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Letter to the Editor

A hidden population of Wolf-Rayet stars in the massive galactic cluster Westerlund 1*

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Abstract. We report the discovery of a hitherto undetected population of Wolf-Rayet stars in the young galactic open cluster Westerlund 1. Optical spectroscopy of the cluster identified 11 such objects; provisional classification suggests that 6 are nitrogen rich (WN) and 5 carbon rich (WC). Including the previously identified Blue, Yellow & Red Super- & Hypergiants, Westerlund 1 clearly has a very rich population of massive post-Main Sequence objects. To date, the post-MS population of Westerlund 1 is significantly larger than that of any other galactic young open cluster – with the possible exception of the Arches – implying that it is potentially amongst the most massive young clusters yet identified in the Local Group.

Key words. stars: evolution – stars: Wolf Rayet – galaxies: starbursts

1. Introduction

The highly reddened young open cluster Westerlund 1 (henceforth Wd 1) was first identified by Westerlund (1961). Subsequent broadband photometric surveys by Borgman et al. (1970), Lockwood (1974) and Koornneef (1977) suggested the presence of a number of both early and late type supergiants, while a comprehensive photometric and spectroscopic survey of the brightest cluster members was presented by Westerlund (1987; West87). Despite reporting the presence of a large number of very luminous ($L > 10^5\ L_\odot$) transitional objects only one further (photometric) study of the cluster has been made (Piatti et al. 1998).

Recently, radio continuum observations of Wd 1 revealed that a number of the cluster members appeared to be associated with very bright radio sources (Clark et al. 1998; Dougherty et al. in prep.). Motivated by these results we obtained low resolution optical spectroscopy of a number of the brighter cluster members in order to provide an accurate spectral classification for them. In this paper we present the first results of this program; the discovery of a significant population of Wolf-Rayet (WR) stars within the cluster.

2. Observations

Spectroscopy of cluster members over the red/near-IR spectral region (∼6000–11 000 Å) was taken on 2001 June 23–25 from the ESO 1.52-m telescope at La Silla Observatory, Chile. The telescope was equiped with the Loral #38 camera and the #1 (night 1) and #13 (night 2 and 3) gratings, giving dispersions of ∼5 Å/pixel and ∼7 Å/pixel – leading to resolutions of ≈11 Å and ≈16 Å – respectively. Data reduction was accomplished with packages within the *Starlink* software suite.

Due to the crowded nature of the field, each long slit integration included a number of different cluster members. Examination of the fainter objects present in several of the exposures revealed the presence of a number of objects with rich emission line spectra (see Figs. 1 and 2). Given that the integrations were optimised to avoid saturating on the brighter cluster members, the serendipitous sources are of a low S/N ratio – though sufficient to identify the emission line objects as a previously unidentified population of massive, hydrogen depleted WRs.

3. Results

Despite the low S/N of many of the spectra, it is immediately possible to identify both nitrogen rich WN (6 objects) and carbon rich WC (5 objects) stars (Figs. 1 and 2 respectively); a finding chart and co-ordinates for each object are presented in Fig. 3 and Table 1.

Accurate determination of the spectral types of the WN and WC stars in this spectral region is difficult, given that most commonly used diagnostics lie at shorter wavelengths. However initial spectral classification of the WR candidates using the catalogues of Vreux et al. (1983, 1990) was possible.

For preliminary classification of the WC candidates we use the ratio of C III(8500 Å)/C IV(8856 Å) and

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* Based on observations collected at the European Southern Observatory, La Silla, Chile (ESO 67.D-0211).

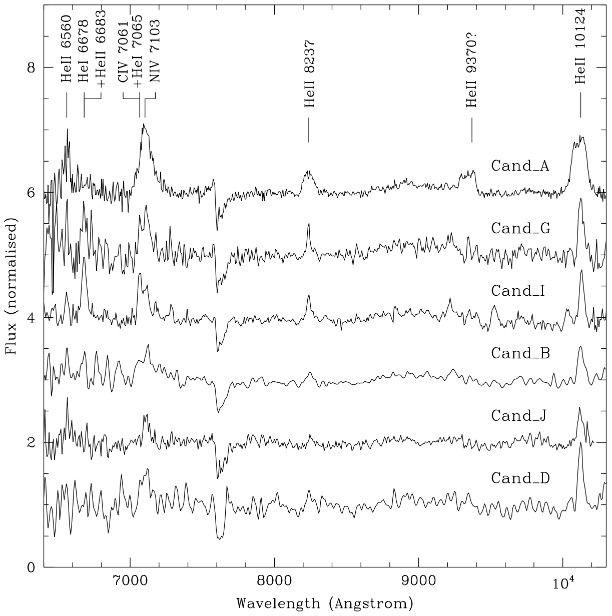

Fig. 1. Spectra of the newly discovered WN candidates in Wd 1, with prominent transitions identified.

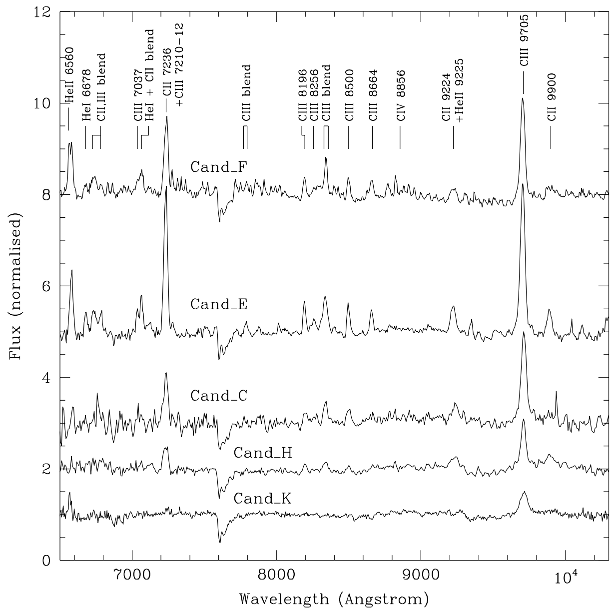

Fig. 2. Spectra of the newly discovered WC candidates in Wd 1 with prominent transitions identified.

C ii(9900 Å)/C iii(9710 Å) lines (Vreux et al. 1983; Howarth & Schmutz 1992; Crowther priv. comm.). C iv(8856 Å) is absent from the spectra of all candidates, with an upper limit to emission in candidates F, E and C constraining spectral types to later than WC6. No constraints are possible for H and K due to weak or no emission in C iii(8500 Å)). C ii(9900 Å)/C iii(9710 Å) ratios of 0.17 ± 0.04, 0.18 ± 0.03 and 0.18 ± 0.04 for candidates F, E and H respectively, suggest WC9 classifications while a ratio of <0.08 suggests a WC8 classification for candidate C[1], while a classification for candidate K is not possible.

Classification of the WN spectra proved more difficult, as there are fewer lines present and there is no linear progression in e.g. the N iv:He ii ratios that might be used for classification (Vreux et al. 1983). Based on the strength of the N iv 7103–7128 Å feature we can exclude extreme WN3/WN9 subtypes for all objects, since these are the only spectral types for which it is not seen in emission. Candidate A appears to be a WNE (WN4-5) given the large lines widths (~3000 kms^{-1}) and lack of strong He i 7065 Å emission (seen for all stars between WN6-8; Vreux et al. 1983, 1990). On the basis of emission in this line and the small emission line widths, candidates G, I and D appear to be WN6-8 objects. Classification of candidates B and J is complicated by the low S/N in the blue regions of the spectra due to the CCD response curve, but are also probably WNL objects.

4. Discusion and conclusions

Unfortunately, uncertainty in the distance and reddening estimates to Wd 1 (West87; Piatti et al. 1998), coupled with the poorly determined bolometric corrections for many massive transitional objects make determination of the luminosities of the WRs and the other evolved cluster members difficult. Indeed, the lack of accurate luminosity estimates for the yellow hypergiant candidates (YHG; West87) is particularly concerning, given that bolometric luminosity is one of several classification criteria for such objects (e.g. de Jager et al. 1998). If we are to constrain the post-MS population of Wd 1 in order to determine such fundamental properties as cluster age and mass we must address these issues.

For the WR candidates A, E and F (for which West87 provide photometry), adopting the reddening and distance estimates given by West87[2] and the (conservative) bolometric

Table 1. Co-ordinates (J2000) for the newly identified Wolf Rayet stars in Wd 1 determined from 3.6 cm radio images (Dougherty et al., in prep.) Formal errors are $\sigma_\alpha = \pm 0.003^{s}$, and $\sigma_\delta = \pm 0.04''$, although given that the crowded fields in the vicinities of candidates H, J and K make identification of the correct counterpart difficult, the errors for these objects are likely to exceed the formal error quoted.

Candidate	α	δ
A	16h47m8.324s	−45°50′45.51″
B	16h47m5.354s	−45°51′05.03″
C	16h47m4.395s	−45°51′03.79″
D	16h47m6.243s	−45°51′26.48″
E	16h47m6.056s	−45°52′08.26″
F	16h47m5.213s	−45°52′24.97″
G	16h47m4.015s	−45°51′25.15″
H	16h47m3.905s	−45°51′19.88″
I	16h47m1.668s	−45°51′20.40″
J	16h47m0.885s	−45°51′20.85″
K	16h47m2.697s	−45°50′57.35″

[1] EW(CII)/EW(CIII) = 0.05–0.08 for WC8 (from WR 135, 113 and 53) and EW(CII)/EW(CIII) = 0.14–0.3 for WC9 (from WR 92 and 104).

[2] Note that radio observations of the WR stars suggest that the cluster is more distant than the alternative distance of 1 kpc proposed by Piatti et al. (1998); see Dougherty et al., in prep.

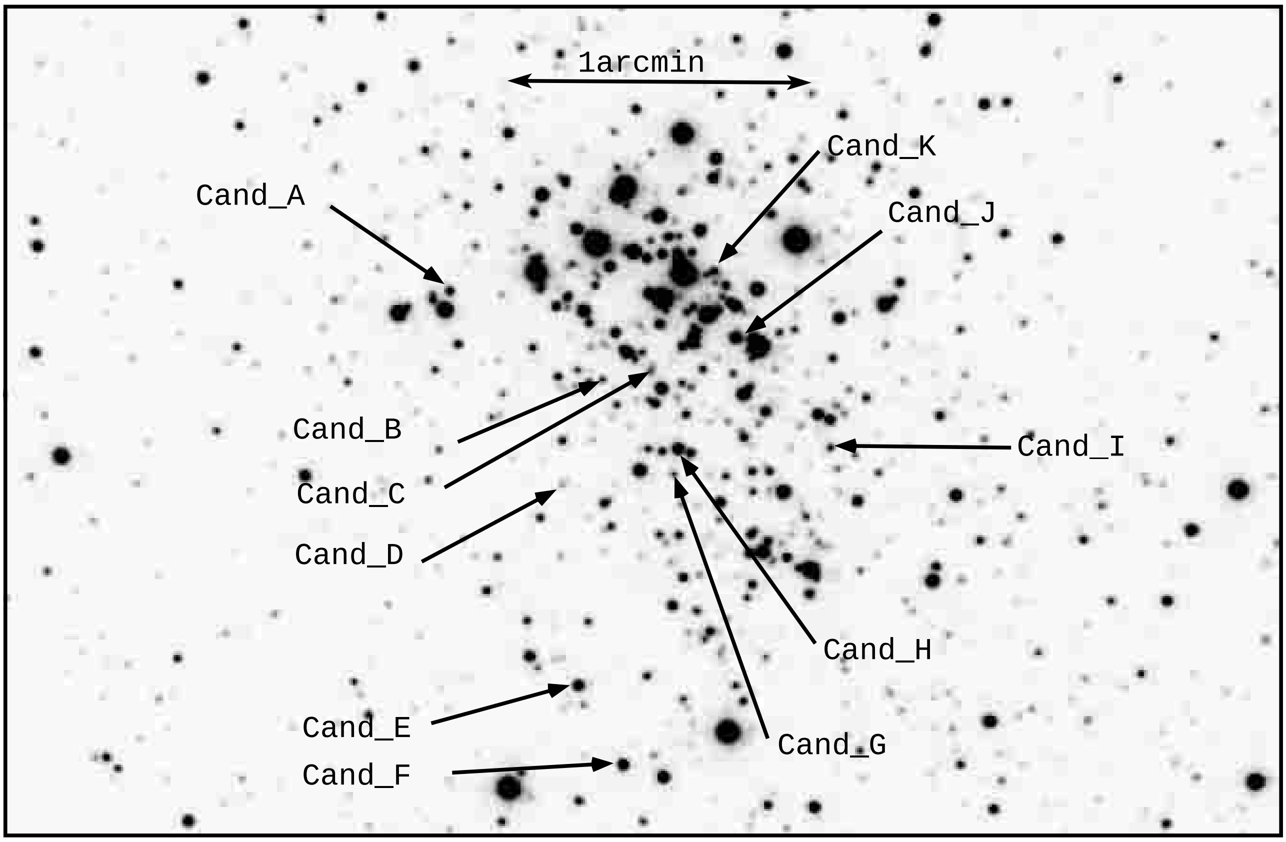

Fig. 3. *R* broadband finding chart for the newly discovered Wolf Rayet candidates in Wd 1. Note that the exact counterparts of candidates H, J and K should be regarded as provisional since the crowded field in these regions of the cluster make identification of the correct counterpart difficult. Candidates A, E and F correspond to stars number 72, 241 and 239 respectively in the notation of West87.

corrections of Smith et al. (1994) we find that their luminosities comfortably exceed 10^5 $L_\odot$. For luminous A, F and G stars the strength of the O I 7774 Å feature can be used to provide an additional measure of the absolute visual magnitude[3]. Comparison of the YHG candidates W4, W12, W16 and W265 and the YSG W7 (notation from West87) to the luminosity: line strength calibrations of Ferro & Mendoza (1993) and Slowik & Peterson (1995) indicates that they are all likely to be intrinsically highly luminous. Indeed the *EW*(O I) for these objects are *significantly greater than any* of the stars in these studies – including the bona fide YHG ρ Cas ($L_* = 10^{5.7}$ $L_\odot$) – implying luminosities of $L_* \gg 10^5$ $L_\odot$. Additionally, high mass loss rates for these objects are implied by radio detections (W4, W12, W16 and W265) and broad Hα emission (W7, W12, W16 and W265); therefore all these objects meet the classification criteria of de Jager (1998) for bona fide YHGs.

4.1. Comparison to other clusters

Including the WRs and YHG candidates, the large population of luminous post-MS objects in Wd 1 (West87 and Table 4) suggests that it is unique in both the number and variety of massive post-MS objects present. Of the 26 clusters within the solar circle studied by Eggenberger et al. (2002), 6 contain both B and RSGs. Of these, only 3 – Collinder 228, Trumpler 27 and Berkley 87 – also contain WRs (1–2 per cluster; Table 4) and only Trumpler 27 contains a yellow SG, albeit of significantly lower luminosity ($\sim 10^{4.7}$ $L_\odot$) than those in Wd 1 (Massey et al. 2001; note however that they claim the cluster is *not* co-eval.).

Of the galactic centre clusters, the Quintuplet cluster appears to contain 8 WRs of both WN and WC types along with a number of early OB supergiants and a single RSG ($10^{4.9}$ $L_\odot$; Figer et al. 1999). In addition to the single luminous RSG IRS 7 ($10^{5.4}$ $L_\odot$; Carr et al. 2000), Paumard et al. (2001) detect 16 "helium stars" in the Galactic Centre cluster, of which they suggest the 7 narrow line objects correspond to mass losing BSGs (possible LBVs) and the 9 broad line objects WRs (noting that a further 3 stars Blum et al. (1996) suggest are WCs lie outside their f-o-v). Only the Arches cluster – which is significantly younger – appears to contain a comparable number of WRs to Wd 1, with Blum et al. (2001) identifying 15 candidate O4 If/WN7 stars on the basis of narrow band imaging. However, as with the Quintuplet and Galactic Centre clusters, the rich population of very luminous cool stars present in Wd 1 is absent[4].

[3] Note that our values of *EW*(O I) are consistent with those given by West87; Negueruela & Clark (in prep.).

[4] The very young clusters NGC 3603 and R 136 also contain a few high luminosity WRs although these are thought to be very massive O stars where the high mass loss rates simulate the spectra of more chemically evolved lower mass WRs (e.g. de Koter et al. 1997).

Table 2. Transitions and equivalent widths for the WN candidates. Errors are estimated at 10% for lines longwards of ~7000 Å and 20% for those shortwards. Transitions for which the S/N is too poor to attempt an identification are indicated with "S/N".

Candidate Transition	A	G	I	B	J	D
He II 6560	27	S/N	9	S/N	S/N	S/N
He I 6678+He II 6683	–	30	37	S/N	S/N	S/N
C IV 7061+He I 7065	–	59	50	45	–	46
N IV 7103-28	110	Bl	Bl	Bl	19	Bl
He II 8237	33	20	19	12	7	11
HeII 5-8?	38	–	–	–	–	–
He II 10124	106	56	42	33	32	41

Table 3. Transitions and equivalent widths for the WC candidates; terminology as for Table 2.

Candidate Transition	F	E	C	H	K
He II 6560+C II 6578	42	49	S/N	S/N	13
He I 6678	9	17	S/N	S/N	–
C II 6725-42+C III 6727-73	Bl	Bl	S/N	S/N	–
C II 6780	28	45	S/N	S/N	–
C III 7037	Bl	Bl	S/N	S/N	–
He I 7065+C II 7064	15	32	S/N	S/N	–
C II 7236+C III 7210-12	55	108	45	24	3
C III 7772-96	S/N	8	S/N	–	–
C III 8196	12	15	16	5	–
C III 8256	Bl	9	Bl	–	–
C III 8328-59	39	27	18	10	–
C III 8500	14	17	11	6	–
C III 8664	19	12	–	–	–
He II 9225+ C II 9224	16	25	20	14	–
C III 9705	103	139	97	50	26
C II 9903	18	25	S/N	9	–

Clearly, such comparisons indicate that Wd 1 is both very young and very massive; however uncertainties in the post-MS evolution of massive stars, exacerbated by the lack of an identifiable MS turnoff and accurate bolometric luminosities for the evolved stars makes determination of the age and total mass of Wd 1 difficult.

4.2. The age and mass of Wd 1

Following the analysis of the Quintuplet cluster by Figer et al. (1999), the presence of WC stars – apparently the most evolved stars present in Wd 1 – implies a lower limit to the age of 2.5 Myr. The presence of a number of very luminous RSGs within Wd 1 potentially provides an upper limit to the cluster age; Figer et al. (1999) suggests that the Quintuplet cluster requires an age of ≥4 Myr given the presence of a single (low luminosity) RSG, broadly consistent with the age (7 Myr) Carr et al. (2000) claim for IRS 7. However, large uncertainties in the mass loss rate for very luminous cool stars render estimates of their ages, lifetimes and progenitor masses highly uncertain; particularly concerning given the large population of YHGs within Wd 1.

Considering their extreme rarity, the lifetime of YHGs is probably less than 10^5 yr for any luminosity and progenitor mass. At very high luminosities it is likely that a very large mass loss rate limits the YHG to a single passage from red to blue across the HR diagram, resulting in a short lifetime (≤30 000 yr; Stothers & Chin 1999). At lower luminosities dynamical instabilites in the outer atmosphere of the star result in multiple blue loops for the star out of the RSG region, leading to a longer lifetime as a luminous yellow star (e.g. Stothers & Chin 2001). Such estimates are *qualitatively* consistent with the results of unpublished simulations for the behaviour of $M_{\rm initial}$ = 25 and 40 $M_\odot$ stars (Maeder & Nieuwenhuijzen, priv. comm. 2002) which suggest YHG phases after 6.9 and 4.4 Myr lasting ~49 000 and 2700 yr respectively; i.e. the YHG phase occurs earlier and is shorter the more massive the progenitor is.

Despite the many uncertainties, the present stellar population of Wd 1 appears consistent with an age of order 4–8 Myr *if the cluster is co-eval*, suggesting it is potentially younger than previously thought (7 and 8 ± 3 Myr; West87 and Piatti et al. 1998, respectively).

The uncertainties in post-MS evolution and incomplete stellar census inevitably makes a determination of the total cluster mass uncertain. Maeder & Meynet (1994) find that for solar metallicities, adopting *twice* the standard mass loss rate results in the appearance of a WN phase for stars ≥25 $M_\odot$ – consistent with the findings of Massey et al. (2001) – and a WC phase at ≥40 $M_\odot$. Given that the super- and hyper-giants are less chemically evolved than the WRs, their progenitors are likely to have been less massive.

Regarding the completeness of our sample we estimate that the spectral survey of potential cluster members of a similar visual magnitude as the fainter WR candidates is at best 33 per cent complete, while preliminary analysis of our low resolution optical spectroscopy (Negueruela & Clark, in prep.) finds many additional supergiant candidates e.g. W70 and W71 (BSG), W32 and W33 (YSG) and W75 and W237 (RSG). Additionally, we might expect that if originally present very massive stars will have been lost to SN; Maeder & Meynet (1994) suggest that stars of ≥85 $M_\odot$ will have a lifetime comparable to the lower estimate of the cluster age.

Nevertheless, *conservatively* assuming that the present stellar census is complete (see Table 4) and furthermore that the progenitor masses for these objects were ≥30 $M_\odot$ we can derive a lower limit to the *initial* cluster mass. Adopting a Salpeter mass function ($N(M) \propto M^{-\alpha}$) with upper and lower cut offs of 100 $M_\odot$ and 0.2 $M_\odot$ respectively and a slope, $\alpha = 2.35$) we might expect a total mass of stars of ~750 $M_\odot$ for every star with an initial mass of ~30 $M_\odot$, leading to a mass estimate of a few $\times 10^4$ $M_\odot$ (S. Goodwin priv. comm. 2002).

This *lower* limit to the initial mass of Wd 1 suggests that it is directly comparable to the galactic centre clusters such as the Arches cluster (4×10^4 $M_\odot$; Portegies Zwart et al. 2001). More reasonable estimates of completeness and progenitor mass suggest a mass for Wd1 of a few $\times 10^5$ $M_\odot$ making it by far the most massive young Galactic cluster, and one of the most massive in

Table 4. Numbers of B and RSGs and WRs for galactic open clusters containing one or more of each type of object. The numbers of B & RSGs for Wd 1 are those from West87; preliminary analysis of our data suggest they are likely to be lower limits. Note that the Quintuplet cluster also contains 5 "Cocoon" objects with featureless IR spectra that have been proposed as dusty WCL stars. ([a] Massey et al. 2001 and references therein; [b] Figer et al. 1999; [c] Paumard et al. 2001; [d] Carr et al. 2000; [e] Blum et al. 2001).

Cluster	Age(Myr)	$N_{\rm BSG}$	$N_{\rm RSG}$	$N_{\rm WR}$
Wd 1	4-8	≥6	≥2	≥11
Trumpler 27[a]	NA	8	1	2
Collinder 228[a]	~2	3	1	1
Berkley 87[a]	~3	4	1	1
Quintuplet[b]	4 ± 1	14 (+ 2 LBVc)	1	8
Gal. Center[c,d]	3–8	7 He I	1	9 He I
Arches[e]	2−4.5	0	0	15

the Local Group. This conclusion is further reinforced by considering the large number of YHGs within Wd 1, which is comparable to the total population of the Milky Way (6; de Jager 1998). Assuming a lifetime for the YHGs of ~25 000 yr, following the arguments of Geballe et al. (2000) for the likelihood of finding several examples of a short lived evolutionary phase within a single cluster also leads to the conclusion that a very large O star population (~several hundred) is required to produce the number of YHGs observed.

Evidently a combined spectroscopic and photometric approach to both identify the MS turn-off and to properly classify evolved stars will be required to accurately determine the age and mass of Wd1. However if the above estimates are correct then Wd 1 would appear to be a Galactic equivalent of the super star clusters observed in merging and interacting galaxies and may possibly be more massive than the 30 Doradus cluster in the LMC. Therefore, as well as providing a unique laboratory for studying hot star evolution, Wd 1 would provide an unprecidented insight into an extreme mode of cluster formation, previously not thought to be occuring in the Milky Way.

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