VLT/FORS Surveys of Wolf-Rayet Stars beyond the Local Group: Type Ib/c Supernova Progenitors?

Paul A. Crowther, Lucy J. Hadfield
(University of Sheffield, United Kingdom)

Wolf-Rayet (WR) stars are the chemically evolved descendents of O stars, such that they trace massive star formation. Here we present results of recent VLT/FORS surveys of WR stars in nearby spiral and irregular galaxies and consider individual WR stars as progenitors of Type Ib/c core-collapse supernovae. Young massive clusters hosting large WR populations may be used as templates for high-redshift Lyman break galaxies.

Massive stellar evolution

Massive stars form in star clusters within star-forming galaxies, pollute the interstellar medium, injecting energy and momentum via powerful stellar winds and core-collapse supernovae (SNe). The detection of massive stars within Lyman-break galaxies at high redshift, either directly via their UV continua or indirectly via ionised H II regions, provides some of the most stringent constraints upon their physical properties.

The Initial Mass Function favours the formation of low- and intermediate-mass stars with respect to high-mass stars, for which the boundary is conventionally set at 8 $M_{\odot}$ – the division between stars ultimately forming a CO white dwarf or an iron core, the latter subsequently undergoing a core-collapse SN. Spectroscopically, stars with initial masses of 8–20 $M_{\odot}$ are B-type dwarfs on the main sequence, or O-type dwarfs at higher initial mass. Such high-mass stars possess convective cores, and radiative envelopes, a situation reversed in the Sun and other low-mass stars. Although there is energy transport from the convective and radiative regions, only the convective core participates in nuclear reactions, unless hydrogen-rich material is mixed downwards from the outer zones.

Once the core hydrogen is exhausted, the star leaves the main sequence and becomes a blue supergiant, and ultimately a red supergiant (RSG) for stars with initial mass up to perhaps 20–30 $M_{\odot}$. Observationally, there is an absence of luminous RSGs, known as the Humphreys-Davidson limit, such that initially more massive stars circumvent the RSG phase, pass through a Luminous Blue Variable stage, before ending their life as Wolf-Rayet (WR) stars, exhibiting either the products of core-H burning (WN subtypes) or subsequent core-He burning (WC, WO subtypes).

Consequently, the prime candidates for core-collapse SN are RSG and WR stars for H-rich (Type II) and H-poor (Type Ib/c) cases, respectively. Indeed, within the past few years a direct connection has been established between certain Type Ic SNe and gamma-ray bursts (GRBs), supporting the collapsar model in which the GRB results from the death throes of a rapidly rotating WR star.

Relative to lower-mass stars, the evolution of high-mass stars is complicated by: (a) the metallicity dependence of their radiatively line-driven stellar winds, producing weaker winds at low metallicity; and (b) their initial rotational velocities, providing rotationally-induced mixing within their interiors. It is only within the past decade that allowance for both effects has been considered within evolutionary models, most recently implemented into spectral synthesis models (Vazquez et al. 2007).

Surveys of Wolf-Rayet stars in star-forming spiral galaxies

WR stars exhibit a unique, broad emission line spectral appearance which provides the basis for their detection in external galaxies. Notably, narrowband interference filter techniques have been independently developed by Moffat and Massey that permit their detection from their strong emission lines at He II λ 4686 (WN stars) and C III λ 4650 (WC stars) with respect to their nearby continuum. Such techniques have been applied to regions of the Milky Way disc, the Magellanic Clouds and other Local Group galaxies.

It is well established that the absolute number of WR stars and their subtype distribution are metallicity dependent. N(WR)/N(O) ~ 0.15 in the relatively metal-rich Solar Neighbourhood, yet N(WR)/N(O) ~ 0.01 in the metal-deficient SMC on the basis of only 12 WR stars *versus* ~ 1000 O stars (Crowther 2007). This observational dependence follows since the hydrogen-rich envelopes of O stars are more easily removed at high metallicity. O-type stars possess strong winds that are driven by metallic lines (primarily CNO and Fe-peak elements), for which the empirical dependence upon metallicity Z is $\dot{M} \propto Z^{0.8}$ for stars between SMC and Milky Way metallicities (Mokiem et al. 2007).

Attempts have been made with 4-m telescopes to extend the interference filter technique to star-forming galaxies beyond the Local Group, although this proved to be challenging (e.g. Testor and Schild 1993). The advent of efficient multi-object spectrographs such as FORS1/2 at the Very Large Telescope has permitted surveys of WR populations in galaxies at distances beyond 2 Mpc (Table 1). An example of our FORS1 imaging approach is presented in Figure 1 for the barred spiral galaxy NGC 1313 (see also the cover page of the current Messenger). The boxed region 60 × 60 arcsec in size within NGC 1313 hosts in excess of twenty WR stars, most of which are within a large giant H II region. Overall, the success rate of identifying WR stars from

Galaxy	D (Mpc)	log (O/H)+12	N (O7V)	N(WN)	N(WC)	Reference
NGC 300	1.9	8.6:	800	$\geq$ 16	~ 15:	Schild et al. 2003; Crowther et al. 2007
NGC 1313	4.1	8.2	6500	$\geq$ 51:	~ 33:	Hadfield and Crowther 2007
M83	4.5	9.0?	40000	$\geq$ 470	$\geq$ 560	Hadfield et al. 2005
NGC 3125	11.5	8.4	3600	200	40	Hadfield and Crowther 2006

Table 1: Summary of southern star-forming galaxies whose WR populations have been surveyed with FORS1/2 to date. The O star contents are based upon a SFR for an assumed O7V Lyman continuum flux of 10^{49} per second, omitting regions excluded from our WR surveys, i.e. the outer disc of NGC 300 and the nuclear starburst of M83.

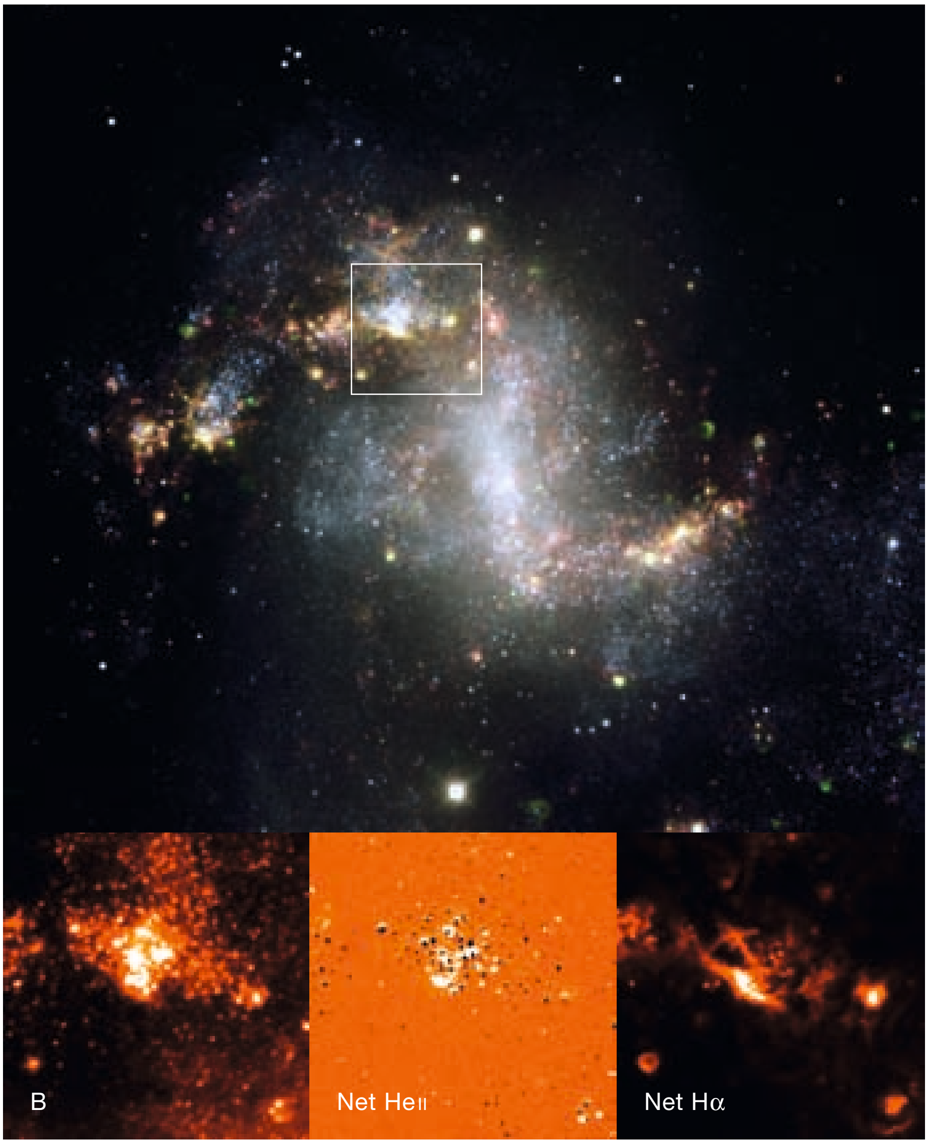


Figure 1: The upper panel shows a composite FORS1 image of NGC 1313 (ESO Press Photo 43a/06) showing a 60 × 60 arcsec box, for which the lower panels show FORS1 images of broadband B, continuum subtracted He II 4686 (excesses are shown in white), continuum subtracted Hα, from left to right.

our FORS surveys is high. For the case of NGC 1313 we have identified 94 candidate WR stars, for which a subset of 83 % have been spectroscopically observed. Within this subset, 90 % of the sources have been spectroscopically confirmed as WR stars, as indicated in Figure 2 (Hadfield and Crowther 2007).

Regarding WN and WC subtype distributions, similar numbers are observed in the Solar Neighbourhood. In contrast, WN stars exceed WC stars by a factor of ~ 5 and ~ 10 for the LMC and SMC, respectively (Crowther 2007). At low metallicity the reduced WR population and the relative dominance of WN subtypes most likely results from the metallicity dependence of winds from their evolutionary precursors. Consequently, only the most massive single stars reach the WR phase in metal-poor environments.

Not all WR subtypes are observed in all environments. Early-type WN and WC subtypes dominate in metal-poor galaxies, such as the SMC, while late WC stars are more common at super-Solar metallicities, such as M83 (Hadfield et al. 2005). This observational trend led to suggestions that early-type WC stars are richer in carbon than late-type WC stars. However, quantitative analysis of WC subtypes, allowing for radiative transfer effects, do not support a subtype dependence of elemental abundances in WC stars.

In contrast, Crowther et al. (2002) proposed that late spectral types follow in metal-rich environments, and early types at low metallicity due to metallicity dependent WR winds. Indeed, WO stars (extreme WC early types) are preferentially seen at low metallicity. Consequently, the representative WC subtype of a galaxy permits an estimate of its metallicity. Metal-poor WR stars possess harder Lyman continuum ionising flux distributions than high-metallicity counterparts, in agreement with the association of nebular He II λ 4686 with low-metallicity WR stars (e.g. Hadfield and Crowther 2007).

Evolutionary models for the Wolf-Rayet stage have typically assumed metallicity independent mass-loss rates, which both observational and theoretical evidence now challenges. The metallicity dependence of WN winds appears to be similar to O stars, with a somewhat weaker dependence for WC stars due to their high carbon and oxygen abundances; the latter is of relevance to the observed ratio of WC to WN stars predicted by evolutionary models (Eldridge and Vink 2006).

One related topic involves the search for Wolf-Rayet stars in close binary systems with neutron-star or black-hole companions. Such systems represent a natural, though rare, end state for close binary evolution, for which Cyg X-3 in the Milky Way has been the sole example up until recently. The combination of high spatial resolution X-ray surveys plus our WR surveys of nearby galaxies has increased this number to three, IC 10 X-1 in the northern sky, and NGC 300 X-1 in the south, both of which are probable WR plus black-hole systems (e.g. Crowther et al. 2007).

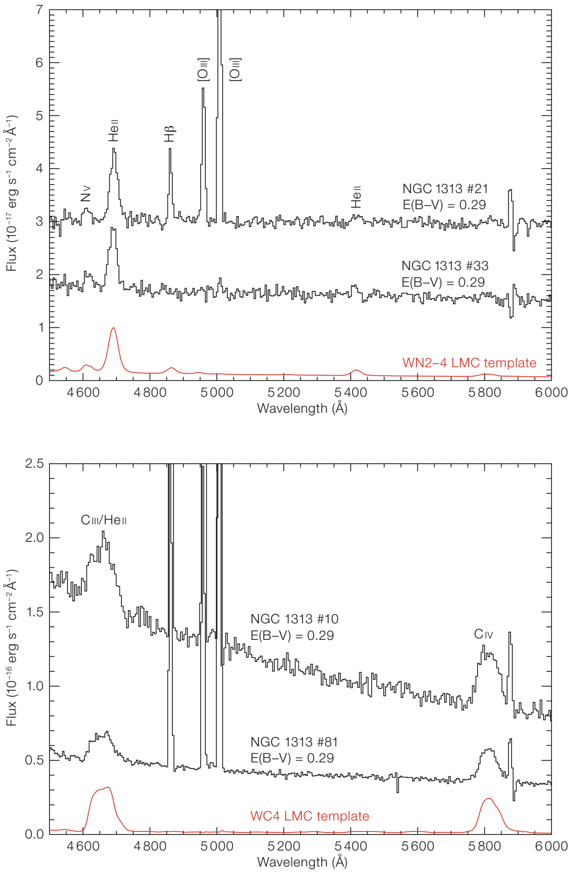


Figure 2: Representative early-type WN (upper panel) and WC (lower panel) stars identified in our NGC 1313 survey (Hadfield and Crowther 2007), together with average LMC template spectra (shown in red) from Crowther and Hadfield (2006).

Type Ib/c supernova and gamma-ray burst progenitors?

At solar metallicity, stars initially more massive than ~ 25 $M_{\odot}$ apparently end their lives as either a nitrogen-rich (WN) or carbon-rich (WC) WR star. WN and WC stars are believed to be the immediate progenitors for a subset of Type Ib (H-poor) and Type Ic (H and He-poor) supernovae, respectively. Alternatively, lower-mass binaries may produce Type Ib (Type Ic) SN in which H (both H and He) has been stripped away due to Roche lobe overflow and/or common envelope evolution. Some Type Ib/c SN do occur in elliptical/S0 host galaxies – explicitly 4 from 50 Type Ib/c SNe within the last decade within 50 Mpc – in favour of such lower-mass progenitors. Nevertheless, the vast majority are preferentially in actively star-forming galaxies. So are most Type Ib/c SN from massive WR stars or lower-mass interacting binaries?

To date, broadband surveys of local (≤ 10 Mpc) star-forming galaxies have been undertaken with Hubble Space Telescope and ground-based 8-m telescopes by groups in the UK and US. These have been successful in identifying RSG progenitors of the most common core-collapse SN (Type II-P, Smartt et al. 2004). Unfortunately, WR stars are visually much fainter than RSG and may not be distinguished from blue supergiants on the basis of existing broadband surveys alone. Observationally, SN 2002ap (Type Ic) in M74 so far provides the most stringent constraints upon a potential WR progenitor, revealing an upper limit of $M_B = -4.2$ mag (Crockett et al. 2007). The precursor of SN 2002ap was either a relatively faint WC star, or more likely a lower-mass binary system.

One application of our WR surveys with the VLT would be to establish whether a WR star was the progenitor of a future Type Ib/c SN, if it occurred in one of our surveyed galaxies. For the case of M83, we have identified in excess of 1000 WR stars within the galactic disc. The star-formation rate (SFR) in M83 may be estimated from its global Hα flux of 7 × 10^{-11} erg s^{-1} cm^{-2} (Kennicutt, priv. comm.), corrected for average extinction (E_{B-V} ~ 0.5 mag), i.e. a SFR of 4.3 $M_{\odot}$ yr^{-1} (Kennicutt 1998) for an adopted distance of 4.5 Mpc. If we are able to study ~ 10 nearby galaxies with such a high SFR, we would sample in excess of 10^{4} WR stars. Statistically one of those stars would be expected to collapse to a Type Ib/c SN within the next decade, given that WR lifetimes are ~ 10^{5} yr. Indeed, we have already come close to success. Our FORS1 narrowband imaging of the merging 'Antennae' galaxies (NGC 4038/9) for WR stars was obtained in June 2005, sadly six months *after* the Type Ic SN 2004gt.

Of course, astrometry is rather challenging from ground-based imaging. High spatial resolution imaging helps greatly, as indicated in Figure 3 where we compare the location of a (rare) WO star in NGC 1313, identified from FORS1 narrowband imaging and spectroscopic follow-up, to HST/ACS broadband imaging.

This general topic has received renewed interest since a number of nearby, bright Type Ic SNe have been observationally associated with several nearby GRBs (e.g. SN 2003dh = GRB 030329 Hjorth et al. 2003). These favour the 'collapsar' scenario, involving the core collapse of a rotating Wolf-Rayet star to a black hole via an accretion disc, in which the rotational axis provides a preferred direction for the jet (MacFadyen and Woosley 1999). Hammer et al. (2006) identify WR stars within a giant H II region of ESO 184–G82 several hundred pc from the location of SN 1998bw = GRB 980425, and propose that the GRB progenitor was ejected from the WR cluster.

Rotation is critically important since the collapsar model involves highly collimated jets produced along the polar axes, due to a dense, equatorial accretion disc feeding the central black hole. At low metallicity, the spin-down induced by mechanical mass-loss during the Wolf-Rayet phase may be avoided due to the relatively weak winds, resulting in sufficient angular momentum in the core upon core collapse. Of course, only a tiny fraction of SNe produce a GRB, with an apparent bias towards metal-poor environments (Modjaz et al. submitted) with respect to

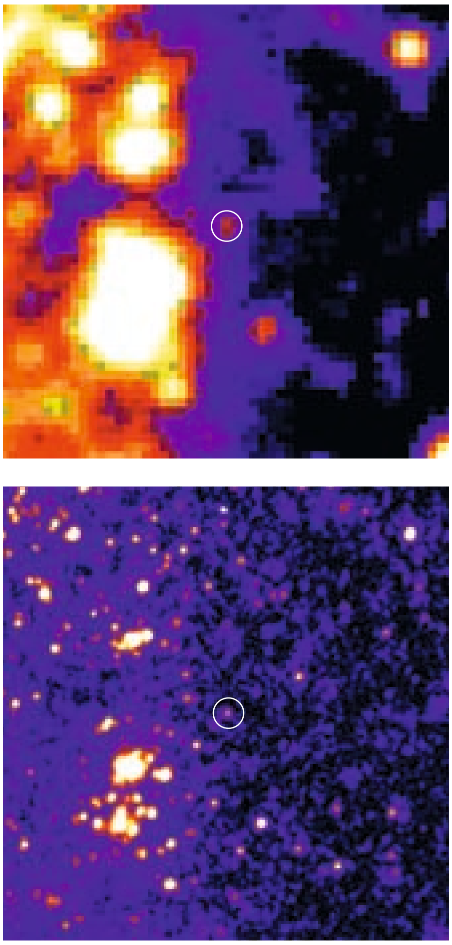


Figure 3: Comparison of a 10 × 10 arcsec (200 × 200 pc) region of NGC 1313 centred upon a WO star imaged by FORS1 (He II λ 4686 filter, top) and HST/ACS (F435W/WFC, bottom). The WO has a F435W magnitude of 23.4 mag, suggesting $M_{F435W} \sim -5.2$ mag for a distance modulus of 28.0 mag (4.1 Mpc) and $A_{F435W} \sim 0.6$ mag.

non-GRB Type Ic SN. As such, GRBs would trace the low-metallicity star-formation history of the Universe. The low metallicity bias favours the single star scenario, with respect to alternative close binary models.

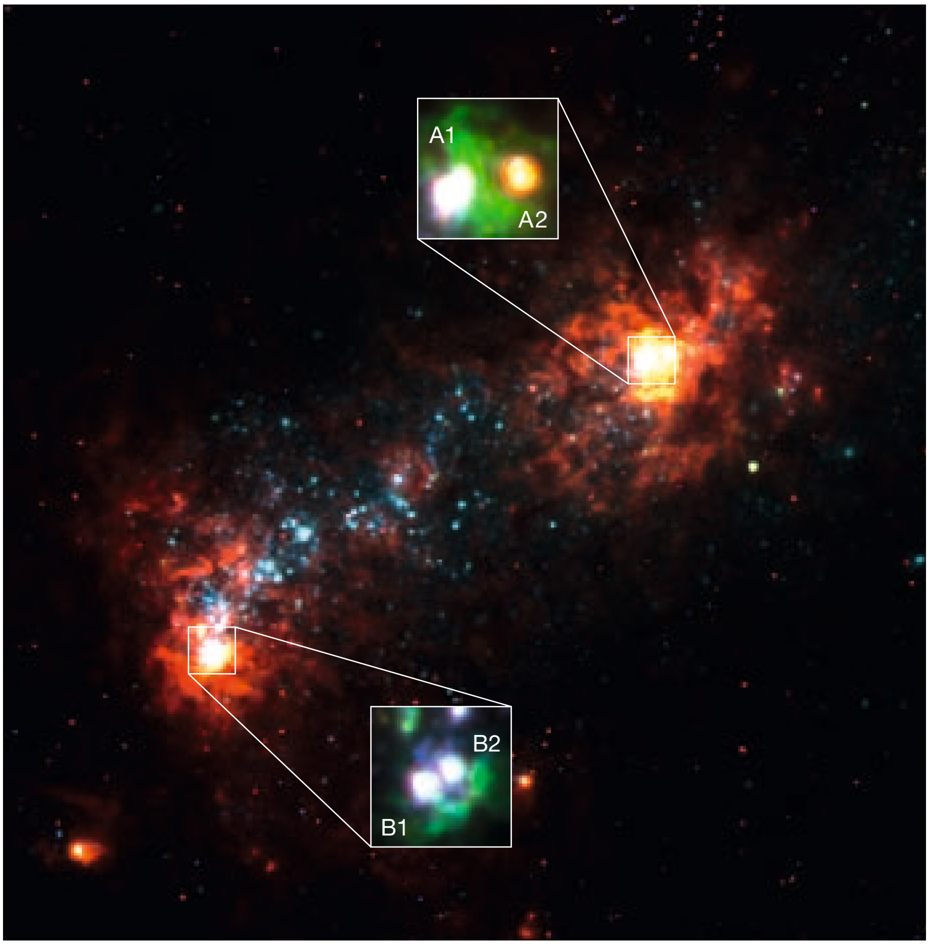
WR clusters as templates for Lyman break galaxies

Individual WR stars may, in general, be resolved in Local Group galaxies from ground-based observations, whilst the likelihood of contamination by nearby sources increases at larger distances. For example, a typical slit width of 1″ at the 2 Mpc distance of NGC 300 corresponds to a spatial scale of ~ 10 pc. Relatively isolated WR stars have been identified, albeit in the minority (recall Figure 3). This is even more problematic for more distant galaxies such as M83 where the great majority of WR stars are observed in clusters or associations (Hadfield et al. 2005).

So-called ‘WR galaxies’ are typically starburst regions exhibiting spectral features from tens, hundreds, or even thousands of WR stars. Indeed, such knots of star formation, hosting young massive clusters ($\sim 10^6\,M_\odot$) often reveal significant WR populations, seen at UV or visual wavelengths. Their appearance is reminiscent of the composite rest-frame UV spectrum of $z \sim 3$ star-forming galaxies ($\sim 10^{10-11}\,M_\odot$) which also show broad He II λ 1640 emission (Shapley et al. 2003).

A recent ultraviolet HST/STIS survey of local starburst galaxies also revealed strong He II λ 1640 emission in a few cases, most notably a young massive cluster within NGC 3125, alias Tol 3 (Chandar et al. 2004). This LMC-metallicity galaxy is dominated by a central starburst region which consists of two main emission knots, NGC 3125-A and -B, shown in Figure 4. From UV spectroscopy, Chandar et al. (2004) estimated 5 000 WR stars for a cluster within knot A, with a remarkable $N(WR)/N(O) \geq 1$. In contrast, optical studies of NGC 3125-A infer a WR population that is an order of magnitude lower, in better agreement with the relative massive star content of other local starburst galaxies. If NGC

Figure 4: Composite *B*, *V*, *Hα* HST/ACS image of NGC 3125 (20 × 20 arcsec = 1 × 1 kpc) in which young massive clusters within knot A (upper right) and knot B (lower left) host significant WR populations (Hadfield and Crowther 2006). Insets are composite *U*, *V* and *I* ACS images for the central 1 × 1 arcsec for each knot, revealing clusters A1-2 and B1-2. Our study, based upon VLT/FORS1 imaging and spectroscopy resolves previously inconsistent massive stellar populations for cluster A1 from UV (HST/STIS) versus optical diagnostics.



3125-A is an analogue for Lyman-break galaxies, one must be able to reconcile optical and UV diagnostics for this starburst galaxy.

Hadfield and Crowther (2006) re-investigated the massive stellar content of NGC 3125 from FORS1 imaging and spectroscopy, supplemented by archival HST imaging and spectroscopy. FORS1 narrowband imaging confirms that the NGC 3125-A and -B knots represent the primary sites of WR stars. HST imaging resolves each knot into two young massive clusters, as shown in Figure 4. Our FORS1 imaging reveals that both clusters within knot A host WR stars (A1 and A2), for which the visually fainter cluster A2 is heavily reddened. From ground-based imaging is not clear whether B1 or B2 (or both) host WR stars, since their separation is ~ 0.2 arcsec (10 pc).

LMC template WN and WC spectra from Crowther and Hadfield (2006) were matched to the FORS1 visual WR features in A1 and B1+B2, permitting their relative contributions to be determined. From Figure 5, we derive N(WN) ~ 105 in cluster A1, a factor of ~ 3 lower than previous optical studies, owing to a lower nebular-derived interstellar reddening. Using Starburst99 theoretical energy distributions to estimate O star populations for each cluster, we find N(WR)/N(O) = 0.1–0.2 for clusters A1-A2 (each 2×10^5 M$_\odot$), in broad agreement with evolutionary models.

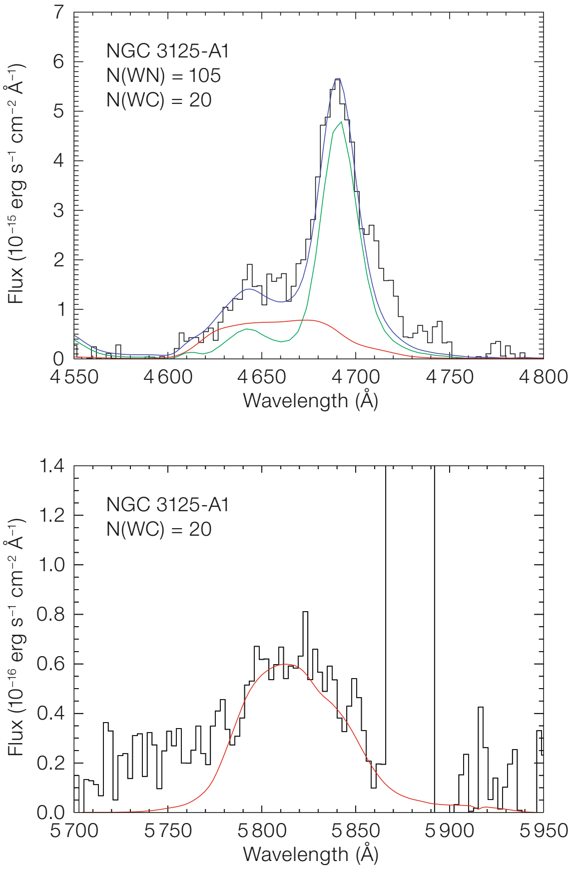


Figure 5: De-reddened, continuum subtracted VLT/FORS1 spectroscopy of NGC 3125-A1 (black, Hadfield and Crowther 2006), together with scaled LMC-metallicity templates for WN (green) and WC (red) stars, plus their sum (blue).

Archival HST/STIS UV spectroscopy confirms the low interstellar extinction towards A1, assuming an SMC-like reddening law. We obtain N(WN) = 110 from the slit loss corrected He II λ 1640 line flux, in excellent agreement with optical results. Our HST/STIS result is however a factor of 35(!) times lower than that inferred from the same data set by Chandar et al. (2004). The discrepancy is primarily due to an anomalously high far-UV-derived extinction from their use of the generic starburst law. Consequently, far-UV-based results for other nearby starburst knots should be treated with caution.

In conclusion, our ongoing WR surveys of nearby galaxies permit studies of young massive stellar populations across a range of ambient metallicities, with influence on evolutionary synthesis models for massive stars, WR stars, enable Type Ib/c supernova and GRB progenitors, and local young massive clusters as templates for high-redshift star-forming galaxies. In the near future we aim to extend our surveys to other galaxies with high SFRs in the southern hemisphere with the VLT and in the northern hemisphere with other facilities. Indeed, WFPC2 (until SM4) and WF3 (after SM4) aboard HST possess a narrow He II filter. These may be used with broadband continuum filters to identifty WR candiates at high spatial resolution.

Acknowledgements

Thanks to Hans Schild for the introduction to WR surveys beyond the Local Group, ESO for including He II filters within the standard filter set of FORS, and the support of the OPC sub-panels since Period 65.

References

Chandar R. et al. 2004, ApJ 604, 153
Crockett R. M. et al. 2007, MNRAS, in press, arXiv:0706.0500
Crowther P. A. 2007, ARA&A 45, 177
Crowther P. A. and Hadfield L. J. 2006, A&A 449, 711
Crowther P. A. et al. 2002, A&A 392, 653
Crowther P. A. et al. 2007, A&A 469, L31
Eldridge J. and Vink J. 2006, A&A 452, 295
Hadfield L. J. and Crowther P. A. 2006, MNRAS 368, 1822
Hadfield L. J. and Crowther P. A. 2007, MNRAS, in press, arXiv:0708.2039
Hadfield L. J. et al. 2005, A&A 439, 265
Hammer F. et al. 2006, A&A 454, 103
Hjorth J. et al. 2003, Nature 423, 847
Kennicutt R. C. 1998, ARA&A 36, 189
MacFadyen A. and Woosley S. 1999, ApJ 524, 262
Mokiem M. R. et al. 2007, A&A, in press, arXiv:0708.2042
Schild H. et al. 2003, A&A 397, 859
Shapley A. et al. 2003, ApJ 347, 127
Smartt S. et al. 2004, Sci 303, 499
Testor G. and Schild H. 1993, The Messenger 72, 31
Vazquez G. A. et al. 2007, ApJ 663, 995