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Metallicity Dependent Wolf-Rayet Winds

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Observational and theoretical evidence in support of metallicity dependent winds for Wolf-Rayet stars is considered. Well known differences in Wolf-Rayet subtype distributions in the Milky Way, LMC and SMC may be attributed to the sensitivity of subtypes to wind density. Implications for Wolf-Rayet stars at low metallicity include a hardening of ionizing flux distributions, an increased WR population due to reduced optical line fluxes, plus support for the role of single WR stars as Gamma Ray Burst progenitors.

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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 HeII λ4686 (WN stars) and CIII λ4647-51, CIII λ5696, CIV 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).

At solar metallicity, single star models predict that the core is spun down either during the red supergiant (via a magnetic dynamo) or Wolf-Rayet (via mass-loss) phases. The tendency of GRBs to originate from metal-poor environments (e.g. Stanek et al. 2006) suggests that stellar winds from single stars play a role in their origin since Roche lobe overflow in a close binary evolution would not be expected to show a strong metallicity dependence.

In this article, evidence in favour of a metallicity dependence for WR stars is presented, of application to the observed WR subtype distribution in Local Group galaxies, plus properties of WR stars at low metallicity including their role as GRB progenitors.

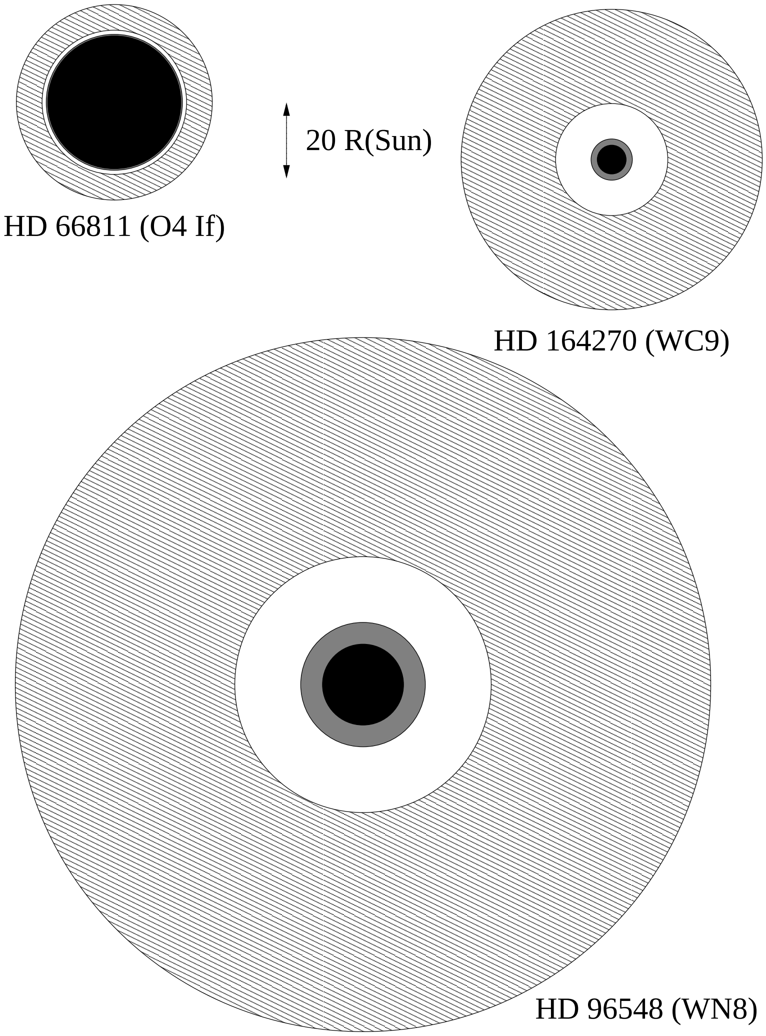

FIGURE 1. Comparisons between stellar radii at Rosseland optical depths of 20 (= R_*, black) and 2/3 (= $R_{2/3}$, grey) for HD 66811 (O4 If), HD 96548 (WN8) and HD 164270 (WC9), shown to scale, together with the wind region corresponding to the primary optical wind line forming region, $10^{11} \leqslant n_e \leqslant 10^{12}$ 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

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 earlier, higher ionization, WN and WC subtypes at low metallicity as illustrated in Fig. 2, whose origin is yet to be established.

Mass-loss rates for WN stars in the Milky Way and LMC show a very large scatter. The presence of hydrogen in some WN stars further complicates the picture since WR winds are denser if H is absent (Nugis & Lamers 2000). This is illustrated in Fig. 3, which reveals that the wind strengths of (H-rich) WN winds in the SMC are lower than corresponding H-rich stars in the LMC and Milky Way (Crowther 2006). Fig. 4 shows

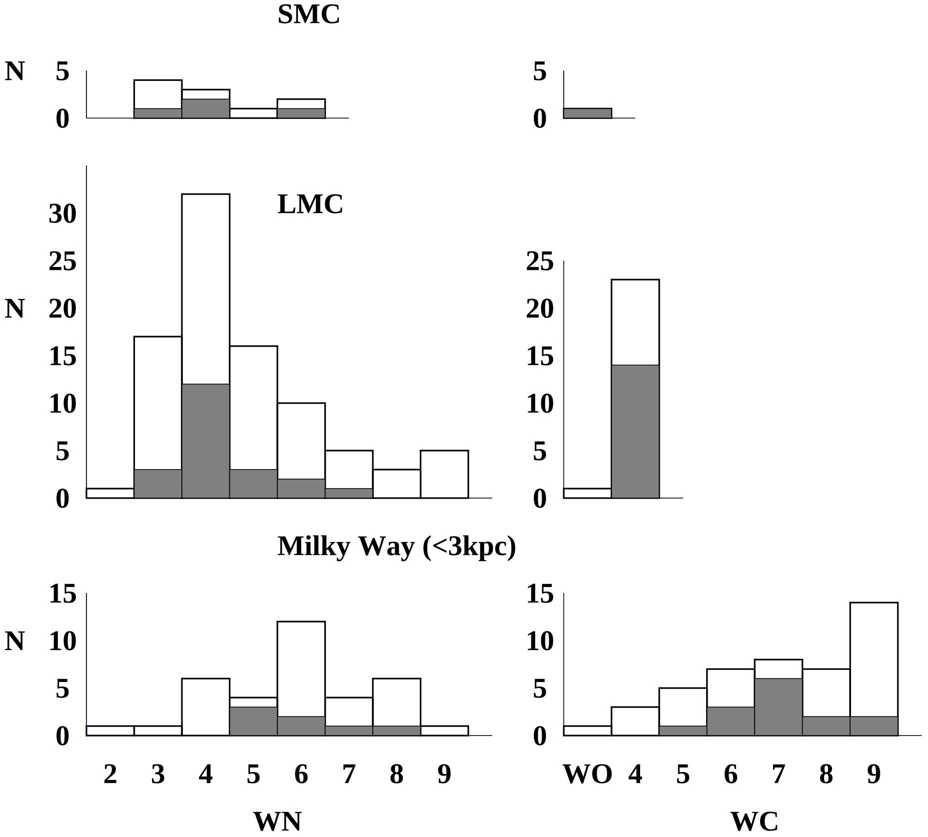

FIGURE 2. Subtype distribution of Milky Way (<3kpc), LMC and SMC WR stars, in which known binaries are shaded (Crowther 2007).

that the situation is rather clearer for WC stars, for which LMC stars reveal ∼0.2 dex lower mass-loss rates than Milky Way counterparts (Crowther et al. 2002)

The observed trend to earlier subtypes in the LMC (Fig. 2) was believed to originate from a difference in carbon abundances relative to Galactic WC stars (Smith & Maeder 1991), yet quantitative analysis reveals similar carbon abundances (Koesterke & Hamann 1995; Crowther et al. 2002).

Theoretically, Nugis & Lamers (2002) argued that the iron opacity peak was the origin 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 a decreasing Fe content and constant C and O content at low metallicity. Empirical results for the Solar neighbourhood, LMC and SMC presented in Figs. 3–4 are broadly consistent with theoretical predictions, although detailed studies of individual WR stars within galaxies broader range in metallicity would provide stronger constraints. Theoretical wind models also predict smaller wind velocities at lower metallicity, as is observed for WO stars, which are presented in Fig. 5 (Crowther & Hadfield 2006).

The impact of a metallicity dependence for WR winds upon spectral types is as follows.

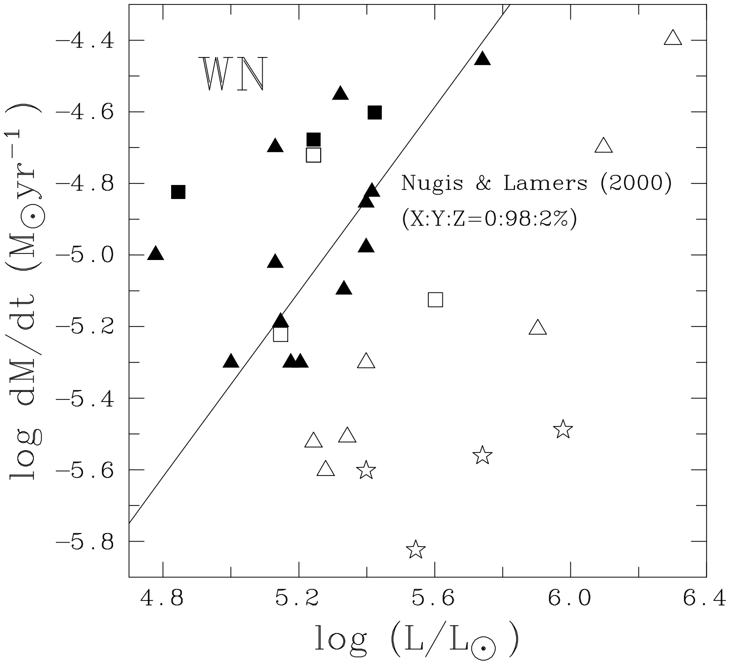

FIGURE 3. Mass-loss rates for WN stars in the Galaxy (squares), LMC (triangles) and SMC (stars) revealing a wide spread in wind densities for WN stars, for which stars without hydrogen (filled symbols) possess stronger winds. The solid line is from eqn 22 of Nugis & Lamers (2000).

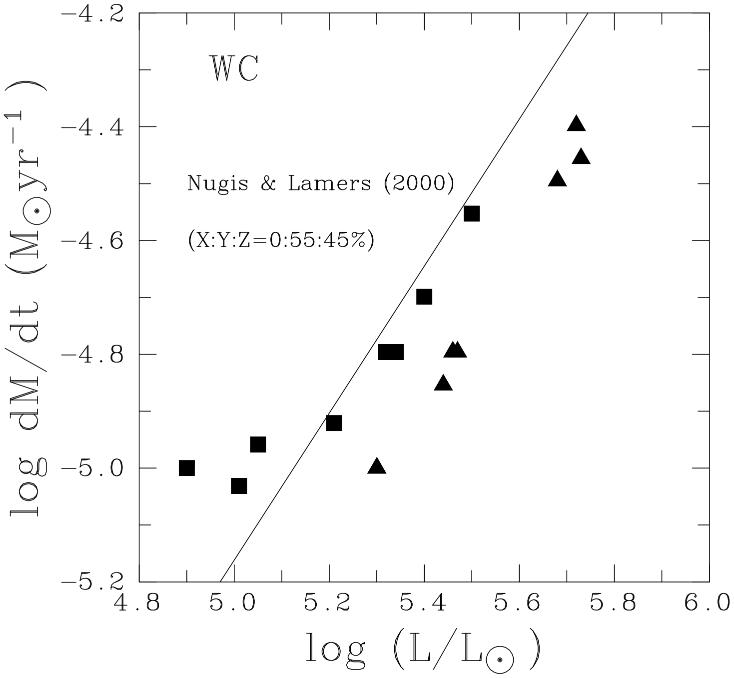

FIGURE 4. Mass-loss rates for WC and WO stars in in the Galaxy (squares) and LMC (triangles). The solid line is from eqn 22 of Nugis & Lamers (2000).

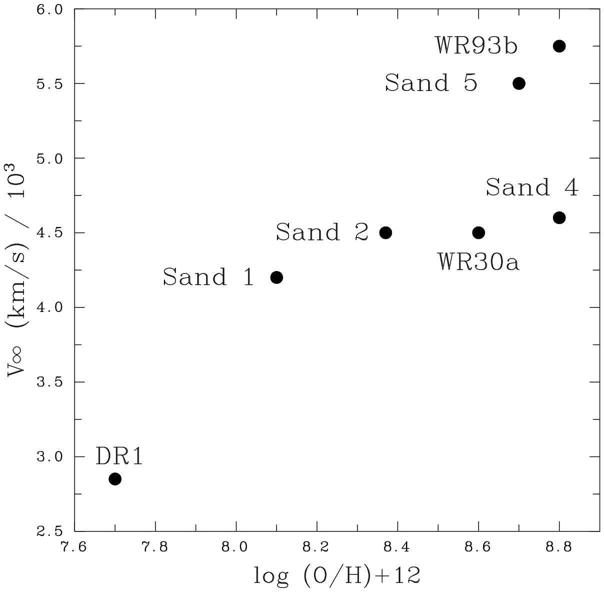

Figure 5. Wind velocities for WO stars as a function of metallicity (Crowther & Hadfield 2006).

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. The situation is illustrated in the upper panel of Fig. 6, where we present synthetic WC spectra obtained from identical models except that their wind densities differ by a factor of 10, and the weak wind model is assumed to be extremely Fe-poor (adapted from Crowther & Hadfield 2006). The high wind density case has a WC4 spectral type whilst the low wind density case has an earlier WO subtype. Crowther et al. (2002) noted that a further increase in wind density by a factor of 2 predicts a WC7 subtype. 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.

3. WR populations at low metallicity

The effect of reduced WR wind densities at low metallicity on WR populations is as follows. WR optical recombination lines will (i) decrease in equivalent width, since their strength scales with the square of the density, and (ii) decrease 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. The equivalent widths of optical emission lines in SMC WN stars are well known to be lower than Milky Way and LMC 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

	LMC		SMC	
	$\log L$ (erg s^{-1})	N	$\log L$ (erg s^{-1})	N
WN2–4	35.92	36	35.23	8
WN5–6	36.24	15	35.63	2
WN7–9	35.86	9		

TABLE 1. Mean HeII $\lambda4686$ line luminosities for Magellanic Cloud WN stars including known binaries (Crowther & Hadfield 2006)

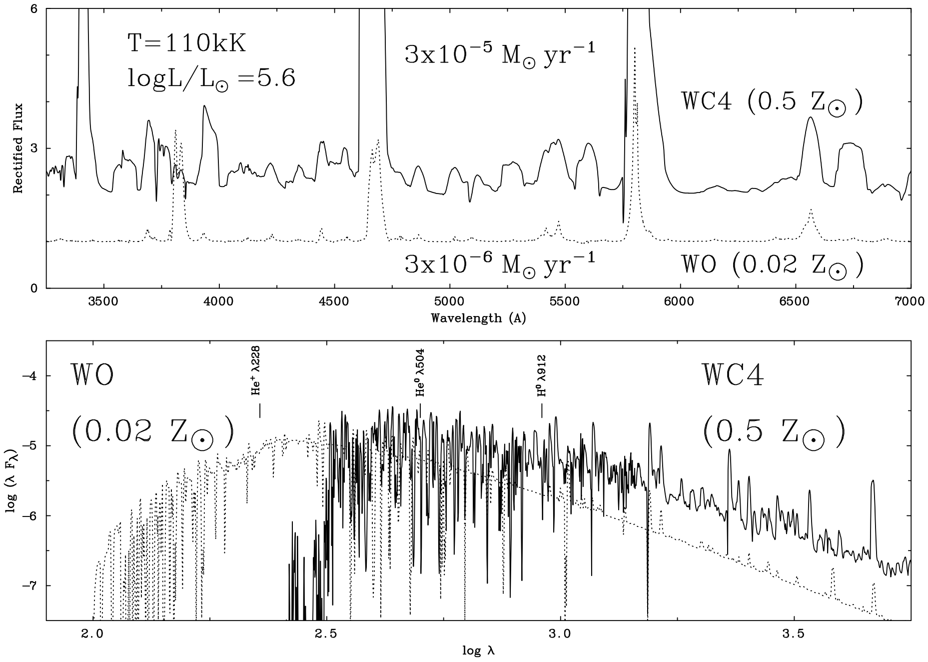

FIGURE 6. Comparison between theoretical stellar atmosphere models which differ solely in wind density (factor of 10), revealing an earlier spectral type (WC4 → WO) and harder ionizing flux distribution at low metallicity, adapted from Crowther & Hadfield (2006)

based observations in more distant galaxies, which span a larger spread in metallicity. Line luminosities for optical emission lines in LMC and SMC WR stars are compared in Table 1, illustrating significantly lower (factor of 5–6) luminosities for the lower metallicity of the SMC.

Reduced WR line fluxes are also predicted for WR atmospheric models at low metallicity if one follows the metallicity dependence from Vink & de Koter (2005), such that WR populations inferred from Schaerer & Vacca (1998) at low metallicity may underestimate actual populations by an order of magnitude. This is potentially problematic for single star evolutionary models at very low metallicities ($\sim 1/50 Z_\odot$) since the WR populations inferred for I Zw 18 and SBS0335-052E using Milky Way line fluxes compare well with evolutionary models (e.g. Izotov et al. 1997; Papaderos et al. 2006). If WR populations are in fact a factor of $\sim$10 larger, similar to that of the SMC, close binary evolution would represent the most likely origin for such large WR populations.

For Magellanic Cloud metallicity starburst galaxies, one may employ appropriate template spectra (e.g. Crowther & Hadfield 2006) to reproduce WR features, as shown in the

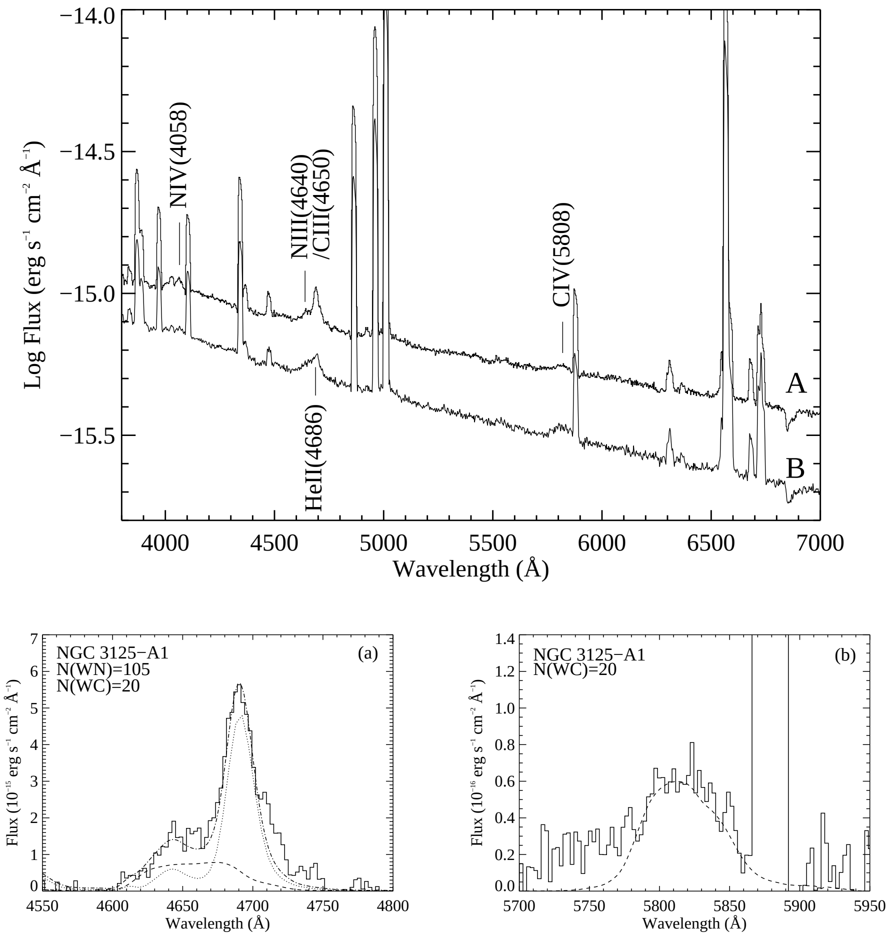

Figure 7. Top panel: Optical spectroscopy of knots A and B within the LMC metallicity starburst galaxy NGC 3125, indicating the CIII 4650/HeII 4686 (blue) and CIV 5801-12 (yellow) WR bumps. Lower panels: Fit to the blue and yellow bumps for cluster A1 using LMC template WN (dotted lines) and WC (dashed lines) stars (Hadfield & Crowther 2006)

upper panel of Fig. 7 for the starburst galaxy NGC 3125. Indeed, consistent fits to the blue and yellow WR bumps may be achieved for the A1 cluster within NGC 3125 using LMC template WR stars, as shown in the lower panels of Fig. 7 (Hadfield & Crowther 2006).

4. Ionizing fluxes and GRB progenitors

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). Indeed, relatively soft ionizing fluxes are observed in the super-Solar metallicity WR starburst galaxy NGC 3049 (Gonzalez Delgado et al. 2002).

At low metallicities, one anticipates a combination of weak UV and optical spectral lines from WR stars (i.e. weak stellar HeII λ4686) but very strong H and He Lyman continua (i.e. strong nebular HeII λ4686), as is indicated in the lower panel of Fig. 6. Indeed, low metallicity star forming galaxies display strong nebular HeII λ4686, although shocks from supernovae remnants may also contribute to nebular emission.

The typically environment of nearby ($z < 0.25$) long duration GRBs is unusually metal-poor, as emphasized by Stanek et al. (2006) with respect to star forming galaxies from the Sloan Digital Sky Survey. Reduced WR mass-loss rates at low metallicity will lead to reduced densities in the immediate environment of GRBs with respect to typical WR stars, as is observed (Chevalier et al. 2004). In addition, massive single stars undergoing homogeneous evolution in which WR mass-loss rates are low may maintain their rapidly spinning cores through to core-collapse (Yoon & Langer 2005; Langer & Norman 2006).

5. Summary

Observational and theoretical evidence supports reduced wind densities and velocities for low metallicity WR stars, which addresses the relative WR subtype distribution in the Milky Way and Magellanic Clouds, plus the reduced WR line strengths in the SMC with regard to the Galaxy and LMC. The primary impact at low metallicity is as follows; (a) an increased WR population due to lower line fluxes from individual stars, of particular relevance to I Zw 18 and SBS0335-052E; (b) harder ionizing fluxes from WR stars, potentially responsible for the strong nebular HeII λ4686 seen in low metallicity HII galaxies; (c) responsible for the reduced density of GRB environments with respect to Solar metallicity WR counterparts.

Finally, a metallicity dependence for WR winds may help to reconcile the relative number of WN to WC stars observed in surveys (e.g. Massey & Johnson 1998) with evolutionary predictions. Evolutionary models for which rotational mixing is included yet metallicity dependent WR winds are not (Meynet & Maeder 2003) fail to predict the high N(WC)/N(WN) ratio observed at high metallicities (Hadfield et al. 2005), whilst models which account for the Vink & de Koter (2005) WR wind dependence compare much more favourably with observations (Eldridge & Vink 2006), in spite of the neglect of rotational mixing.

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