Wolf-Rayet Stars
W.-R. Hamann, A. Sander, H. Todt, eds.
Potsdam: Univ.-Verlag, 2015
URL: http://nbn-resolving.de/urn:nbn:de:kobv:517-opus4-84268

Physical properties of the WR stars in Westerlund 1

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The Westerlund 1 (Wd1) cluster hosts a rich and varied collection of massive stars. Its dynamical youth and the absence of ongoing star formation indicate a coeval population. As such, the simultaneous presence of both late-type supergiants and Wolf-Rayet stars has defied explanation in the context of single-star evolution. Observational evidence points to a high binary fraction, hence this stellar population offers a robust test for stellar models accounting for both single-star and binary evolution. We present an optical to near-IR (VLT & NTT) spectroscopic analysis of 22 WR stars in Wd 1, delivering physical properties for the WR stars. We discuss how these differ from the Galactic field population, and how they may be reconciled with the predictions of single and binary evolutionary models.

1 Introduction

Westerlund 1 (Wd1) is amongst the most massive young clusters in the Galaxy ($>10^5 M_\odot$ Clark et al. 2005, C05) and contains a plethora of massive stars. The pre-Main Sequence (MS) population in Wd1 indicates a very narrow age spread (Kudryavtseva et al. 2012), implying a narrow range in initial mass for the current post-MS. Wd1 therefore provides an excellent opportunity to constrain the initial mass ranges and evolutionary connections of post-MS phases.

Evidence for binarity is prevalent amongst the Wolf-Rayet (WR) stars, including dust production in WC stars and coincidental hard X-ray sources – both signposts of colliding stellar winds. The contribution of a binary evolution channel to the WR population at large is still debated, but evidence is growing. The present-day orbits and mass configurations of many field WR binaries can only be explained by previous interactions (Petrovic et al. 2005). Furthermore, the observed rate of H-free core-collapse supernovae and long-gamma ray bursts are better reproduced with a binary channel producing H-free massive stars (Smith et al. 2011; Trenti et al. 2015).

1.1 The Westerlund 1 cluster

The simultaneous presence of WR and RSG stars is consistent with narrow age spread (Vanbeveren et al. 1998). Population synthesis models (Eldridge & Tout 2004) best reproduce the observed WR/BSG fraction at an age of 4.5–5.0 Myr, and OB supergiants give 5–6 Myr (Negueruela et al. 2010). Brandner et al. (2008) fit pre-MS and MS isochrones to deep near-IR photometry to derive 3.6 ± 0.7 Myr, and Kudryavtseva et al. (2012) perform similar fits to MS stars deriving 5.0 Myr (with a spread <0.5 Myr). We assume an age of 5.0 ± 1.0 Myr for Wd1, with an age spread smaller than this uncertainty. Kothes & Dougherty (2007) present the most direct (kinematic) distance measurement to Wd1 of 3.9 ± 0.7 kpc. Koumpia & Bonanos (2012) use the eclipsing binary W13 to measure 3.7 ± 0.6 kpc. We assume a distance of 4.0 ± 0.5 kpc.

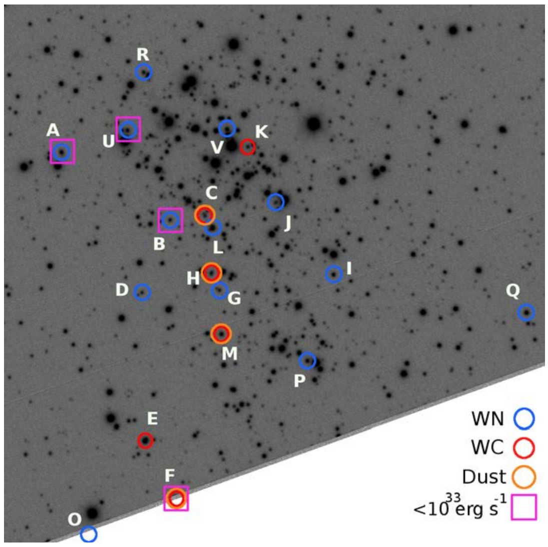

Fig. 1: Archival VLT R-band image of the central $2.5' \times 2.5'$ (2.9×2.9 pc at 4 kpc) of Wd1, with known WR stars indicated.

The first 11 WR stars in Wd1 were reported by Clark & Negueruela (2002). Crowther et al. (2006) completed a near-IR census of the cluster, bringing the total to 23 (8 WC + 15 WN) and finding strong evidence of circumstellar dust in the majority of WC stars.

The only bona-fide spectroscopic binary WR in Wd1 is Wd1–B (Koumpia & Bonanos 2012). However, Bonanos (2007) detected optical variability in half of the WR stars, including smooth periodic (7.63 d) variations in Wd1–A. Three WN (A, B, U) and 1 WC (F) are >0.1 dex above the median $L_X = 10^{32.2}$ erg s^{-1} for WN stars in Wd1 (Clark et al. 2008), and are typical of colliding-wind binaries. Of the 12 WRs detected in X-rays, 9/9 WN and 2/3 WC display hard spectra, indicative of colliding winds. Moreover, these two WC stars are also amongst the 6/8 showing warm circumstellar dust.

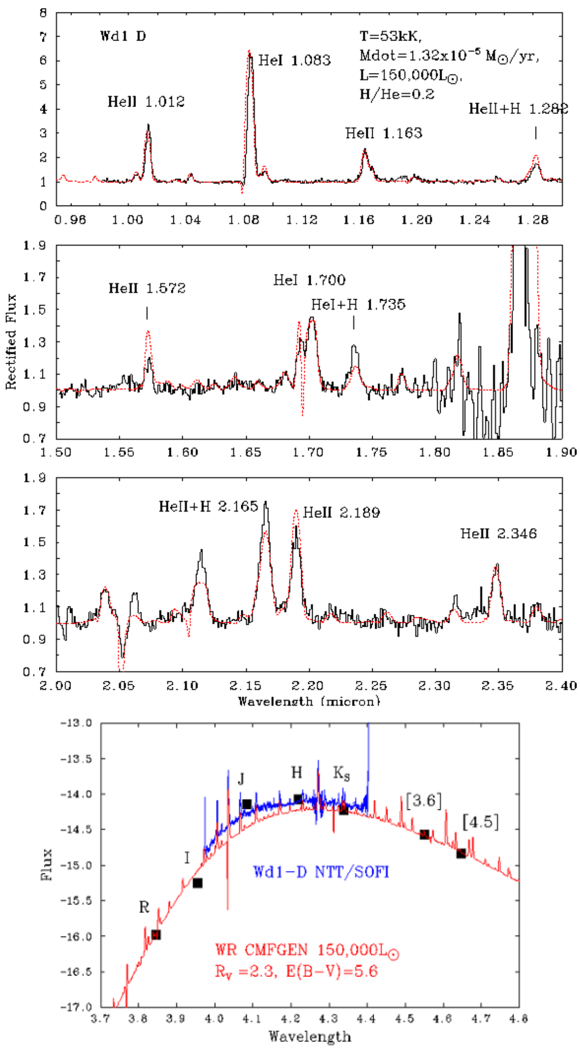

Fig. 2: Example model fit to the spectrum and SED of Wd1-D (WN7o). Key diagnostic lines are labelled. The models is shown in red, spectra in black/blue, and photometric points as black squares.

2 Data

We retrieved archival VLT/FORS2 and NTT/EMMI optical spectra (∼5500–8000 Å) for 3 WN and 7 WC stars. Additionally, we utilised a uniform set of flux-calibrated NTT/SOFI spectra, with R∼1000 covering 0.9–2.5μm for every WR star in Wd1 (Crowther et al. 2006).

We toook BVRI photometry for 7 of the WR stars from C05. Due to the importance of R and I photometry in constraining the reddening to individual stars, we re-derived a consistent set of photometry in these bands by performing PSF fitting (DAOPHOT) photometry on archival VLT/FORS2 (R_SPECIAL, shown in Fig 1) and WFI MPG/ESO 2.2m (I_c) images.

We suplemented these with IR photometry from the 2MASS and *Spitzer* GLIMPSE catalogues for isolated stars.

3 Spectral modelling

Initial parameter estimates for each star were obtained by comparison of their spectra to published grids models generated by the non-LTE `PoWR` code (Gräfener et al. 2002). We then calculated tailored models using the `CMFGEN` code (Hillier & Miller 1998) ($\beta = 1.0$, $f = 0.1$). An example model fit is shown in Fig 2.

For WN stars, we derive temperatures ($T_\star$) using the relative strengths of HeII/HeI lines, giving an estimated uncertainty of 2.5kK. We measured surface H abundances by comparing Paβ+HeII 1.282μm and Brγ+HeI+II 2.164–2.166μm to the nearby pure HeII lines. The overall strength of the recombination line spectrum was used to determine $\dot{M}$, particularly HeI 1.083μm.

For WC stars, we derive temperatures using the relative strengths of CII/CIII lines, with less weight given to CIV. We used the general strength of the carbon spectrum with respect to helium to derive a surface carbon abundance (C/He). It was essential to derive $\dot{M}$ and $T_\star$ in unison, as changes in ionisation structure resulting from changes in wind density have a more profound effect on the ionisation structure of carbon.

We determined the luminosity (L) of each star by matching the observed K-band flux, and used the SED shape shortward of this to determine reddening to each star individually. The flux contributions of a binary companion or circumstellar dust, represented by a scaled Kurucz model O7V stars or black body with T=1000–1400K respectively (where included), were gauged by spectral line-dilution and the SED shape.

4 Results

In Figure 3 we present a H-R diagram showing $T_\star$ and L for all analysed WR stars. The WN stars in Wd1 have median $X_H = 0.02$, significantly below that for Galactic WN6–8 stars (0.1, Hamann et al. 2006), but are similar in luminosity to the H-free field population.

For four of the WC9 stars in Wd1, we measure similar L and $T_\star$ to the field and GC cluster populations (Sander et al. 2012; Martins et al. 2007) but three (Wd1–E, H, N) have a somewhat higher L, and lower $T_\star$, indicating unusually large radii for WC stars.

Mass-loss rates derived for the WC and WN stars are largely consistent with the Nugis & Lamers (2000) $\dot{M}$–L relation, with the exception of the strong-line Wd1–A.

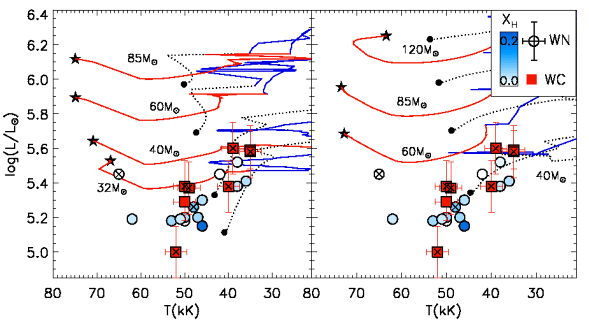

Fig. 3: H-R diagram showing the WR stars in Wd1 (WN circles, WC squares), with non-rotating (left) and fast rotating (right) stellar models (Ekström et al. 2012).

5 Discussion

In Figure 3 I show single-star models with initial masses from $32\,M_\odot$ to $120\,M_\odot$ at solar metallicity ($Z = 0.014$), with (left) and without (right) stellar rotation (Ekström et al. 2012). However, it should be noted that $\geq 40\,M_\odot/\geq 60\,M_\odot$ non-rotating/rotating models terminate at an age <5 Myr. The moderately super-solar metallicity of Wd1 – exceeding that of the Orion nebula by $\sim$40% – has little effect on $\leq 40\,M_\odot$ models shown ($<$0.1 dex in L). The majority of WN stars are sub-luminous compared to single-star models. All WC stars but Wd1-F are consistent in L with rotating $40\,M_\odot$ and $32\,M_\odot$ tracks. However, the carbon abundances we measure ($X_C \geq 0.17$) are much higher than at the WN→WC transition in the stellar models models ($X_C \sim 1\%$).

Regarding the progenitors fo the WR stars, the youth of Wd1 prohibits $\lesssim 25\,M_\odot$, and the presence of RSGs – assuming coevality – suggest an upper limit 40–50 $M_\odot$. Therefore, any single-star origin would require additional mass-loss in 25–50 $M_\odot$ stars. Such stars are not expected to obtain Eddington factors close to one, and so are not candidates for enhanced mass-loss in the upper H-R diagram (Gräfener et al. 2011), leaving episodic mass-loss via an LBV phase as the leading single-star scenario.

Alternatively, the evidence for a high binary fraction appeals to a binary origin for these low-L H-free WR stars. A $40\,M_\odot$ primary star, which expands to fill its Roche-lobe, will be H-free at an age of 5 Myr (Eldridge et al. 2008). However, despite uncertainties in mass transfer efficiency, most close binary interactions are thought to result in a *more* luminous secondary (Langer 2012). Adequate spectral fits using single-star models provide an approximate flux limit of $F_O/F_{WR} < 1.0$. The formation of such faint secondary stars requires highly non-conservative mass-transfer, which may occur if initial mass ratios are low (Petrovic et al. 2005).

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Andreas Sander: You just mentioned that you do not see the O-star in your combined fit. How did you constrain the models you are using in your analyses?

Christopher Rosslowe: At ∼6000 Å the flux is mostly WR+O, at ∼2 μm it's mostly WR+dust – so we use the variation in the flux ratios and emission line dikution to constrain the relative contributions.

Anthony (Tony) Moffat: Given the high number of evolved stars in Wd1, there should be many more (hundreds!) of upper main-sequence stars. Have you looked for such stars? This would be very important to constrain the cluster age and check for a normal IMF.

Also: what is the latest news on the putatively associated magnetar in Wd1? What kind of star could have been its progenitor, assuming it is a cluster member?

Christopher Rosslowe: Such stars are difficult to confirm spectroscopically. Due to the high cluster reddening, an O7V would have V 20 – this is about the depth of the published spectroscopic follow-up (Clark et al. 2005, A&A 434, 939).

The peculiar B hypergiant Wd1-5 has been identified as a high-velocity runaway, and has been shown to have a CNO abundance pattern incompatible with single-star evolution (Clark et al. 2014, A&A 565, A90) – this has lead Clark et al. to propose Wd1-5 as the pre-SN companion to the magnetar.