

Spectrophotometry of ring nebulae around Wolf-Rayet stars^{*)}

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ABSTRACT. Long-slit spectrophotometric observations of HII regions around Wolf-Rayet stars in the Galaxy, the Magellanic Clouds and in IC1613 are employed to measure the ionizing radiation from these stars. The sample includes all known WR stars in the SMC and 14 regions in the LMC comprising most of the known ring nebulae. Apart from previously known HeII $\lambda 4686$ emitting nebulae around a few WO stars, HeIII regions were discovered within the nebulae N76 and N79W which are being photoionized by the strong He⁺ Lyman continuum emission from the Magellanic WNE stars AB7 and Br2, respectively. The Zanstra blackbody temperatures and luminosities (80 000, 95 000 K and $\log L/L_{\odot} = 5.4, 6.0$, respectively) agree remarkably well with more elaborate WN model calculations and suggest a much higher bolometric correction ($BC = -5.8$ mag) than generally admitted for WN stars. The nebular $\lambda 4686$ fluxes are several times higher than the corresponding broad stellar features suggesting that the highly ionized gas would remain detectable at much larger distances (i.e. in HII galaxies) than the underlying hot WNE population.

1. INTRODUCTION

The presence of highly-ionized HII regions in Local Group galaxies and the detection of narrow HeII $\lambda 4686$ emission lines in X-ray ionized nebulae (Pakull & Angebault, 1986; Pakull & Motch, 1989a,b) and many HII galaxies (i.e. Campbell, 1988) has motivated us to systematically study the EUV emission of advanced stages of massive stellar evolution. Broad HeII and CIV emission lines in the integrated spectra of many giant HII regions and HII galaxies have revealed large populations of Wolf-Rayet stars. However, the question of whether or not WR stars do also contribute substantially to the ionizing radiation, in particular at photon energies beyond the He⁺ Lyman edge ($> 4R_{yd}$, hereafter EUV) has remained open since adequate WR model atmospheres have become available only recently. On the other hand, it has been suggested that massive stars in very advanced evolutionary stages (early WC's and WO's) might not only be very luminous, but also extremely hot, reaching "effective" temperatures $> 100\,000$ K (see c.f. Maeder & Meynet, 1987) that are comparable to those of the nuclei of highly ionized planetary nebulae (PN). Accordingly, such stars might be expected to photoionize large HII regions to PN-like excitation (i.e. presence of He⁺⁺ ions which are not observed in normal HII regions around O stars). This consideration forms also the basis for the Terlevich and Melnick (1985) hypothesis, namely that WO stars ("warmers") might be responsible for the high nebular ionization in at least some types of active galaxies. However, this view has not been widely accepted, not least because sufficiently high WO star EUV luminosities had not

^{*)} Based on observations collected at the European Southern Observatory, La Silla, Chile, and at the Observatoire de Haute-Provence, France

been firmly established. Moreover, the *nebular* $\lambda 4686$ recombination radiation should then be accompanied by even stronger *broad* HeII+CIV $\lambda\lambda 4600-4700$ emission generated in the stellar winds; this is generally not observed (Pakull & Motch, 1989b).

In this paper I address the question of ionizing radiation from WR stars and hence, their temperatures and luminosities in a more systematic fashion. The work is based on recent observations of the ionization structure of diffuse or swept-up interstellar gas around WR stars which, in many cases, assumes the morphology of a ring-like structure (ring nebulae; cf. review by Chu in this volume). Here, I report on the results of long-slit spectroscopic observations of several Magellanic and IC1613 Wolf-Rayet stars and the surrounding interstellar medium that provide crucial information on the EUV emission of these stars.

2. LONG SLIT SPECTROPHOTOMETRY OF WR STARS

2.1. THE SAMPLE

The sample of Wolf-Rayet stars (c.f. Table 1) was selected on the basis of: (i) presence of ring nebulae, (ii) associated diffuse nebulosities, and after it turned out that certain WR types are particularly likely to be strong EUV emitters, (iii) WNE and WO subtypes.

TABLE 1: Sample of WR stars / nebulae^{*)} observed in the present study

star	type	nebula	$\lambda 5007/\beta$	$\lambda 4686/\beta$
AB 1	WN 3 + O4:	(RN ?)	5	<0.5
AB 2	WN 4.5/Of	(RN ?)	3 - 5	
AB 3	WN 3 + O4:	-	2	<0.3
AB 4	WN 4.5	-	1	
AB 5	WN 4 + O7I:	N66	6 - 7	
AB 6	WN 3: + O6.5I:	-		
AB 7	WN 1 + O6III _f	N76 (RN !)	6 - 7	0.3
AB 8	WO 4 + O4V	(-)		
Br 2	WN 1	N79W (RN !)	6-10	0.7
Br 4	WN 1(?)	N83 (?)	3	<0.04
Br 12	WN 3	N16A (RN)	6	<0.03
Br 16	WN 2.5	N105	4 - 5	<0.03
Br 25	WN 3	N44C (RN !)	6	<0.02
Br 26	WN 7	N198 (RN)	3	
Br 29	WN 3/WCE	N138 (RN)	6 - 8	
Br 48	WN 4 + OB	N57C (RN)		
Br 51	WN 3	N62 (RN !)	9 - 11	<0.03
Br 52	WN 4	N56 (RN)	6-8	<0.03
Br 65a	WN5 + abs	N59B	1	<0.004
Br 66	WN 3 (+WN3 ?)	N157	4	<0.007
Br 93	WO 4	N157 (RN !)	4 - 7	<0.07
Br 100	WN 4	N74 (RN)		
IC1613	WO	IC1613 #3 (RN)	5	0.3

^{*)} RN- ring nebulae; RN! denote Magellanic ring-nebulae not included in the compilation of Chu & Lasker (1980)

Special emphasis was put on Magellanic Wolf-Rayet stars, not least because the projected spectrographic slit lengths (≈ 3 arc min on the CCD detectors of the 2.2 and 1.5 m ESO telescopes) cover most of the extent of known ring nebulae in these galaxies. Moreover, the small interstellar extinction towards, and within, the Clouds favors the detection of weak nebular emission lines since intensity is independent of distance as long as the regions are spatially resolved. Table 1 lists the observed WR stars and spectral types together with the associated nebulae (if present) and diagnostic emission line ratios for most of them. Note that in many cases the "excitation parameter" $I(\lambda 5007)/I(H\beta)$ turns out to be extremely high (> 6) indicating that the ionizing WR stars are probably at least as hot as the earliest O stars.

Three stars in the sample emit sufficiently strong EUV continua to excite nebular HeII $\lambda 4686$ recombination radiation in the nebulae. They are the WO star in IC 1613 #3 (Davidson & Kinman, 1982; Pakull & Motch, 1989b), and the WNE stars AB7 and Br2 in the SMC and LMC, respectively (Pakull et al. 1990; Pakull & Bianchi, this volume; Niemela, this volume). To this list, WR 102 (WO2; Dopita et al. 1990; Dopita & Lozinskaya, this volume) and Br 40a (WNE; Niemela, this volume) must be added. The absence of $\lambda 4686$ nebular emission in the ring nebula around Br 93 which was independently discovered also by Heydari-Malayeri & Melnik (this volume) implies that WO stars are not necessarily strong EUV sources; in the case of the SMC WO star AB 8 the situation is less clear since there probably is no nearby interstellar gas which could "reprocess" the EUV radiation into observable line emission.

2.2. THE EARLIEST WN STARS: WN1

A continuation of WNE types towards high excitation of the stellar emission lines has recently been proposed by Conti and Massey (1989) who introduced the WN1 classification for the galactic stars WR2 and the LMC member Br4 on the basis of undetectable NV ($3p\ 2P^\circ - 3s\ 2S$) $\lambda\lambda 4603,19$ emission, whereas the UV resonance NV ($2p\ 2P^\circ - 2s\ 2S$) $\lambda\lambda 1238,40$ doublet remains strong. In AB7 and Br2, the ratios between the NV $\lambda\lambda 4609,19$ equivalent width (EW) and the HeII $\lambda 4686$ EW, (NV/HeII), are < 0.02 and 0.04 , respectively, both values being significantly smaller than in the galactic and LMC stars which Conti and Massey classify as WN2, or later. The (NV/HeII) ratio for the latter stars are all > 0.1 , suggesting that we might draw a dividing line between WN1 and the later WN subtypes, according to whether (NV/HeII) is smaller or larger than about 0.07.

It is of some interest to note that whereas the $\lambda\lambda 4603,19$ lines become weaker towards earlier WN spectral types, the largely recombination fed NV(7-6) subordinate $\lambda\lambda 4933,45$ doublet (Hillier, 1988) remains comparatively strong. The latter emission lines are not part of the classical classification scheme; however, my CCD spectra of the galactic WN1 "standard" WR2 clearly display this emission at about the same strength as in Br2 (EW ≈ 10 Å).

2.3. AB7 AND BR 2

These WN1 stars do completely photoionize helium in the inner ~ 20 pc of their ring nebulae. The electron temperatures, $T_e(\text{OIII}) \approx 16\ 000$ K, in both the nebulae around AB7 (N76) and around Br2 (N79W) indeed strongly suggest that photoionization rather than ionization by shocks is the dominant process that feeds the nebular HeII recombination radiation. These results have several interesting consequences. First of all, the stellar wind layers in which the EUV radiation is formed must be sufficiently hot to strongly emit in the He⁺-Lyman continuum. Moreover, the outer wind zones have to be optically thin in the EUV, i.e. helium should be completely ionized throughout the wind (see below). Then, using the photon-counting property of the nebular $\lambda 4686$ recombination line one can derive the rate of He⁺-ionizing photons (Q_4 ; i.e. $h\nu > 4$ Ryd) escaping from the Wolf-Rayet wind.

Using the beautifully simple, but nevertheless extremely powerful Zanstra method which compares nebular $\lambda 4686$ flux to the stellar flux at observable wavelengths yields blackbody temperatures of 80 000 and 95 000 K, and luminosities, $\log L/L_{\odot} = 5.3$ and 6.0, for these Magellanic WN1 stars (see Table 2). The analysis is rather straightforward for the single star Br2; in the case of the WR+O6f binary AB7, the visual magnitude of the WN1 component was estimated by subtracting from the binary spectrum appropriately scaled spectra of a single O6 star until the the H, HeI and HeII *absorption* lines disappeared (Pakull et al. 1990).

One might argue that the extremely high HeII $\lambda 4686/H\beta$ line ratio ($= 0.7$!) in the brightest parts of the ring nebula N79W implies a significantly harder ionizing spectrum than a 95 000 K blackbody. For example, from their analysis of nebular lines ($\lambda 4686/H\beta = 0.55$) around the WO star WR102, Dopita et al. (1990, and this volume) derive an ionizing temperature $T_{BB} \approx 150$ 000 K. Moreover, Stasinska & Tylenda (1986) have pointed out that this line ratio levels off at $T_{BB} > 250$ 000 K and never exceeds a value of about 0.6. However, it should be kept in mind that the observed ratio in N79W mainly refers to the He⁺⁺ zone within a larger (ill defined) HII region rather than to the total emission calculated in the model nebulae. Another effect increasing the $\lambda 4686/H\beta$ ratio is the possibility that N79W might well be partially transparent to the H-ionizing photons but optically thick in the He⁺ Lyman continuum (EUV).

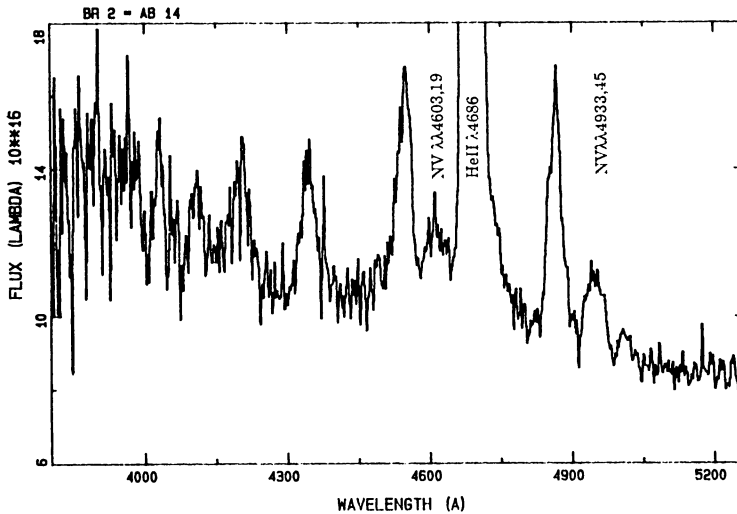


FIG. 1: Blue CCD spectrum of the WN1 star Br2. Note the presence of $\lambda\lambda 4933,45$ emission (EW ≈ 9 Å) and the very weak NV $\lambda\lambda 4603,19$ doublet (EW ≈ 6 Å). The equivalent width of the strong HeII $\lambda 4686$ line is 160 Å.

3. COMPARISON WITH WR MODEL SPECTRA

The condition that the (helium) winds of AB7 and Br2 must be completely ionized allows to draw an important lower limit on the rate of He⁺ ionizing photons, Q_4 , emitted by WR "cores". Assuming for simplicity a constant wind velocity law, $v(R) = v_{\infty}$, and furthermore provided that photoionization from the ground state is the dominant process for

the He ionization beyond the radius R_{EUV} where the EUV continuum is formed, this translates to:

$$Q_4 > 1 \cdot 10^{49} \text{ s}^{-1} [M_{\cdot 4} / v_{2500}]^2 [R_{\text{EUV}}/R_{\text{O}}]^{-1},$$

where an electron temperature of 80 000 K has been assumed, $M_{\cdot 4}$ is the mass loss rate in units of $10^{-4} M_{\text{O}}/\text{y}$, and $v_{2500} = v_{\infty}/(2500 \text{ km/s})$. This order-of-magnitude estimate suggests that even very hot WR "cores" cannot ionize the wind completely, once the mass loss-rates become sufficiently high. On the other hand, the relatively low M/v_{∞} ratios together with the lower limit of the temperature parameter, T^* , which were derived from the optical and UV spectra (see below) already strongly favour the escape of EUV radiation from AB7 and Br2 beyond the stellar wind.

A remarkable result of this simple analysis is that the (pure helium) WR model spectra calculated by the Kiel group (Schmutz, Hamann & Wessolowsky, 1989 and references therein; Schmutz, these proceedings; Hamann, these proceedings) agree rather well with the observed stellar He emission line strengths and absolute magnitudes of AB7 and Br2, if Zanstra blackbody temperatures are identified with the effective temperatures, T^* , at the "core radius", R^* , which is the inner boundary of the model atmospheres. According to these models, emission lines and continuum emission of WN stars are largely determined by T^* and the radius parameter, $R^* [M_{\cdot 4}/v_{2500}]^{-2/3}$.

TABLE 2: WN1 star parameters

Object	MV	BC	Q_4 [s^{-1}]	v_{∞} [km/s]	T_{BB} [kK]	LBB [L_{O}]	T^* kK	L_{model} [L_{O}]	M $10^{-4} M_{\text{O}}/\text{y}$
AB7	-4.4	-5.9	$1.5 \cdot 10^{48}$	1600	80	$9 \cdot 10^5$	75	$1 \cdot 10^6$	0.14
Br2	-2.6	-5.7	$8 \cdot 10^{47}$	2500	95	$2 \cdot 10^5$	90	$2 \cdot 10^5$	0.15

The non-detection of HeI features in WNE stars have so far only allowed to place lower limits on T^* . Now, the observation of *nebular* $\lambda 4686$ emission around some of these stars opens the possibility to substantially narrow down the allowed range of parameters for a given Wolf-Rayet star. After this conference, Werner Schmutz (1990b) has kindly informed me of his extended model calculations concerning the continuum emission down to wavelengths of 100 Å. At least in the parameter range covered by this work the validity of the EUV emitter criterion mentioned earlier is nicely confirmed. In Table 2 the relevant Kiel-model stellar parameters for AB7 and Br2 are summarized together with the results based on naive blackbody fits. The advocates of a WN "universal" bolometric correction of - 4.5 might in particular note that both BB and more sophisticated modeling of these WN1 stars imply $BC < - 5.5$.

4. CONCLUSIONS

The main result of the present study concerns the discovery of strong EUV radiation from some WNE stars in the Magellanic Clouds. This constitutes the first *direct* proof of their significantly higher effective temperatures as compared to the O star progenitors. Although the EUV emitters AB7 and Br40a are in binary systems, the lack of a luminous companion of Br2 suggests that also single star evolution might lead to $\approx 100\,000$ K WN-type remnants.

The discovery of strong HeII $\lambda 4686$ recombination radiation from the WNE ring nebulae N76 and N79W also suggests a natural explanation for the previously puzzling presence of this line in a number of giant HII regions and HII galaxies in terms of a population of such WNE stars. In fact, one might call these objects genuine *warmers* since the EUV fed $\lambda 4686$ emission turned out to be about 8 times stronger than the corresponding broader stellar feature. These *warmers* will not be detectable any more in distant galaxies except for their ionizing radiation.

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DISCUSSION

Cassinelli: Most impressive stars. Radiation pressure would not have any trouble driving their winds. Does this violate the newer picture for evolution?

Langer: You would not really conclude that these positions fit very well to the tracks. However, after the core helium exhaustion, the tracks are nearly predicted to lead to very high effective temperatures and also to somewhat higher luminosities again. So, this picture would really mean that these warmers correspond to the latest evolutionary stage, carbon burning or something like that which would also account for the small number of those objects.

Pakull: These stars are WN's, not WC's.

Langer: But still, you have the possibility of some WN stars being treated as supernova candidates too, so, you must not lead all WR stars to the WC stage.