet codes. Since the only generally available WR models are unblanketed, pure helium energy distributions of Schmutz *et al.* (1992), how do new results compare? The calculation of a large multi-parameter grid of line-blanketed models is a formidable computational challenge. For the moment, I have obtained models for WR stars with the Hillier & Miller (1998) code, varying solely temperatures (30 to 150 kK). WN models span WN4 to WN9 spectral types and include the effects of complex model atoms of H I, He I-II, C II-IV, N II-V, Si III-IV and Fe III-VII. In Fig. 3, selected synthetic UV, optical and near-IR spectra are presented. Similar calculations for WC stars spanned WC4 to WC9 and included He I-II, C II-IV, O II-VI

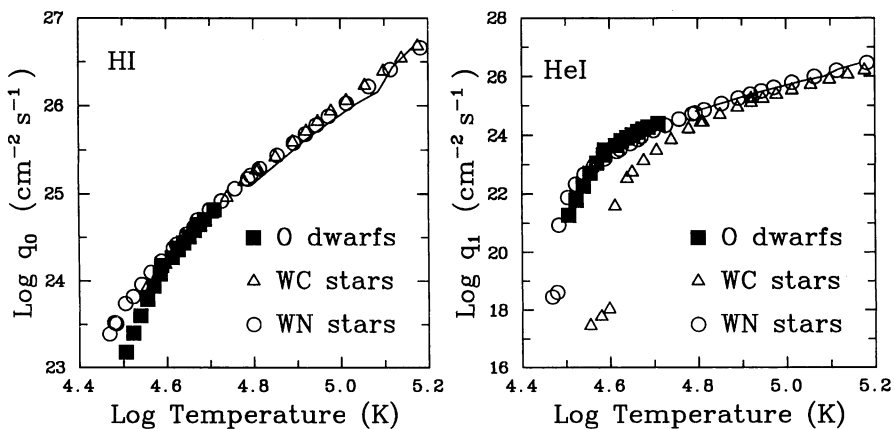


Figure 4. Comparison between ionizing fluxes ($\text{photons s}^{-1} \text{cm}^{-2}$) of line-blanketed WN and WC models with O-types (Schaeerer & de Koter 1997), and pure helium WR models of Schmutz *et al.* (1992, solid line).

and Fe III-VII in detail. Their predicted Lyman continuum distributions are fairly soft in all cases, with negligible emission above the He⁺ edge at 54 eV.

In Fig. 4 the ionizing fluxes of these models in the H⁰ and He⁰ continua (in units of photons s⁻¹ cm⁻²) are compared with recent solar metallicity O-star models (Schaerer & de Koter 1997), plus the pure helium Schmutz *et al.* (1992) models. The line-blanketed WN flux distributions support the pure helium Schmutz *et al.* (1992) predictions, although the additional blanketing from C and O in WC stars produces a softer ionizing spectrum at an identical temperature, with negligible flux emitted $\lambda \leq 300 \text{ \AA}$. WR stars also compare closely with comparable temperature O-types in their ionizing flux per unit area.

5.3. The effect of wind density

Schmutz *et al.* (1992) stress the importance of stellar wind density on the ionizing flux distributions of WR stars, such that emission at $\lambda \leq 228 \text{ \AA}$ relies on the WR wind being relatively transparent. Denser winds, such as those presented above for representative Galactic WR stars, destroy photons beyond this edge. To illustrate this, additional calculations have been performed for lower wind densities. Although a mass-loss versus metallicity (*Z*) scaling for WR stars has not been identified, let us assume that their winds are radiatively driven with a dependance of $\dot{M} \propto Z^{0.5}$ (as obtained for radiatively driven O-type stars by Kudritzki *et al.* 1989).

I have taken the 150 kK WC model, whose synthetic spectrum approximates a WC4-type star, and solely reduced its mass-loss rate (by a factor of three) and Fe-content (by a factor of ten). The optical and ionizing spectrum of the low wind density model are compared with the WC4 model in Fig. 5, revealing a harder flux distribution (increasing the BC by 1.2 mag), and a dramatic change in the emergent optical spectrum. O VI emission is very strong so the low wind density case resembles a WO-type star. Consequently, a modest change in mass-

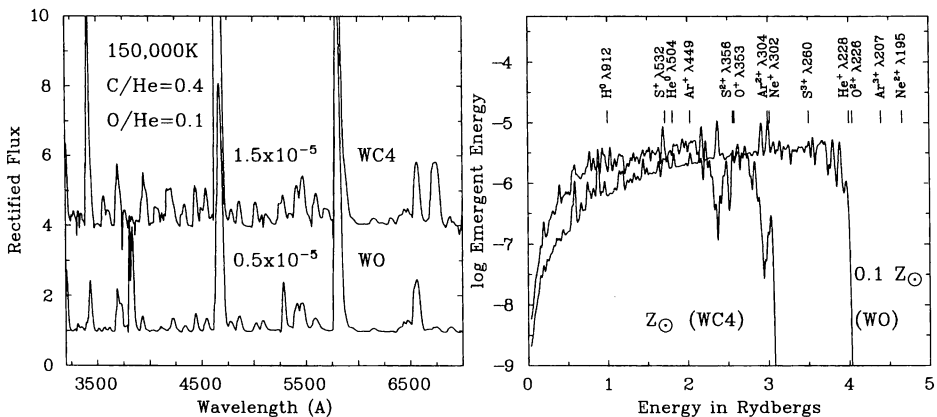


Figure 5. Comparison between WCE models at fixed stellar parameters (150kK, C/He=0.4, O/He=0.1), except that mass-loss rates (and Fe-contents) differ by a factor of three (ten). The low metallicity/mass-loss model would be classified as a WO-type star instead of a WC4 star, despite its identical atmospheric composition.

loss rate has a major influence on the ionizing energy distribution and observed spectral appearance. Strong O VI emission in a WR spectrum is connected principally with the wind density, rather than elemental abundance (Smith & Maeder 1991 identified WO stars as the chemically evolved descendants of WC stars). In WC4 stars, the high wind density and consequently very efficient wind cooling means that O^{6+} recombines to O^{5+} and subsequently O^{4+} interior to the optical line formation region, producing observed O IV-V lines. The less efficient cooling of WO winds, through a lower wind density (because of lower mass-loss rates and higher wind velocities) permits O^{6+} recombination in the optical line formation region, producing strong O VI emission. In support of this, recall that WO stars outnumber the WC population at low metallicities (SMC, IC 1613).

5.4. Nebular He II λ 4686 and bolometric corrections

For my second case, I have taken the earlier 130kK WN model, with a synthetic spectrum of a strong-lined WN4 star, and reduced its mass-loss rate by a factor of ten (scaling its metal content to $0.01 Z_{\odot}$). The resulting optical spectrum would be classified as a weak-lined WN2 star, as shown in Fig. 6. Its ionizing flux distribution is extremely hard, with a very strong flux above 54 eV ($\sim 40\%$ of its entire luminosity!). *If mass-loss rates of WR stars are driven by radiation pressure, their spectral appearance and ionizing properties will be very sensitive to metallicity.* The low metallicity WR model presented here may have application in very metal-poor starbursts, such as I Zw 18 which is thought to contain WR stars (de Mello *et al.* 1998).

The above results suggest that solely hot WR stars with weak winds produce a significant flux in the He⁺ continuum, most likely at low metallicities. This is supported by the known sample of WRs whose nebulae show strong He II λ 4686 emission by Garnett *et al.* (1991), namely WR 102 (WO, Galaxy), Brey 2 (WNE, LMC), Brey 40a (WNE+O, LMC), AB 7 (WNE+O, SMC), DR 1 (WO, IC 1613).

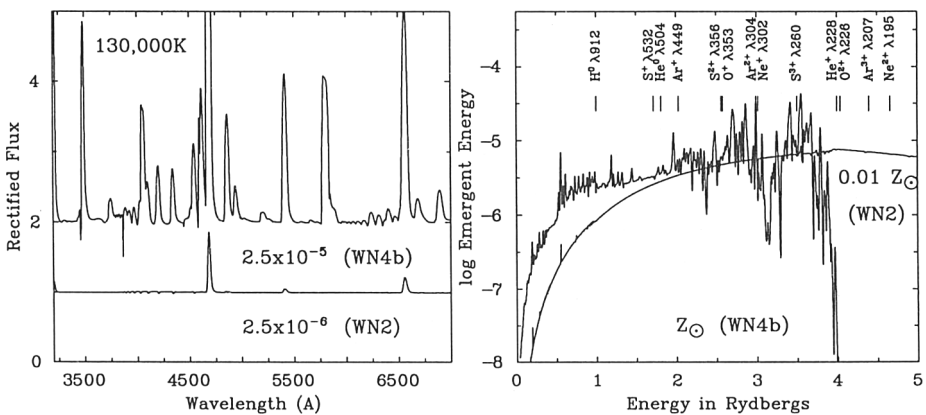


Figure 6. Comparison between WNE models at fixed stellar parameters (130kK), except that mass-loss rates (Fe-contents) differ by a factor of ten (100). The low mass-loss rate model mimics a WN2-type spectral appearance, with a huge ionizing flux in the He II continuum.

Young, low metallicity starbursts would be expected to exhibit strong nebular He II $\lambda 4686$ emission from WR stars, in contrast with high metallicity starbursts.

For the grid of high wind density models, representative of strong-lined Galactic WR stars, BCs in the range -2.6 to -4.4 mag (WN), and -3.1 to -4.6 mag (WC) are obtained. Since wind density affects the ionizing spectrum of WR models, bolometric corrections are also affected. BCs for the WO and WN2 models are much higher and very wind density sensitive, (-5.8 and -7.1 mag, respectively). Smith *et al.* (1994) used observations of clusters in the Galaxy to estimate WR masses and BCs, namely -4.5 mag for WC stars, and -4 to -6 mag for WN stars, in fair accord with predictions. Massey (these Proceedings) has repeated this for the LMC, and finds BCs of -6 to -8 mag for cluster WNE stars. From calculations performed here, such stars would be expected to have low wind densities and emit strongly above 54 eV. Detailed analysis of individual LMC WNE stars are sought in order to verify these predictions.

Overall, I have discussed the techniques used to derive stellar and chemical properties of WR stars, highlighting the importance of clumping, line-blanketing on derived parameters, and the role of wind density and metallicity on the emergent spectrum and ionizing properties of WR stars.

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Discussion

Marston: Regarding the use of nebulae to determine stellar parameters: although photo-ionization is likely to dominate the emission from most nebulae (including M1-67), many have evidence for shock emission, which would need to be removed before being able to obtain stellar parameters in the way you describe.

Crowther: I agree! In theory, all WR nebulae can be used to probe theoretical flux distributions, from photo-ionization modelling, in practice most examples (M1-67 excluded) suffer from uncertainties in nebular properties (ΔR , filling factor, n_e) and contributions from shocks. In several WC-type central stars of PNe they may represent superior probes.