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An exceptional population of late-type WC stars in the metal-rich spiral galaxy M 83*

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Abstract. We have surveyed the metal-rich spiral galaxy M 83 (NGC 5236) for its Wolf-Rayet population using VLT-FORS2 narrow-band imaging and follow-up spectroscopy. From a total of 280 candidates identified using He II λ4686 imaging, Multi Object Spectroscopy of 198 sources was carried out, revealing 132 objects containing bona-fide Wolf-Rayet features. From this sample, an exceptional W-R content of ~1030 is inferred, with N(WC)/N(WN) ~ 1.3, continuing the trend to larger values at higher metallicity amongst Local Group galaxies. More dramatic is the dominance of late-type WC stars in M 83 with N(WC8−9)/N(WC4−7) = 9 which we attribute to the sensitivity of the classification line C III λ5696 to mass-loss, providing the strength of WC winds scale with metallicity. One young massive compact cluster, #74 in our catalogue, hosts 20% of the entire galactic population, namely ~180 late WC stars and ~50 late WN stars.

Key words. galaxies: individual: M 83 – stars: Wolf-Rayet

1. Introduction

Wolf-Rayet stars represent excellent diagnostics of recent star formation in starbursts. Though few in number, they possess very powerful winds and so contribute significantly to the energy released into the ISM in young starbursts (Crowther & Dessart 1998), and are believed to represent the immediate precursors of Type Ib/c Supernovae and long duration Gamma-Ray Bursts. Individual WR stars are readily identified in nearby galaxies via their characteristic strong, broad emission lines, whilst their collective presence can be seen in the integrated light of distant starbursts.

Mass-loss rates of hot, massive stars prior to the WR phase are known to scale with metallicity (Vink et al. 2001), such that the relative number of WR stars increases with higher metallicity (Maeder & Meynet 1994). In addition, the distribution amongst nitrogen-rich WN versus carbon-rich WC subclasses is also known to vary with metallicity for Local Group galaxies (Massey & Johnson 1998). Studies of resolved WR populations at metallicities higher than the Solar value have proved difficult to date because the inner Milky Way is visibly obscured, whilst the other metal-rich Local Group member, M 31, lies at an unfavourable inclination.

Towards this goal, M 83 (NGC 5236) is a massive spiral galaxy that is believed to be particularly metal-rich: log(O/H) + 12 = 9.0–9.3 as derived from strong-line nebular methods (Bresolin & Kennicutt 2002)[1] and is the focus of the present Letter. A more detailed discussion of the WR population of M 83 and presentation of the full catalogue is given by Hadfield et al. (in preparation).

2. Observations

2.1. Imaging

We observed M 83 with the ESO Very Large Telescope UT4 and Focal Reducer/Low Dispersion Spectrograph #2 (FORS2) between Apr.–Jun. 2002. FORS2 has a 6.8′ × 6.8′ field-of-view using the standard collimator, with an image scale of 0.2″/pixel. FORS2 was used to obtain narrow-band λ4684 (C III/He II, $FWHM$ = 66 Å) and λ4781 (continuum, $FWHM$ = 68 Å) images of M 83 in order to detect WR candidates which possess net λ4686 emission, with exposure times of 1800 s.

Since M 83 subtends 12.9′ by 11.5′ on the sky, the entire galaxy could not be imaged using a single FORS2 frame. Consequently, four overlapping fields were selected in order to cover the entire galaxy, each ~210 arcsec from the nucleus. WR line and adjacent continuum images for each field were taken concurrently, with seeing conditions better than 0.8″.

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[1] However, see Kennicutt et al. (2003) regarding the reliability of strong nebular line techniques at high metallicity.

In addition to our He II narrow-band imaging, we also acquired broad-band Bessell B (120 and 600 s) plus on- and off- narrow-band Hα (60 and 600 s) images. The data were de-biased, cosmic-ray cleaned and flat-fielded, and calibrated using images of either a standard field (Bessell B filter) or via images of a suitable spectrophotometric standard (narrow-band filters). Photometry was carried out using DAOPHOT. We estimate a photometric accuracy of ~0.1 mag for most sources from comparison between identical sources observed within different fields.

We obtained difference images from our λ4684 and λ4781 frames, from which a large number of candidate λ4684 emission sources were identified, following the technique of Schild et al. (2003). In total 280 candidates were found, for which photometry in (at least) the λ4684 filter was obtained in 75% of cases. Severe crowding was a major limitation with obtaining reliable photometry for the remainder of cases.

2.2. Spectroscopy

We used FORS2 in Multi Object Spectroscopy (MOS) mode during Apr.–June 2003 to obtain spectroscopy of individual M 83 candidates using the 300V grism, centred at λ = 5900 Å. Up to 19 objects may in principal be observed simultaneously, whilst in practice typically 15 candidates could be suitably positioned. A total of 198 candidates were observed spectroscopically with FORS2 in 17 settings, each with a 0.8 arcsec slit, during seeing conditions superior to 0.8″. The 2 pixel spectral resolution obtained was ~7 Å. On-source exposures ranged from 720 s for the brightest sources to 4800 s for the faintest, each split into 2–3 individual exposures.

A standard reduction technique was applied using IRAF. For most sources an absolute flux calibration was achieved by comparing the photometry of an individual object in the λ4684 filter with a synthetic photometric measurement, determined by convolving our spectroscopy with a suitable Gaussian filter and zero-point. The average slit loss factor was 3.1 from 160 sources brighter than 24.0 mag. This factor was adopted for several spectroscopically observed sources for which photometry was unavailable.

3. Analysis

We have inspected our 198 candidates for which spectroscopy was obtained. In 132 cases we have identified genuine, broad WR emission features, namely either the blue λ4647-51 C III – λ4686 He II blend, and/or yellow λ5696 C III or λ5801-12 C IV lines. For the remaining 66 cases in which spectroscopy was obtained, either no emission was identified or the object was a foreground, late-type star. For a small number of cases either the S/N achieved from spectroscopy was insufficient to confirm the presence of WR features, or the dataset started longward of the blue visible region, necessary for identification of WN stars.

Our aim was to characterize the WR population in M 83. Consequently, we have attempted to measure intrinsic WR line fluxes and estimate the total number of WR stars in each object from comparison with Galactic counterparts. A distance to M 83 of 4.5 Mpc was adopted from Cepheid measurements of Thim et al. (2003). For 70% of our 132 sources for which WR features were identified, interstellar reddenings were derived from nebular Hα and Hβ lines measured from the extracted spectra. Assuming Case B recombination theory for typical electron densities 10^2 cm^{-3} and temperatures 10^4 K (Hummer & Storey 1987), we obtain $0.1 \leq E(B-V) = c(\mathrm{H}\beta)/1.46 \leq 1.0$ mag. Estimated accuracies are typically ±0.1 mag, although reddenings for regions with weak Hβ will likely represent overestimates given the neglect of stellar Hβ absorption. In 31 cases no nebular lines were observed, in which case an estimate of $E(B-V)$ could be made from a comparison with a theoretical energy distribution for a late O star (Kurucz 1992). In 11 cases with neither nebular lines nor a clear continuum, our average reddening of $E(B-V) = 0.43$ was adopted.

Table 1. Total distribution of WR stars in M 83 inferred from dereddened line fluxes based on a distance of 4.5 Mpc (Thim et al. 2003) and line luminosity (in erg s^{-1}) calibration adapted from Schaerer & Vacca (1998). The total number of regions add up to greater than 132 since 5 regions contain both WC and WN stars.

Subtype	WNE	WNL	WC4–6	WC7	WC8–9
Line	λ4686	λ4686	λ5801-12	λ5801-12	λ5696
log L(Line)	35.72	36.20	36.20	36.15	35.85
Regions	20	32	13	8	64
N(WR)	220	229	29	26	525

The WR content of individual objects are grouped into either early or and late subtypes as follows. WNL subtypes are identified if He II λ4686 is accompanied by N III λ4634–41, and WNE if He II λ4686 is accompanied with N V λ4603–20 or $FWHM$(He II) ≥ 20 Å. Amongst WC subtypes, we have indicated WC4–6 if C IV λ5801–12 is present, with C III λ5696 weak or absent, WC7 if $0.25 \leq F_\lambda(\mathrm{C\,III})/F_\lambda(\mathrm{C\,IV}) \leq 0.8$, and WC8−9 otherwise. Total numbers of WR stars in each object were determined using the calibration of Schaerer & Vacca (1998). It is of course possible that our choice of representative line luminosities is inappropriate to the environment of M 83, however many Galactic WR stars, particularly late WC stars are located towards the Galactic Centre (see discussion in Schaerer et al. 2000).

4. WR population of M 83

Representative WR spectra are presented in Fig. 1. In some cases a single WR star is identified, whilst others typically contain ~10, numbers comparable to WR populations in nearby giant H II regions (Drissen et al. 1993). Table 1 summarizes the derived population of WR stars in M 83 obtained from our analysis. We identify a total of 1030 WR stars from our 132 spectroscopically confirmed regions, ranging from $M_\mathrm{B} = -6$ to −14 mag, with $M_\mathrm{B} = -9$ mag on average. Our statistics rely solely upon those sources for which spectroscopic follow-up was obtained. Since we have attempted to observe a genuinely representative sample, we expect ~50 our of the

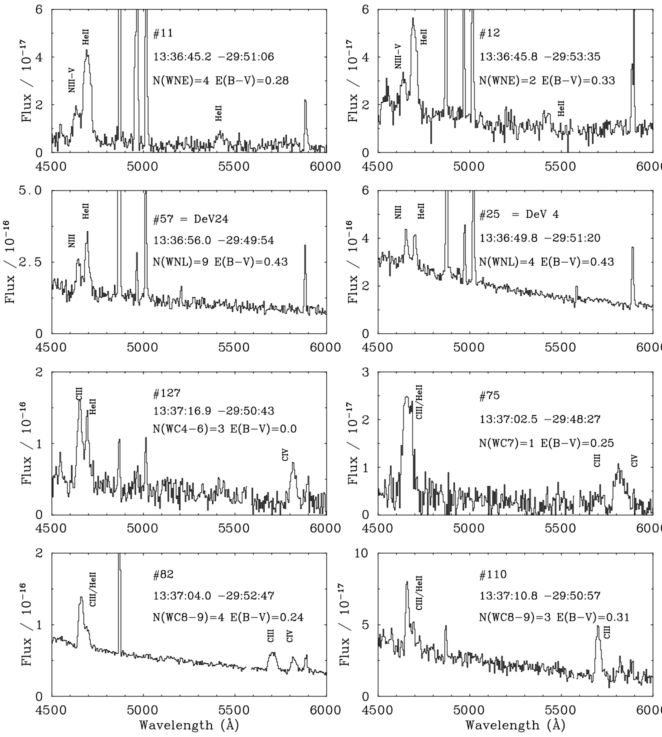

Fig. 1. Representative examples of sources containing early WN, late WN, early WC and late WC stars in M 83 including J2000 co-ordinates, and association with clusters from De Vaucouleurs et al. (1983, DeV) where available.

remaining 82 candidates to contain genuine WR features, such that the total WR population of M 83 may approach 1500. Indeed, one of our remaining candidates is M 83-5 from Bresolin & Kennicutt (2002) who confirmed WN and WC features via spectroscopy.

4.1. The WN/WC ratio and late WC population

Massey (1996) first highlighted the sensitivity of N(WC)/N(WN) to metallicity. As metallicity increases, the relative fraction of WC stars increases from ≤0.1 in the SMC to ~0.7 in the Milky Way (van der Hucht 2001). For M 83, we obtain N(WC)/N(WN) ~ 1.3 which fits in rather well with the extrapolation of previous determinations. WC stars are, of course, more readily identified in external galaxies than WN stars due to their intrinsically stronger lines. Nevertheless, our approach is optimised for net emission at λ4686, such that we have 4σ spectroscopic WNL detections with W_λ(He II λ4686) ~ 1 Å.

The most dramatic finding from Table 1 is that half of the total WR population in M 83 are of WC8–9 subtype. To put this into context, 18% of the known WR population comprise WC8–9 stars (van der Hucht 2001), whilst no WC late stars are known elsewhere except a handful in M 31 (Moffat & Shara 1987). We obtain a remarkably small population of WCE stars in M 83, such that N(WC8–9)/N(WC4–7) ~ 9, versus 0.9 in the Milky Way, ~0.2 in M 31 (Massey & Johnson 1998) and 0.0 elsewhere. We confirm previous Local Group studies of WR stars that WCL stars are uniquely located in metal-rich environments. In our conclusions we shall attempt to explain this subtype behaviour. In contrast, the WN population of M 83 is rather more familiar. The relative fraction of late WN stars to early WN stars is rather low in metal poor galaxies such as the SMC and high in the Milky Way, with N(WNL)/N(WNE) ~ 1.6 (van der Hucht 2001). We find a very similar ratio of N(WNL)/N(WNE) = 1.3 in M 83.

Table 2. M 83 clusters containing large (N(WR) ≥ 40) numbers of WR stars. Observed line fluxes are expressed in units of erg s^{-1}cm^{-2} and are derived from our spectrophotometry with the exception of Hα which originates from our continuum subtracted images.

Catalogue #	74	31	48
B (mag)	18.1	18.3	21.0
$E(B-V)$	1.0	0.6	0.31
M_B	–14.2	–12.4	–8.6
F(N III-V 4603-40)	1.1×10^{-15}	–	4.5×10^{-16}
F(C III 4647-51)	1.0×10^{-15}	2.4×10^{-15}	–
F(He II 4686)	1.0×10^{-15}	8.4×10^{-16}	3.2×10^{-15}
F(C III 5696)	3.5×10^{-15}	2.4×10^{-15}	–
F(C IV 5801-12)	1.4×10^{-15}	7.1×10^{-16}	–
F(Hα)	4.7×10^{-13}	9.8×10^{-14}	7.1×10^{-14}
N(O7V)	810	70	25
N(WNE)	–	–	44
N(WNL)	52		–
N(WC8–9)	179	42	–

4.2. Stellar clusters with large numbers of WR stars

Three regions contain large (≥40) numbers of WR stars. Properties of these clusters are listed in Table 2 with de-reddened FORS2 spectroscopy presented in Fig. 2. The most exceptional of these is #74 from our catalogue (Hadfield et al. in preparation). This source hosts up to 179 WCL stars from C III λ5696[2] plus 52 WNL stars from He II λ4686. Bresolin & Kennicutt (2002) failed to detect WR stars in this region (their region #8) since the WR excess is offset by several arcsec N-E of the peak Hα emission. We have derived a net integrated, de-reddened, Hα flux of 4.6×10^{-12} erg s^{-1} cm^{-2}, equal to ~810 O7V star equivalents (Vacca 1994) for the cluster as a whole. From comparison with evolutionary synthesis models for a 5 Myr instantaneous burst (Leitherer et al. 1999) we estimate a mass of 2×10^5 $M_\odot$ for #74. Inspection of archival HST/Advanced Camera for Surveys (ACS) Wide Field Camera (WFC) datasets of M 83 reveals #74 to be very compact, with a diameter of ≤0.2 arcsec or 5 pc at the distance of M 83, such that it is a young massive compact cluster (or Super Star Cluster, Whitmore 2003) instead of a conventional giant H II region.

Prior to the present study, solely Rosa & D'Odorico (1986) and Bresolin & Kennicutt (2002) have identified the presence of WR stars in selected H II regions in M 83. For the 5 regions for which the presence of WR stars was identified by Bresolin & Kennicutt, one was in the nucleus for which our datasets are saturated, the remainder hosted between 1 and 10 late

[2] A reduced number of 82 WCL stars is inferred from C III λ4650, assuming a line luminosity of 1×10^{36} erg s^{-1} (Schaerer & Vacca 1998).

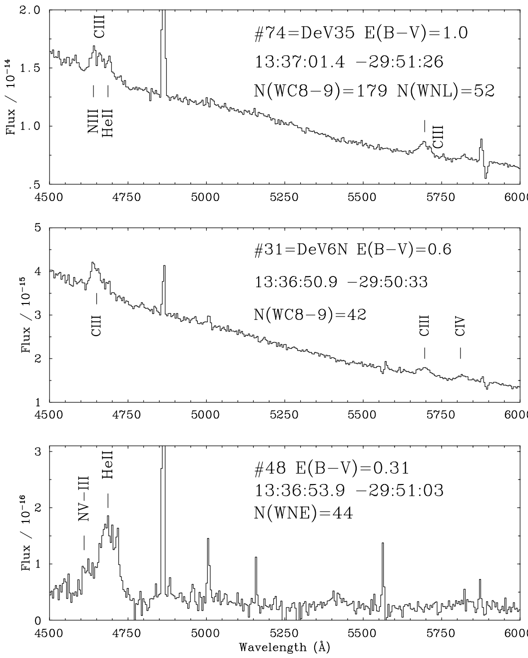

Fig. 2. De-reddened, radial velocity corrected (516 km s^{-1}), FORS2 spectroscopy of three clusters in M 83 containing many WR stars.

WN stars. Differences for sources in common are primarily due to the assumption of a smaller distance of 3.2 Mpc by Bresolin & Kennicutt (2002), plus generally higher reddenings in the present study.

5. Summary and conclusions

We have surveyed the nearby metal-rich galaxy M 83 for the presence of WR stars using VLT-FORS2. From follow up spectroscopy of 198 out of 280 candidates, 132 regions containing WR stars are identified. Assuming intrinsic line fluxes comparable to Galactic counterparts (Schaerer & Vacca 1998), we identify 1030 WR stars in M 83, with N(WC)/N(WN) $\sim$ 1.3, continuing the trend observed amongst Local Group galaxies to higher metallicity (Massey & Johnson 1998). Accounting for the remaining candidates the total WR population may be as high as 1500. More than 50% of the known WR are identified as late WC stars, versus $\leq$5% early WC stars, which is unprecedented relative to more metal-poor Local Group galaxies. One young massive compact cluster, #74, hosts $\sim$230 late WN and WC stars.

The relatively large WC population with increasing metallicity can readily be understood from comparison with evolutionary models (Maeder & Meynet 1994). At higher metallicity, mass-loss rates during and subsequent to the main-sequence evolution of massive stars strips away higher layers earlier on, such that a star with a particular initial mass advance to later (WC) phases at higher metallicity.

But why are there exclusively *early* WC stars in the LMC, a mixed population in the Milky Way and almost exclusively *late* WC stars in M 83? A decade ago it was believed that (C+O)/He increases from WC9 to WC4 (Smith & Maeder 1991). However, subsequent spectral analysis failed to confirm any systematic trend in C/He with subtype (Koesterke & Hamann 1995; Crowther et al. 2002). If carbon abundances do not play a dominant role, what does? We suggest differences in wind densities are primarily responsible. The wind densities of WC stars in the LMC are $\sim$50% lower than those of their Milky Way counterparts according to Crowther et al. (2002), which they attributed to a metallicity dependence of their winds. Since C III λ5696 increases dramatically in strength with increasing mass-loss rate (see their Fig. 12), one would expect yet higher mass-loss rates and even stronger C III λ5696 in M 83 WC stars if WC winds are metallicity dependent. Our present results are fully consistent with such a population. A genuine metallicity dependence of WR winds has implications for the hard ionizing fluxes of young starbursts (Smith et al. 2002). Regardless, the presence of late WC stars is definitely a indicator of a metal-rich environment.

Finally, should a supernova be observed in M 83 in the near future, we now possess a reasonable statistical sample with which we should be able to verify whether a WR star was a potential immediate precursor.

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