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Wolf-Rayet Populations at High Metallicity

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Observed properties of Wolf-Rayet stars at high metallicity are reviewed. Wolf-Rayet stars are more common at higher metallicity, as a result of stronger mass-loss during earlier evolutionary phases with late WC subtypes signatures of solar metallicity or higher. Similar numbers of early (WC4–7) and late (WC8–9) stars are observed in the Solar neighbourhood, whilst late subtypes dominate at higher metallicities, such as Westerlund 1 in the inner Milky Way and in M83. The observed trend to later WC subtype within metal-rich environments is intimately linked to a metallicity dependence of WR stars, in the sense that strong winds preferentially favour late subtypes. This has relevance to (a) the upper mass limit in metal-rich galaxies such as NGC 3049, due to softer ionizing fluxes from WR stars at high metallicity; (b) evolutionary models including a WR metallicity dependence provide a better match to the observed N(WC)/N(WN) ratio. The latter conclusion partially rests upon the assumption of constant line luminosities for WR stars, yet observations and theoretical atmospheric models reveal higher line fluxes at high metallicity.

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1. Introduction

Wolf-Rayet (WR) stars represent the final phase in the evolution of very massive stars prior to core-collapse, in which the H-rich envelope has been stripped away via either stellar winds or close binary evolution, revealing products of H-burning (WN sequence) or He-burning (WC sequence) at their surfaces, i.e. He, N or C, O (Crowther 2007).

WR stellar winds are significantly denser than O stars, as illustrated in Fig. 1, so their visual spectra are dominated by broad emission lines, notably He II λ4686 (WN stars) and C III λ4647-51, C III λ5696, C IV λ5801-12 (WC stars). The spectroscopic signature of WR stars may be seen individually in Local Group galaxies (e.g. Massey & Johnson 1998), within knots in local star forming galaxies (e.g. Hadfield & Crowther 2006) and in the average rest frame UV spectrum of Lyman Break Galaxies (Shapley et al. 2003).

In the case of a single massive star, the strength of stellar winds during the main sequence and blue supergiant phase scales with the metallicity (Vink et al. 2001). Consequently, one expects a higher threshold for the formation of WR stars at lower metallicity, and indeed the SMC shows a decreased number of WR to O stars than in the Solar Neighbourhood. Alternatively, the H-rich envelope may be removed during the Roche lobe overflow phase of close binary evolution, a process which is not expected to depend upon metallicity.

WR stars represent the prime candidates for Type Ib/c core-collapse supernovae and long, soft Gamma Ray Bursts (GRBs). This is due to their immediate progenitors being associated with young massive stellar populations, compact in nature and deficient in either hydrogen (Type Ib) or both hydrogen and helium (Type Ic). For the case of GRBs, a number of which have been associated with Type Ic hypernovae (Galama et al. 1998; Hjorth et al. 2003), a rapidly rotating core is a requirement for the collapsar scenario in which the newly formed black hole accretes via an accretion disk (MacFadyen & Woosley 1999). Indeed, WR populations have been observed within local GRB host galaxies (Hammer et al. 2006).

In this review article, the observed properties WR stars at high metallicity are presented and discussed.

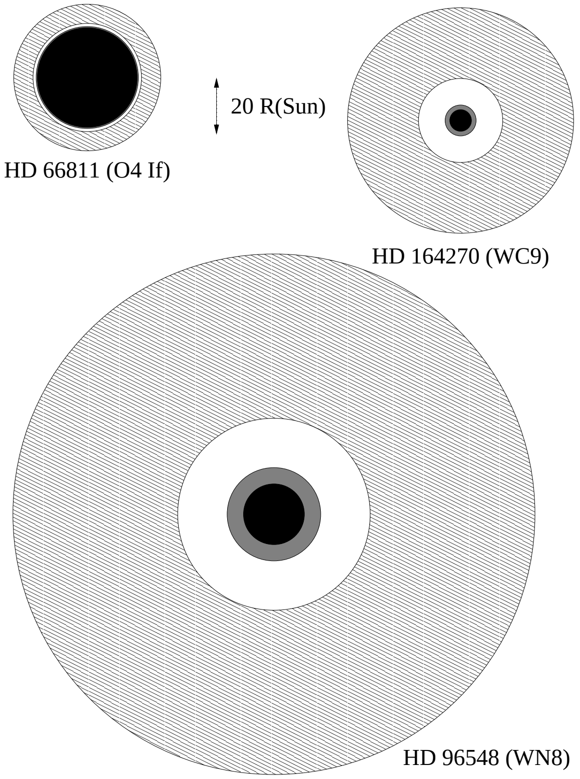

Figure 1. Comparisons between stellar radii at Rosseland optical depths of 20 (= R_*, black) and 2/3 (= $R_{2/3}$, grey) for HD 66811 (O4 If), HD 96548 (WN8) and HD 164270 (WC9), shown to scale, together with the wind region corresponding to the primary optical wind line forming region, $10^{11} \leqslant n_e \leqslant 10^{12}$ cm^{-3} (hatched) in each case, illustrating the highly extended winds of WR stars with respect to O stars (Crowther 2007).

2. WR subtype distribution in Milky Way and Magellanic Clouds

Historically, the wind properties of WR stars have been assumed to be metallicity independent (Langer 1989), yet there is a well known observational trend to later, lower ionization, WN and WC subtypes at high metallicity as illustrated in Fig. 2.

Within the Milky Way, it is well known that late-type WC stars are restricted to within the Solar circle (Conti & Vacca 1990). Indeed, Hopewell et al. (2005) discovered five new WR stars in the inner Milky Way using the AAO/UKST Hα survey – all were found to be WC9 stars.

In addition, Westerlund 1 (Clark et al. 2005) – located at the edge of the Galactic bar, for which a metallicity of ∼60% higher than Orion is expected – possesses 8 WC stars with a bias towards late (WC8–9) subtypes according to recent near-IR spectroscopy (Crowther et al. 2006). The majority of these possess hot dust, indicative of massive binaries, in common with the Quintuplet members of the Galactic Centre Quintuplet cluster (Figer, priv. comm.). Early-type WN stars are also absent in Westerlund 1, with equal numbers of mid (WN5–6) and late (WN7–10) subtypes, for which the majority also appear to be massive binaries, as a result of hard X-ray fluxes.

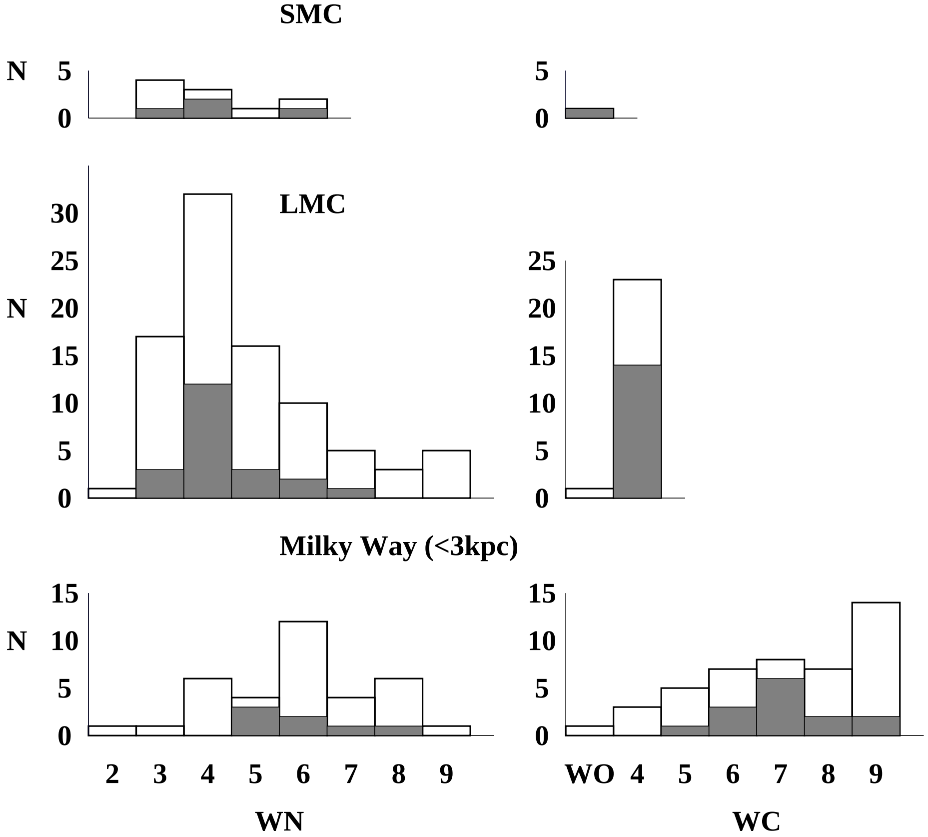

Figure 2. Subtype distribution of Milky Way (<3kpc), LMC and SMC WR stars, in which known binaries are shaded (Crowther 2007).

3. WR populations in M31, M83 and beyond

Within the Local Group, M31 (Andromeda) is the only other candidate metal-rich galaxy, although studies are hindered by its orientation on the sky. Wolf-Rayet populations in M31 were led by Moffat & Shara (1983, 1987) and Massey et al. (1986). As in the Milky Way, WC7–8 stars were located at smaller galacto-centric distances (7±3 kpc) than WC5–6 stars (11±3 kpc). Representative examples of M31 WC stars obtained with WHT/ISIS are presented in Fig. 3, and suggest a weak metallicity-gradient for M31, albeit rather less metal-rich than the Milky Way, according to its observed WC population (see also Trundle et al. 2002).

Further afield, the Wolf-Rayet population of M83 (= NGC 5236) has been studied by Hadfield et al. (2005). M83 is well suited to optical imaging surveys for WR stars at high metallicity (though see Bresolin, these proceedings), since it is face-on, nearby (4.5 Mpc), and possesses a high star formation rate.

VLT/FORS2 revealed a total of 280 (non-nuclear) regions for which the presence of WR stars was inferred from an excess of λ4685 (He II 4686) narrow-band imaging versus λ4781 (continuum) – see Fig. 4. Spectroscopic follow-up of 198 regions confirmed a total of 132 sources, hosting in excess of 1000 WR stars according to the standard calibration of Schaerer & Vacca (1998). N(WC)/N(WN)$\sim$1.2 in M83, confirming the trend towards a higher ratio at high metallicity as indicated in Fig. 6. Notably, the WC population of M83 is totally dominated by late subtypes, i.e. N(WC8–9) / N(WC4–7) $\sim$9, in contrast

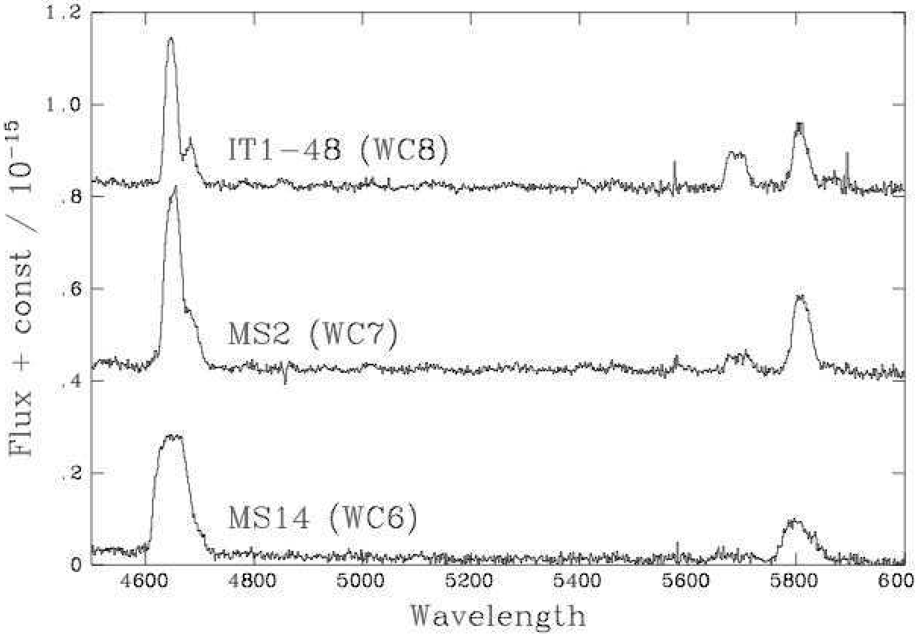

FIGURE 3. Optical WHT/ISIS spectroscopy of representative WC stars in M31.

with ∼1 for the Solar neighbourhood, for which representative examples are presented in Fig. 5.

WR populations are unresolved in more remote metal-rich galaxies, but also confirm the presence of late-type WC stars, as originally discovered by Phillips & Conti (1992) for NGC 1365 within Fornax, and confirmed by Pindao et al. (2002) for NGC 4254 (= M88) within Virgo.

4. Why late WC stars at high metallicity?

The ubiquitous detection of late WC stars within metal rich environments (and absence at low metallicity) requires explanation. The observed trend for WC subtypes in the LMC versus the Milky Way was initially believed to originate from a difference in carbon abundances (Smith & Maeder 1991), yet quantitative analysis reveals similar carbon abundances (Koesterke & Hamann 1995; Crowther et al. 2002). Alternatively, late WC stars might evolve preferentially from relatively low mass OB stars that enter the WR phase owing to stronger stellar winds at earlier evolutionary phases. This scenario is not supported by cluster studies (e.g. Massey et al. 2000; Crowther et al. 2006).

The most compelling evidence suggests that late WC stars are favoured in the case of high wind densities (Crowther et al. 2002). Consequently, the presence of late-WC stars within metal-rich galaxies favours metallicity dependent winds for Wolf-Rayet stars. The impact of a metallicity dependence for WR winds upon spectral types is as follows. At high metallicity, recombination from high to low ions (early to late subtypes) is very effective in very dense winds, whilst the opposite is true for low metallicity, low density winds. Stellar temperatures further complicates this picture, such that the spectral type of a WR star results from a subtle combination of ionization and wind density, in contrast with normal stars.

Theoretically, Nugis & Lamers (2002) argued that the iron opacity peak was the origin

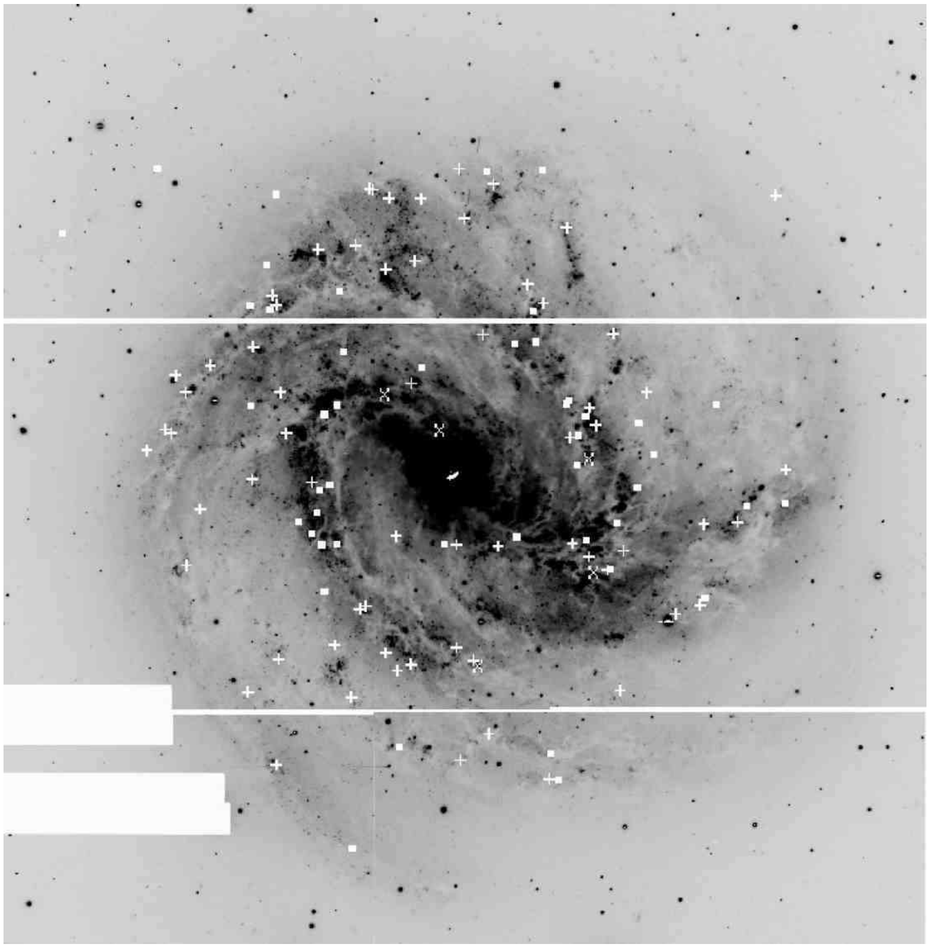

FIGURE 4. Composite $12' \times 12'$ VLT FORS2 image (λ4685) of M83 (= NGC 5236) indicating the location of regions containing WN (squares), WC (plus symbols) and WN+WC (crosses) stars. North is up and east is to the left. Refions to the south east are masked to avoid saturation by bright foreground stars (Hadfield et al. 2005)

of the wind driving in WR stars, which Gräfener & Hamann (2005) supported via an hydrodynamic model for an early-type WC star in which lines of Fe IX-XVII deep in the atmosphere provided the necessary radiative driving. Vink & de Koter (2005) applied a Monte Carlo approach to investigate the metallicity dependence for cool WN and WC stars revealing $\dot{M} \propto Z^{\alpha}$ where α=0.86 for WN stars and α=0.66 for WC stars for $0.1 \leqslant Z \leqslant 1 Z_{\odot}$. The weaker WC dependence originates from an increasing Fe content and constant C and O content at high metallicity. Empirical results for the Solar neighbourhood, LMC and SMC are broadly consistent with theoretical predictions, although detailed studies of individual WR stars within galaxies broader range in metallicity would provide stronger constraints.

A metallicity dependence of WR winds impacts upon evolutionary model calculations as follows. Recent evolutionary models of Meynet & Maeder (2005) allow for rotational mixing, but not a metallicity dependence of WR winds. Improved agreement with respect to earlier models is achieved, but the ratio of WC versus WN stars for continuous star formation does does not reproduce that observed at high metallicity, as illustrated in

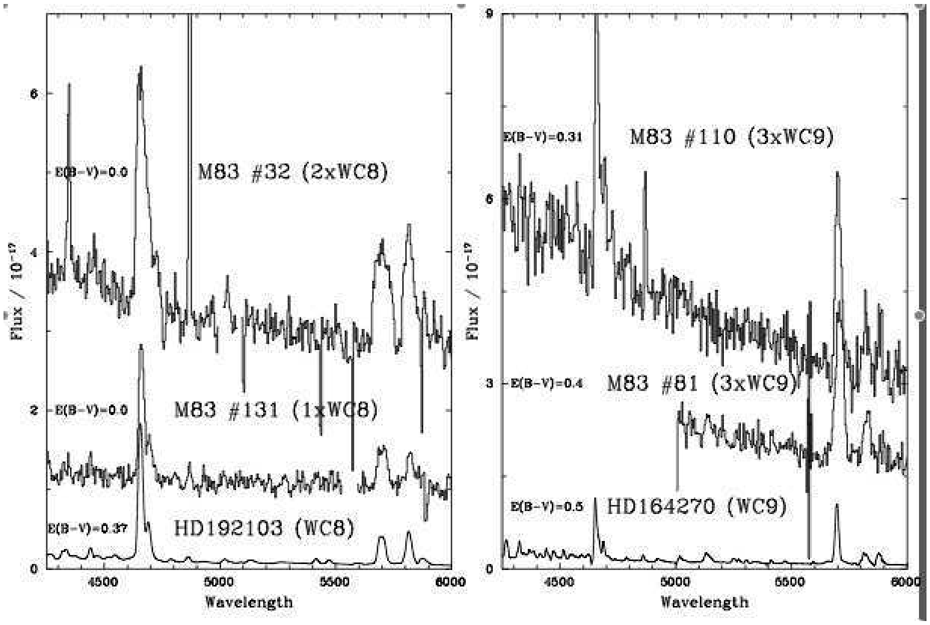

FIGURE 5. Optical VLT/FORS2 spectroscopy of typical regions of M83 hosting late WC8–9 stars, together with individual Milky Way WC stars (WR135, WR103) scaled to a distance of 4.5Mpc (Hadfield et al. 2005).

Fig. 6. In contrast, recent (non-rotating) evolutionary models by Eldridge & Vink (2006) in which the Vink & de Koter (2005) WR metallicity dependence has been implemented provide a much better match to observations.

With regard to the inferred WR populations at high metallicity a note of caution is necessary. At high metallicity, WR optical recombination lines will (i) increase in equivalent width, since their strength scales with the square of the density, and (ii) increase in line flux, since the lower wind strength will reduce the line blanketing, resulting in an increased extreme UV continuum strength at the expense of the UV and optical (Crowther & Hadfield 2006). Indeed, the equivalent widths of optical emission lines of WN stars in the Milky Way and LMC WN stars are well known to be higher than SMC counterparts (Conti et al. 1989).

To date, the standard approach for the determination of unresolved WR populations in external galaxies has been to assume metallicity independent WR line fluxes – obtained for Milky Way and LMC stars (Schaerer & Vacca 1998) – regardless of whether the host galaxy is metal-rich (Mrk 309, Schaerer et al. 2000) or metal-poor (I Zw 18, Izotov et al. 1997). Ideally, one would wish to use WR template stars appropriate to the metallicity of the galaxy under consideration. Unfortunately, this is only feasible for the LMC, SMC and Solar neighbourhood, since it is challenging to isolate individual WR stars from ground based observations in more distant galaxies, which span a larger spread in metallicity.

Enhanced WR line fluxes are also predicted for WR atmospheric models at high metallicity if one follows the metallicity dependence from Vink & de Koter (2005), such that WR populations inferred from Schaerer & Vacca (1998) at high metallicity may overestimate actual populations.

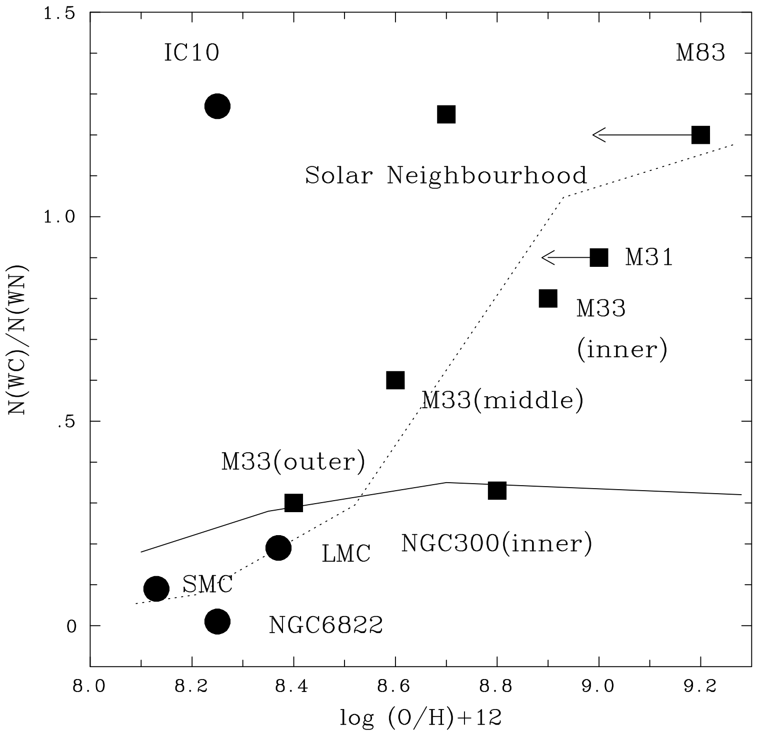

FIGURE 6. Ratio of subtype distribution of WC to WN stars for nearby galaxies, updated from Massey & Johnson (1998) to include M83 (Hadfield et al. 2005). Evolutionary predictions from Meynet & Maeder (2005, solid line) and Eldridge & Vink (2006, dotted line) are included.

5. Impact on ionizing fluxes

Indirect H II region studies have suggested a low upper mass limit, $M_{\rm upper}$, for H II regions at high metallicity (e.g. Thornley et al. 2000), yet Schaerer et al. (2000) claim $M_{\rm upper} > 40 M_{\odot}$ due to large WR populations in high metallicity galaxies such as Mrk 309. However, Schmutz et al. (1992) demonstrated that the ionizing fluxes from WR stars soften as wind density increases. Consequently, a metallicity dependence for WR wind strengths implies that WR ionizing flux distributions soften at increased metallicity, as demonstrated by Smith et al. (2002), and naturally resolves this apparent discrepancy. For example, high temperature WN models predict a strong ionizing flux shortward of the He II Lyman edge at 228Å at low metallicities, but negligible hard ionizing fluxes at Solar metallicities or above, as illustrated in Fig. 7.

To illustrate this, we use the example of the metal-rich WR galaxy NGC 3049 (Schaerer et al. 1999). Gonzalez Delgado et al. (2002) identified a compact nuclear starburst cluster as the principal origin of WR emission within NGC 3049. A nebular analysis based upon the hard (metallicity-independent) WR ionizing fluxes of Schmutz et al. (1992) confirmed previous results, i.e. $M_{\rm upper} < 40 M_{\odot}$. In contrast, use of the revised (metallicity dependent), softer WR ionizing fluxes from Smith et al. (2002) led to a normal, $M_{\rm upper} \geqslant 100 M_{\odot}$, in agreement with UV spectral synthesis studies.

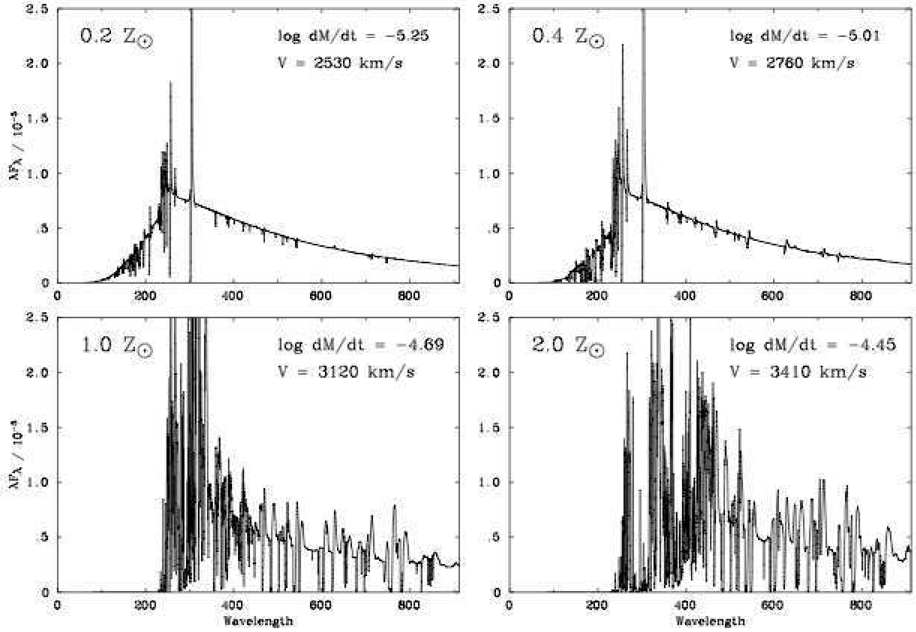

FIGURE 7. Predicted Lyman continuum ionizing fluxes for model reference WN#11 (T_*=100kK, $L = 10^{5.48} L_\odot$) from Smith et al. (2002), illustrating harder ionizing fluxes at lower metallicity, notably below λ=228Å due to weaker stellar winds.

6. Summary

Wolf-Rayet stars are more common at higher metallicity, as a result of stronger mass-loss during earlier evolutionary phases. Late WC subtypes appear to be signatures of solar metallicity or higher, as witnessed within the Westerlund 1 and Quintuplet clusters in the inner Milky Way, M31, M83, NGC 3049, Mrk 309. The observed trend to later WC subtype is intimately linked to a metallicity dependence of WR stars, in the sense that strong winds preferentially favour late subtypes (Crowther et al. 2002). This has relevance to (a) the upper mass limit in metal-rich galaxies, due to softer ionizing fluxes from WR stars at high metallicity (Gonzalez Delgado et al. 2002); (b) evolutionary models including a WR metallicity dependence provide a better match to the observed N(WC)/N(WN) ratio (Eldridge & Vink 2006). The latter item relies in part upon the assumption of constant line luminosities for WR stars (e.g. Schaerer & Vacca 1998), yet observations and theoretical atmospheric models reveal higher line fluxes at high metallicity (Crowther & Hadfield 2006).

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