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VLT/FORS Surveys of Wolf-Rayet Stars in the Nearby Universe

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Abstract. We present results from a series of VLT/FORS narrow-band imaging and spectroscopic surveys of Wolf-Rayet (WR) stars in nearby spiral galaxies and compare observed populations in high- and low metallicity environments. The metal-rich galaxy M 83 is seen to host an exceptional WR content, with over 1000 WR stars being detected. N(WC)/N(WN) $\sim$ 1.2 and late-type WC subtypes dominate the WC population. At low metallicity, $\sim$100 stars has been identified within NGC 1313, with N(WC)/N(WN) $\sim$ 0.5. In contrast to M83, the WC population of NGC 1313 comprises solely early subtypes plus a WO star (the first WO star to be identified beyond the Local Group). Consequently, the dominant WC subtype may serve as a crude metallicity diagnostic for WR galaxies.

In addition, the WR content of the blue compact dwarf galaxy NGC 3125 is examined. Previous UV and optical spectroscopic studies of knot A in NGC 3125 derive WR populations which differ by more than an order of magnitude. New VLT observations and archival HST spectroscopy reconcile this discrepancy via the use of LMC WR spectral templates and a reduced nebular-derived interstellar extinction. Empirical N(WR)/N(O) ratios for clusters within NGC 3125 are a factor of two higher than evolutionary synthesis predictions but are consistent with those observed for other young massive clusters.

Keywords. stars: Wolf-Rayet – galaxies: individual (NGC 1313, M 83, NGC 3125) – galaxies: stellar content

1. Introduction

Wolf-Rayet (WR) stars represent the penultimate evolutionary stage in the evolution of the most massive stars. Believed to represent the bare cores of their O star precursors, their spectra are characterised by broad emission lines of nitrogen (WN), carbon (WC) or oxygen (WO). Their unique spectral appearance allows them to be readily identified in external galaxies such that WR stars can be been detected as individual stars in nearby galaxies (e.g. Massey 1998) and in the integrated starlight of more distant galaxies (Schaerer *et al.* 1999a).

Metallicity, Z, is a key factor in determining the absolute number and subtype distribution of a WR population. Prior to the WR phase, O star winds has been empirically established to depend on metallicity, with the latest results revealing $\dot{M} \propto Z^{\sim 0.8}$ for SMC, LMC and Milky Way O stars (Mokeim *et al.* 2007). Enhanced mass-loss rates in metal-rich environments reduces the minimum mass required for WR formation such that the WR mass cut-off is expected to decrease from $\sim 30\ M_\odot$ in the SMC to $\sim 25\ M_\odot$ for the Milky Way (Meynet *et al.* 2004). Consequently, observed stellar populations provide a vital test of stellar evolution models.

The advent of 8m class telescopes and efficient multi-object spectrographs has allowed WR surveys to move beyond the Local Group, permitting a vital probe into massive stellar evolution under conditions which are not accessible on a local scale. Using a combination of narrow-band imaging filters tuned to WR emission features, Schild *et al.* (2003) identified a significant numbers of WR stars in the nearby (D$\sim$2 Mpc) spiral galaxy NGC 300. Therefore, to increase current WR statistics across a broad range of metallicities our team has undertaken a series of VLT/FORS surveys of the WR populations in several, nearby galaxies.

2. The Wolf-Rayet Population of Nearby Star-forming Spiral Galaxies

2.1. *The WR Population of NGC 1313*

NGC 1313 is an isolated, face-on SB(s)d spiral situated at a distance of 4.1 Mpc (Mendez *et al.* 2002). Oxygen abundance studies reveal that NGC 1313 is intermediate in metallicity between the irregular Magellanic Cloud galaxies, whilst morphologically NGC 1313 is reminiscent of late-type spirals such as NGC 300 and M 33.

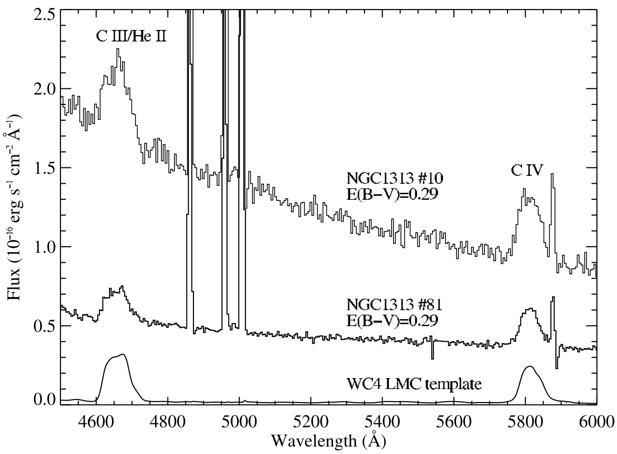

Figure 1. Dereddened spectral comparison between WC regions within NGC 1313 and template LMC WC4 spectra. Individual spectra have been offset by $0.1{\times}10^{-16}$erg s^{-1} cm^{-2} Å^{-1}.

Our VLT/FORS photometric survey of NGC 1313 has identified 94 potential WR regions in NGC 1313. Follow-up spectroscopy of 82 candidates confirms 85% host WR stars. For the majority of confirmed sources, observed line luminosities are consistent with single WR stars, as illustrated in Fig. 1. Ground-based imaging reveals that most sources appear relatively isolated and photometry suggests that they belong to binary systems or small clusters/associations.

Of the 12 cases where WR emission was not detected, two displayed nebular He II λ4686 whilst four spectra started longward of the He II λ4686 feature required for WN classification. Only six candidates showed no evidence of WR emission, of which three were consistent with foreground late-type stars.

Using template LMC WR stars, spectroscopy reveals N(WR)=84, with N(WC)/N(WN) = 0.6 (Hadfield & Crowther 2007). Accounting for the remaining candidates we estimate that the true WR content of NGC 1313 is N(WR)$\sim$115, with N(WC)/(WN)$\sim$0.4 (assuming photometric classifications). The WN stars are evenly distributed amongst early and

Table 1. Summary of nearby spiral galaxies which have been surveyed with FORS1/2. O star numbers are derived from Hα imaging, assuming an O7V Lyman continuum flux of 10^{49}ph/s.

Galaxy	D (Mpc)	log(O/H) + 12	N(O7V)	N(WC)	N(WN)	Reference
NGC 300	1.9	8.6:	800	$\geqslant$16	$\sim$15	Schild *et al.* 2003
						Crowther *et al.* 2007
NGC 1313	4.1	8.23	6 500	$\geqslant$51	$\sim$33	Hadfield & Crowther 2007
M 83	4.5	<9.2	40 000	$\geqslant$470	$\sim$560	Hadfield *et al.* 2005

late subtypes and include a rare WN/C4 transition star. The WC population consists exclusively of early-type stars, to one of which we assign a WO classification. This represents the first WO star to be identified beyond the Local Group. The WR population of NGC 1313 is presented in Table 1.

2.2. *The WR Population of M 83*

The study of WR stars in metal-rich environments has so far been restricted to M 31 (which has an unfavourable inclination) within the Local Group and the integrated light of star forming regions within starburst galaxies. Therefore, we have also investigated the WR population of the nearby (D=4.5 Mpc), metal-rich ($Z \sim 2Z_{\odot}$) environment of the grand design spiral galaxy M 83.

Our VLT/FORS imaging survey encompassed the entire galaxy, but our statistics excludes the starburst nucleus since the central 15$''$ appears saturated on all FORS images. In excess of 280 WR candidate regions have been identified within the disc of M 83, of which 198 have been spectroscopically observed. The presence of WR stars has been confirmed in 131 regions i.e. a success rate of 66%.

Using Galactic WR stars as templates, we infer a WR population of ~1100 stars (Hadfield et al 2005), ten times that estimated for NGC 1313. Observed line luminosities suggests that some sources host a single WR star, whilst others contain larger WR populations (N~10). Both the WC and WN populations of M 83 are dominated by late subtypes, with WO subtypes absent. In contrast to NGC 1313, the majority of WR stars in M 83 are located within bright star forming regions and given that both galaxies are located at comparable distances the lower success rate of our M 83 survey reflects resolution issues of ground-based surveys.

2.3. *Comparison with Evolutionary Predictions*

Surveys for WR stars in Local Group galaxies over the past three decades have revealed a strong correlation between the relative number of WC to WN stars and oxygen content of the host galaxy (Massey & Johnson 1998). Undoubtedly, completeness should be kept in mind given that WC stars are more readily identified due to their intrinsically stronger lines. Nevertheless, our imaging surveys are optimised for net emission at λ4686 and in M 83 we achieved 4σ spectroscopic WNL detections with W_{λ}(He II λ4686) $\sim$ 1Å.

Extrapolating from previous observations, one would expect N(WC)/N(WN) $\geqslant$ 1 for a galaxy with twice the Solar oxygen content (Massey & Johnson 1998) whereas based on the low metallicity of NGC 1313 one would expect N(WC)/N(WN)~0.1. M 83 continues the observed trend with N(WC)/N(WN)~1.2. For NGC 1313, we estimate a significantly higher subtype ratio of ~0.6, or ~0.4 if we include outstanding candidates. This is intermediate between that observed in the outer, sub-solar regions of M 33 [N(WC)/N(WN)~0.35; Massey & Johnson 1998] and the inner region of NGC 300 [N(WC)/N(WN)~0.7; Crowther *et al.* 2007].

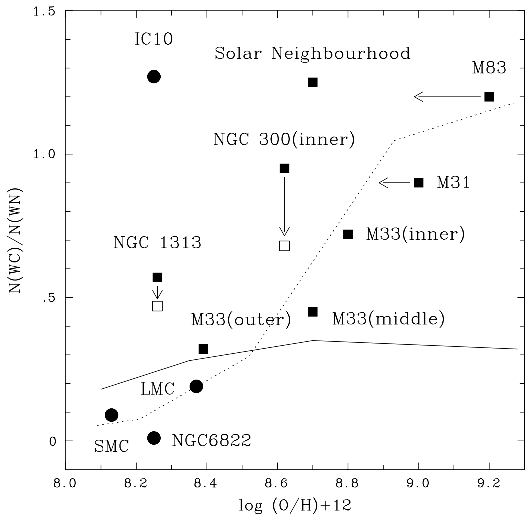

Figure 2. Observed N(WC)/N(WN) ratios for nearby spiral (squares) and irregular (circles) galaxies. Open symbols adopt photometric classifications for remaining WR candidates. Also shown are single star evolutionary model predictions for the rotating Geneva models (solid line; Meynet & Maeder 2005) and those of Eldridge & Vink (2006) (dotted). The latter models include a metallicity wind scaling for WR stars.

At low-metallicities, predictions from rotating evolutionary models are in good agreement with observed WC to WN ratios (see Fig. 2). However, at higher metallicities the Geneva models underestimate the number of WC stars e.g., predicting WC/WN=0.36 at Z=0.04. In contrast, the models which neglect rotational mixing, but include metallicity dependent WR winds, provide a better match to observations across the full metallicity range.

2.4. *Using the WC subtype as a metallicity indicator*

It has long been recognised that late-type WC stars are preferentially associated with metal-rich environments. For example, in the Milky Way WC9 stars are universally located within the inner, metal-rich regions (Conti & Vacca 1990), while metal-poor WC stars such as those observed in the Magellanic Clouds are exclusively early-type WC/WO stars. Results from our VLT/FORS surveys are fully consistent with such conclusions, since we identify an overwhelming WC8–9 population in M 83 and late-type WC stars are notably absent in NGC 1313.

To illustrate the difference in observed WC populations, Fig. 3 compares the ratio of WC7–9 (WCL) to WC4–6 (WCE) stars for a wide range of environments. At high metallicities ($\log(\mathrm{O/H}) + 12 \geqslant 8.8$), late WC subtypes dominate the population (e.g., M 83). For intermediate metallicities ($\log(\mathrm{O/H}) + 12 \sim 8.5 - 8.8$), the WC population is composed of a mixture of early and late WC subtypes, as observed for the Solar neighbourhood, Finally, in metal-poor galaxies such as NGC 1313 ($\log(\mathrm{O/H}) + 12 \lesssim 8.5$) the WC population comprises solely of early-type WC and WO stars.

Exceptions to this general trend do occur. In the metal-poor galaxy IC 10 ($\log(\mathrm{O/H}) + 12 = 8.26$) Crowther *et al.* (2003) identify one WC star as a WC7 subtype. Nevertheless, the dominant WC subtype may serve as a crude metallicity diagnostic for integrated stellar populations (e.g., SDSS WR galaxies). Indeed, the high metal content of NGC 1365 ($\log(\mathrm{O/H}) + 12 = 9.3 - 9.5$) is confirmed by the presence a dominant WCL population (Phillips & Conti 1992).

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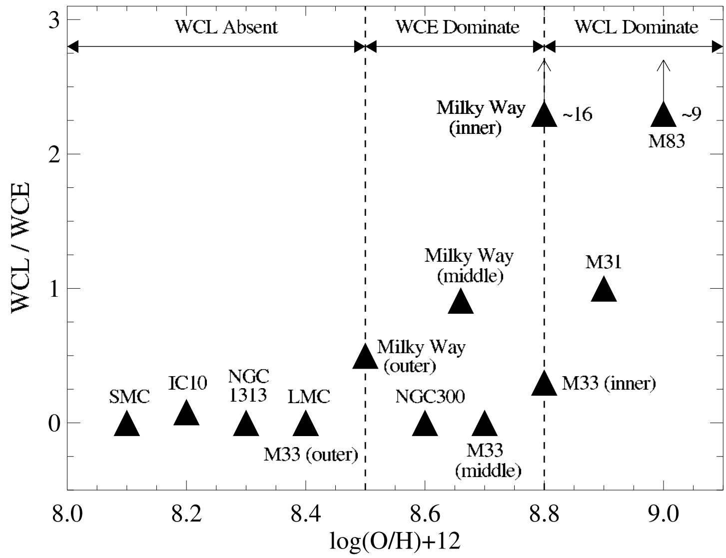

Figure 3. The distribution of WC4–6 to WC7–9 stars in well studied galaxies versus oxygen content (Hadfield & Crowther 2007; their Fig 10).

3. The Starburst Galaxy NGC 3125

NGC 3125 (Tol 3) is a LMC-metallicity irregular dwarf galaxy which is dominated by a central starburst region containing two main knots of star formation (3125-A and -B). From UV spectroscopy, Chandar *et al.* (2004) estimate a WR population of ~ 5000 and N(WR)/N(O)$\geqslant 1$ for knot A; whilst optical studies infer a WR population of only ~ 500 and N(WR)/N(O)~ 0.1 (Schaerer *et al.* 1999b). To resolve discrepancies between UV and optically derived WR populations we have re-investigated the massive stellar content of NGC 3125 using new VLT/FORS1 imaging and spectroscopy, plus archival *HST* imaging and spectroscopy.

Table 2. The WR population of NGC 3125.

	Diagnostic	A1	A2	B
N(WN5–6)	Optical	105	105	40
N(WC4)	Optical	20	–	20
N(WN)	UV	110	–	–
N(O)	UV (SB99)	550	750	350
N(WR)/N(O)	Optical/UV	0.23	0.14	0.14

New FORS1 narrow-band imaging confirms that 3125-A and -B represent the primary sites of WR stars, whilst the superior spatial resolution of *HST* resolves both regions into two dominant clusters. Both clusters within region A (A1 and A2) host WR stars, but the optically fainter cluster A2 appears to be heavily reddened. The resolution of our ground-based narrow-band images is insufficient to identify which cluster within region B hosts WR stars.

In contrast to other studies of unresolved WR populations, the WR content of 3125-A1 and -B has been estimated by matching LMC template WR spectra to the observed WR emission features. For A1, we find that the composite spectrum of 105 WN and 20 WC stars (Hadfield & Crowther 2006) reproduces the blue and red WR bumps exceptionally

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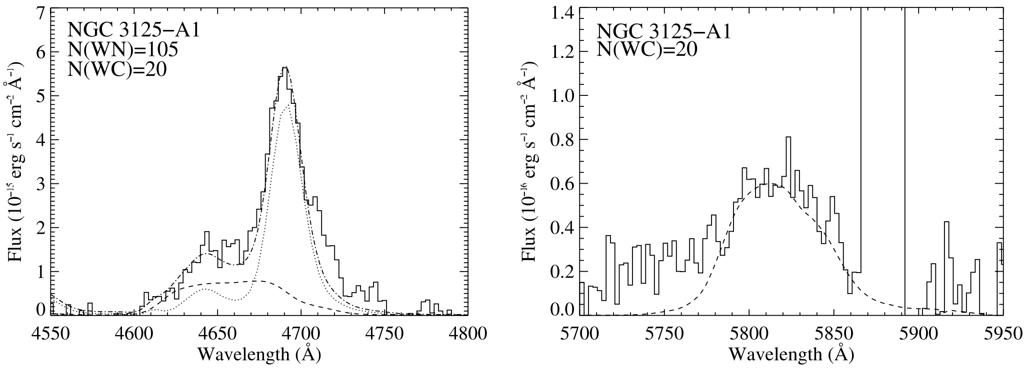

Figure 4. Spectral comparison between the observed (solid) and generic (dashed-dotted) WR emission features for cluster 3125–A1. Generic WC4 (dashed) and WN5–6 (dotted) features are marked. Spectra have been dereddened (SMC law) and continuum subtracted.

well (see Fig 4). This is factor of ∼3 lower than previous optical studies as a result of a reduced Hα/Hβ derived interstellar reddening. Applying this reduced reddening to archival UV STIS spectroscopy, together with an SMC extinction law (Bouchet *et al.* 1985), reveals that 110 generic LMC WN5-6 stars are required to reproduce the observed λ1640 emission, in excellent agreement with our VLT/FORS1 optically derived WN population.

From UV spectroscopy, we derive an O star content of ∼550 for A1 assuming a burst age of 4Myr. Similar results are obtained for region B based upon archival *HST* UV and optical photometry. We estimate N(WR)/N(O)∼0.1–0.2 for clusters within 3125-A and B, significantly larger than single star evolutionary models at LMC metallicities predict. However, our results are consistent with WR populations derived for other young massive clusters in the literature (Moll *et al.* 2007, Sidoli *et al.* 2006).

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