A Massive Star Odyssey, from Main Sequence to Supernova
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The very rich massive post-main-sequence star population of the open cluster Westerlund 1

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Abstract. We report the discovery of a population of Wolf-Rayet stars in the young Galactic open cluster Westerlund 1. In an incomplete shallow spectroscopic survey, we find six nitrogen-rich (WN) and five carbon-rich (WC) WR stars. We also confirm the presence of a large population of yellow supergiants, some of which are candidate hypergiants. Given this population, Westerlund 1 is likely to be one of the most massive young clusters in the Local Group.

1. Introduction

The highly reddened young open cluster Westerlund 1 (henceforth Wd 1) was reported by Westerlund (1987) to contain a number of both early and late-type supergiants and some other massive transitional objects. Exact determination of its parameters was not possible, but Westerlund (1987) estimated $d \simeq 5$ kpc and an extinction $A_V \simeq 11$ mag. Recently, radio continuum observations of Wd 1 revealed that a number of cluster members appeared to be associated with very bright radio sources (Clark *et al.* 1998; Dougherty, Waters & Clark, in preparation). In view of this result, we carried out a spectroscopic survey of the brighter cluster members using the Boller & Chivens spectrograph on the ESO 1.52-m telescope at La Silla Observatory, Chile. Low resolution spectroscopy over the $\sim \lambda\lambda 6\,000 - 11\,000$ Å range was obtained on the nights of June 24 - 26, 2001.

Since the field is very crowded, in addition to the relatively bright objects that were originally targeted, a large number of fainter stars was observed. Inspection of the spectra revealed the presence of a population of faint objects with strong emission lines.

2. The Wolf-Rayet population

Despite the low S/N of many of the spectra, due to the faintness of the objects (the apparently brightest Wolf-Rayet stars have $V > 17$), it is immediately possible to identify both nitrogen rich WN (six objects) and carbon rich WC (five objects) stars. The spectra of all these objects are displayed in Figures 1 and 2.

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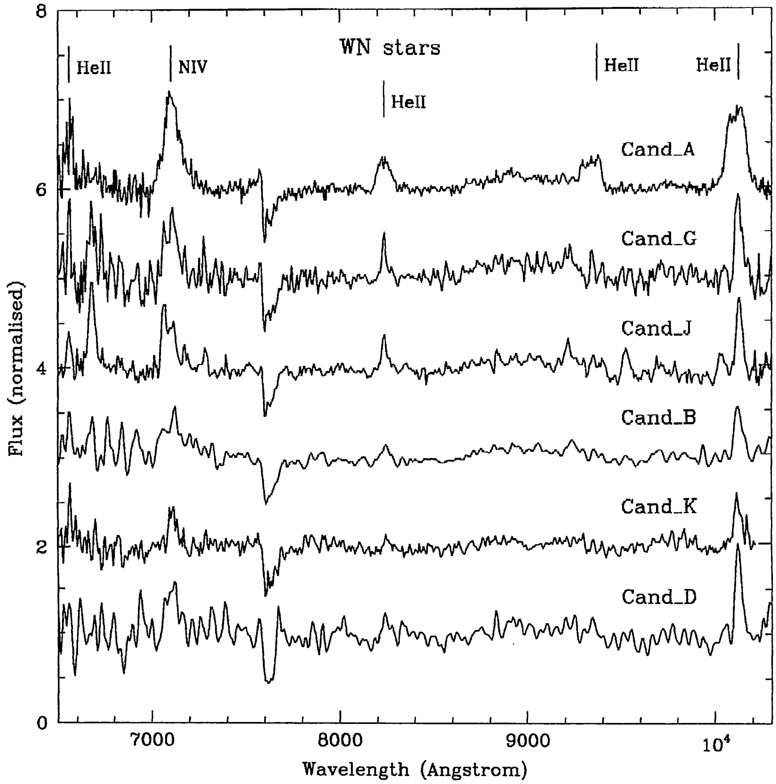

Figure 1. Spectra of the newly discovered WN candidates in Wd 1, with prominent transitions identified. (For Cand_K, read Cand_J.)

Spectral classification of WR stars can only be approximate, since the main spectral indicators lie on the blue region. For the WC candidates, we use the ratio of the C III 8500 Å/C IV 8856 Å and C II 9900 Å/C III 9710 Å lines. All candidates appear to be late, with candidates E, F and H likely to be WC9 stars, while candidate C is likely to be WC8. Among the WN stars, the broad-lined candidate A is likely to be WN4-5, with candidates B and J looking WNE and candidates D, G, and I looking WNL (WN6-8).

3. The supergiant population

A significant number of the spectra obtained seem to correspond to high-luminosity stars, judging from the intensity of traditional luminosity indicators, such as the O I 7 774 Å line or the Ca II triplet in the *I*-band.

In particular, four stars with A or G spectral types have equivalent widths for O I 7 774 Å rather larger than Ia supergiants of similar spectral types, confirming the result of Westerlund (1987). These are stars Wd 1-4, Wd 1-12, Wd 1-16 and Wd 1-265 (following the notation of Westerlund 1987). All four stars are detected as relatively bright radio sources (Dougherty *et al.* in preparation). At

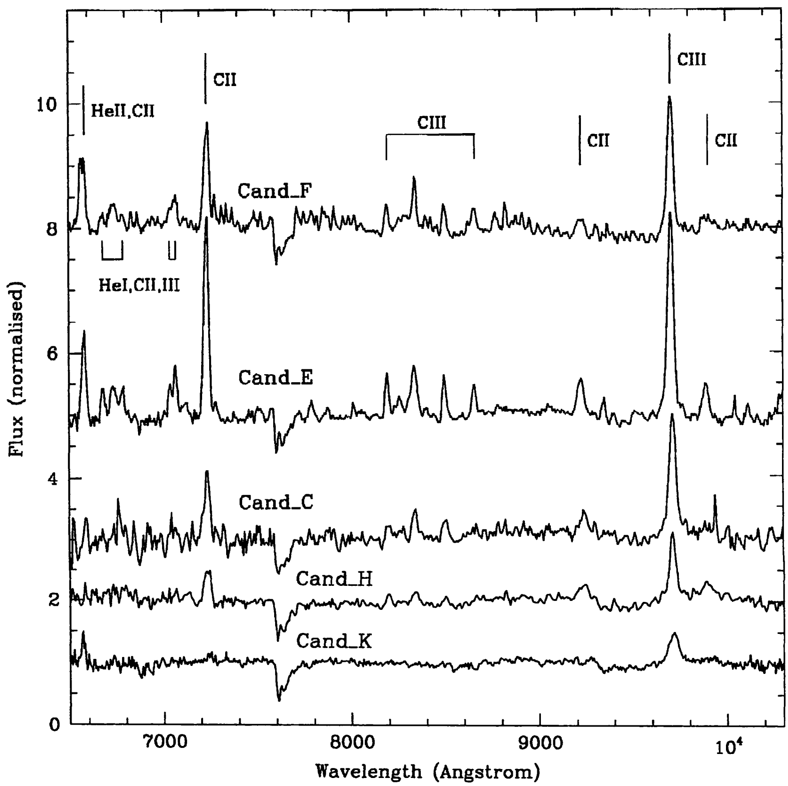

Figure 2. Spectra of the newly discovered WC candidates in Wd 1, with prominent transitions identified.

least two other yellow supergiants are of rather high luminosity. From the very approximate classifications that we can derive from our low-resolution spectra, we find that the total number of A-G supergiants approaches the dozen, with several other stars likely to be luminous B-type supergiants. Many of these objects display Hα in emission.

In addition, there are four objects whose spectra resemble high-luminosity M-type stars. Three of them (Wd 1-20, Wd 1-26 and Wd 1-237) are clearly detected as radio sources. In particular, Wd 1-26 seems to be associated with extended two-lobed radio emission (Clark *et al.* 1998). The optical spectrum of this object displays several emission lines unexpected in an M-type star.

A second object associated with extended radio emission is Wd 1-9. Its optical spectrum is characterised by a blue continuum with many strong emission lines corresponding to both permitted and forbidden transitions. This object is likely a Luminous Blue Variable.

A second very luminous blue object (Wd 1-243) presents moderately strong emission lines and appears to be surrounded by nebulosity. This object is also a radio source. Extended radio emission to the NW of the cluster (Dougherty *et al.* in preparation) is associated with some very faint emission-line objects.

Table 1. Coordinates for the newly identified Wolf-Rayet stars in Westerlund 1 determined from 3.6-cm radio images (Dougherty *et al.* in preparation). Errors in the coordinates are $\sigma_\alpha = \pm 0.^s003$ and $\sigma_\delta = \pm 0.''04$. For three of the objects (A, E and F) Westerlund (1987) provides photographic magnitudes.

WR candidate	Wd 1 no.	WR[a]	spectral type	V (phot)	R.A. (J2000)	Dec. (J2000)
J		77a	WNE	>19	$16^h\,47^m\,0.^s885$	$-45°\,51'\,20.''85$
I		77b	WNL-8	>19	$16^h\,47^m\,1.^s668$	$-45°\,51'\,20.''40$
K		77c	WN	>19	$16^h\,47^m\,2.^s697$	$-45°\,50'\,57.''35$
H		77d	WC9	>19	$16^h\,47^m\,3.^s905$	$-45°\,51'\,19.''88$
G		77e	WN6-8	>19	$16^h\,47^m\,4.^s015$	$-45°\,51'\,25.''15$
C		77f	WC8	>19	$16^h\,47^m\,4.^s395$	$-45°\,51'\,03.''79$
F	239	77g	WC9	17.05	$16^h\,47^m\,5.^s213$	$-45°\,52'\,24.''97$
B		77h	WNE	>19	$16^h\,47^m\,5.^s354$	$-45°\,51'\,05.''03$
E	241	77i	WC9	17.17	$16^h\,47^m\,6.^s056$	$-45°\,52'\,08.''26$
D		77j	WN6-8	>19	$16^h\,47^m\,6.^s243$	$-45°\,51'\,26.''48$
A	72	77k	WN4-5	17.84	$16^h\,47^m\,8.^s324$	$-45°\,50'\,45.''51$

Note *a*: WR number in the catalogue system of van der Hucht (2001).

Other blue stars display strong emission lines and are likely to be different kinds of transitional evolved objects.

4. Discussion

We have detected eleven WR stars in Westerlund 1, the largest number of WR stars known in any Galactic cluster, with the possible exception of the Arches cluster (Blum *et al.* 2001). Moreover, our survey is very incomplete: only about 25% of the stars at the apparent magnitude typical of the WR stars detected have been observed. There is an obvious lack of WR detections in the central region of the cluster (where the most luminous supergiants are located), which strongly suggests that our sample is also affected by observational effects. We can conservatively assume that the actual WR population of Wd 1 is easily twice as large.

Wd 1 appears to be unique among Galactic clusters in both the large number and variety of massive post-main sequence (PMS) objects. Since published determinations of distance and reddening to the cluster are inaccurate and inconsistent (Westerlund 1987; Piatti, Bica & Clariá 1998), and the field is affected by strong and probably variable reddening, we are still unable to provide accurate values for the intrinsic luminosity of members from which good estimates of the cluster age can be derived. Several lines of argument, however, suggest that the cluster is potentially extremely massive.

On one side, the lack of an identifiable main-sequence turnoff in available photometric data prevents us from determining cluster parameters, but at the same time provides us with a clue to the cluster size, suggesting that all ob-

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served members down to $V \simeq 18$ (in excess of 90) are evolved stars with intrinsic magnitudes in the $M_V \approx -6$ to -10 range.

On the other hand, the large number of transitional objects observed in short-lived phases is suggestive of a very large population from which they are evolving. In particular, the number of yellow hypergiants in Wd 1 appears comparable to that in the rest of the Galaxy. Given the short duration of the hypergiant phase, a population of several hundred O-type stars seems to be suggested.

The presence of a large number of yellow supergiants (and a few very luminous red supergiants) indicates that Wd 1 is slightly older than the very massive Arches Cluster. Assuming that the progenitors of the yellow hypergiants had ZAMS masses of ~ 40 - $50\,M_\odot$ (which can be considered an educated guess), the age of the cluster would be ~ 4 - 5 Myr, compatible with the presence of a population of WC stars descending from more massive progenitors. The alternative of considering that the progenitors of the yellow supergiants have lower ($\sim 30\,M_\odot$) masses and taking an older age of 8 - 10 Myr in order to consider that the red stars are normal M-type supergiants seems to conflict with the large population of WR stars if we consider that they are mainly single stars. A large population of WR stars at an age of $\sim$ 8 Myr could, however, be possible if most of them are part of binary systems.

With the much extended data set available after our 2002 observing campaign, we expect to be able to provide accurate determinations for the distance and extinction to Wd 1. The lack of radio detections for most WR stars (Dougherty *et al.* in preparation) suggests that the distance to Wd 1 has to be $\gtrsim 2$ kpc. It cannot be, however, much larger than the 5 kpc advanced by Westerlund (1987), specially since the results of Piatti *et al.* (1998) suggest that the interstellar absorption (which has a very important component local to the cluster region) may be higher than estimated by Westerlund (1987). The cluster is then likely to be located in the Crux Arm, at a distance of 4 - 5 kpc.

In any case, with a true distance modulus $DM < 14$ mag, Wd 1 offers the unrivalled opportunity of observing its whole stellar population using existing instrumentation (at least, in the near-IR). It therefore represents an ideal laboratory for the study of the impact of the presence of a large population of massive stars on its environment and, specifically, on the formation of lower mass stars.

Further details of this study are given in Clark & Negueruela (2002).

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References

Blum, R.D., Schaerer, D., Pasquali, A., Heydari-Malayeri, M., Conti, P.S., Schmutz, W. 2001, ApJ 122, 1875

Clark, J.S., Negueruela, I. 2002, A&A (Letters) 396, L25

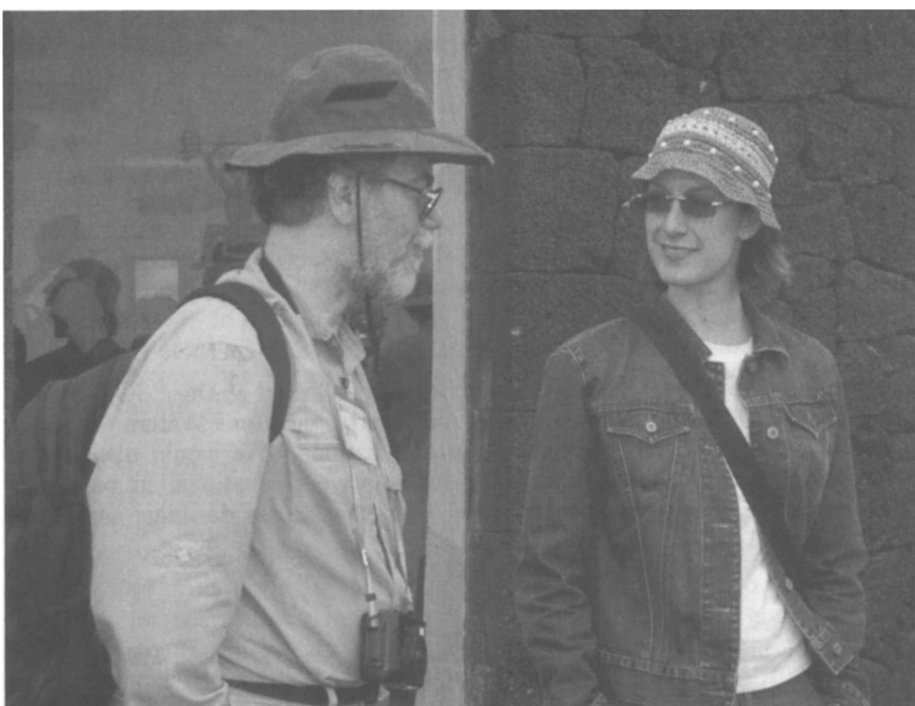
Clark, J.S., Fender, R.P., Waters, L.B.F.M., Dougherty, S.M., Koornneef, J., Steele, I.A., van Blokland, A. 1998, MNRAS (Letters) 299, L43

van der Hucht, K.A. 2001, New Astron. Reviews 45, 135
Piatti, A.E., Bica, E., Clariá, J.J. 1998, A&AS 127, 423
Westerlund, B.E. 1987, A&AS 70, 311

Discussion

CROWTHER: Your discovery that Wd1 contains (at least) 11 WR stars plus RSGs and YHGs is truely remarkable. Its low radio flux, together with the fact that *MSX* mid-infrared images reveal the local environment evacuated around Wd1 surely point to an age closer to 10 Myr than 4 - 5 Myr.

NEGUERUELA: With available data, it is still very difficult to provide much more than a guess for the cluster age. While the presence of several very luminous blue objects seems to favour the lower age, it is true that several lines of argument indicate an age around 10 Myr. We really need to proceed further with our analysis, before we can give a more consistent estimate or even decide on the overall co-evality of the cluster.



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