The massive binary population of the starburst cluster Westerlund 1*

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Abstract: We present initial results from a long-baseline radial velocity survey for massive binaries in the cluster Westerlund 1. Four systems are examined: the dust-producing WC binary W239, the double-lined eclipsing binary W13, and the single-lined B0 supergiants W43a and W3003. Finally, the evolutionary implications for the population of massive stars in Westerlund 1 are discussed.

1 Introduction

The galactic starburst cluster Westerlund 1 (hereafter Wd1; Westerlund 1987; Clark et al. 2005) contains a rich, coeval population of massive stars that trace both the hot (OB supergiant, Wolf-Rayet) and cool (yellow hypergiant, red supergiant) phases of post-Main Sequence evolution. Motivated by X-ray, infra-red and radio observations that show Wd1 to be binary-rich (Crowther et al. 2006; Clark et al. 2008; Dougherty et al. 2010), we have undertaken an intensive multi-epoch radial velocity (RV) survey of Wd1 in order to obtain a census of massive binaries amongst both the highly-luminous transitional supergiants and the lower-luminosity stars just evolving off the main sequence. In these proceedings we discuss four massive binary systems identified by our survey, along with the possible implications of these objects for binary-mediated evolution in Wd1.

2 Observations

A list of targets discussed here is given in Table 1. With the exception of W3003, which is a newly-identified cluster member (Ritchie et al. 2009a), designations are from Westerlund (1987); alternate *WR* designations for the Wolf-Rayet population from Clark & Negueruela (2002) and Crowther et al. (2006) are also given in the text where appropriate. Data were obtained on 11 nights between 20/06/2008 and 20/08/2009, using the FLAMES multi-object spectrograph on VLT UT2 *Kueyen* at Cerro Paranal, Chile. Setup HR21 was used to cover the 8484-9001Å range with a resolving

*Based on observations collected at the European Southern Observatory under programmes ESO 81.D-0324 and 383.D-0633

Table 1: List of targets.

ID	Spectral Type	Period (days)	RA (J2000)	Dec (J2000)	R[a]	I[a]	Notes[b]
W13	B0.5 Ia$^+$+OB	9.27	16 47 06.45	-45 50 26.0	14.63	12.06	X, E
W43a	B0 Ia	16.27	16 47 03.54	-45 50 57.3	15.22	12.26	A
W239 (F)	WC9d	6.5	16 47 05.21	-45 52 25.0	15.39	12.90	X, A
W3003	B0 Ib	11.12	16 47 11.60	-45 49 22.4	16.21	13.31	A

[a]Photometric *R* and *I*-band magnitudes are taken from Clark et al. (2005) or Bonanos (2007).
[b]**X**-ray sources (Clark et al. 2008), **E**clipsing or **A**periodic variables (Bonanos 2007).

power ∼16200; target selection, data acquisition and reduction are described in detail in Ritchie et al. (2009a).

Radial velocities were measured by fitting Gaussian profiles to the cores of strong absorption and/or emission lines using the IRAF *ngaussfit* routines, with the derived velocity an error-weighted average of individual lines. The Paschen 11-15 lines were used to obtain radial velocities for W13, W43a and W3003, with the Pa16 λ8502 line that also falls within our coverage excluded due to blending with an adjacent C III λ8500 line that strengthens rapidly at B0.5 and earlier (Negueruela, Clark & Ritchie, 2010). In the case of the dusty Wolf-Rayet W239 (WR F; Clark & Negueruela 2002), strong C III $\lambda\lambda$8500, 8664 emission lines were used for radial velocity measurement (see Clark et al. 2010). A well-defined DIB at ∼8620Å provides a serendipitous check for zero-point errors in our data, with spectra showing epoch-to-epoch variability of well under 1 km s^{-1}.

3 Results

3.1 The double-lined eclipsing binary W13

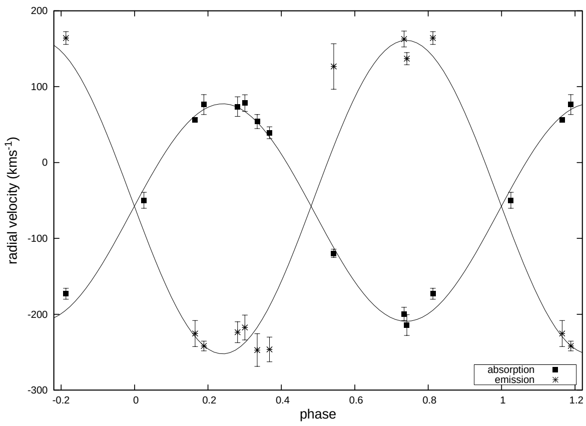

Figure 1: RV curve for the double-lined eclipsing binary W13. T_0 is at MJD=54643.080, which corresponds to the eclipse of the B0.5Ia$^+$ emission-line star.

W13 was identified as an eclipsing binary system by Bonanos (2007), with Ritchie et al. (2009a, 2010) finding it to be a double-lined system consisting of a peculiar O9.5-B0.5 supergiant and an B0.5 Ia$^+$ emission-line object. The strong similarities in spectral morphology between W13, the

WN9h star W44 (WR L) and the WN10-11h star W5 (WR S) suggest that the B0.5 Ia^{+} star is an immediate evolutionary precursor to the Wolf-Rayet phase, although the weakness of the He I emission lines and absence of N II λ6611 emission make it the least-evolved member of the WNL population in Wd1.

Results from our full FLAMES dataset presented by Ritchie et al. (2010) show W13 to have an orbital period of 9.2709±0.0015 days, with lower limits for the masses of the emission-line object and supergiant companion of $21.4 \pm 2.6 M_{\odot}$ and $32.8 \pm 4.0 M_{\odot}$ respectively, rising to $23.2^{+3.3}_{-3.0} M_{\odot}$ and $35.4^{+5.0}_{-4.6} M_{\odot}$ for our best-fit inclination 62^{+3}_{-4} degrees. The evolved state, short orbital period and near-contact configuration all suggest strong interaction during the evolution of the system, with comparison with the evolutionary models of Petrovic, Langer & van der Hucht (2005) suggesting highly non-conservative late-Case A/Case B mass transfer and an initial mass for the emission-line object of $\sim 40 M_{\odot}$. This implies that the magnetar CXOU J164710.2-455216 formed from an even more massive progenitor, with close binary evolution apparently instrumental in shedding sufficient mass to avoid formation of a black hole (Clark et al. 2008; Ritchie et al. 2010).

3.2 The WC9d binary W239 (WR F).

The dust-forming WC9 star W239 (WR F) was noted by Ritchie et al. (2009a) as showing RV changes consistent with binarity, and our full FLAMES dataset confirms a period of ∼6.5 days and a semi-amplitude of ∼45 km s^{-1} that is consistent with a WR+O binary viewed at i∼10–20°. W239 shows strong near-mid IR excess and dilute K-band spectrum, both indicative of hot circumstellar dust (Crowther et al. 2006). However, the ∼6.5d orbital period is a factor of ∼5 shorter than any other known dust-forming WC star, and implies likely Case A or contact evolution in a very close binary (∼4 days) with subsequent wind-driven mass loss widening the orbit (Petrovic et al. 2005). W239 is examined in detail by Clark et al. (2010).

3.3 The B0 supergiant binaries W43a and W3003.

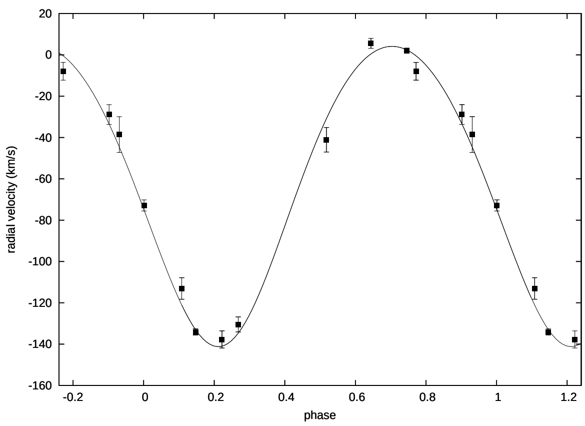

Figure 2: RV curve for the single-lined binary W43a (B0 Ia), with T_0 corresponding to the start of our observations at MJD=54646.185

W43a (B0 Ia; Negueruela et al. 2010) displays an unremarkable R-band spectrum with weak wind emission lines from Hα and C II, and He I in absorption. The star is not detected at X-ray or radio wavelengths (Clark et al. 2008; Dougherty et al. 2010), and no eclipses are apparent in the photometry of Bonanos (2007). Nevertheless, the I-band FLAMES data reveal significant RV changes on a timescale of a few days, although no indication of a companion is seen in the spectrum. A fit to eleven epochs of RV data gives a period of 16.266 ± 0.005 days, a semi-amplitude of 71 ± 6 km s^{-1} and a systemic velocity of -67 ± 4 km s^{-1}; the latter is somewhat blueshifted with respect to other members of Wd1, but this effect is seen also in the OB supergiant companion in W13 and discrepant systemic velocities are commonly observed in early-type spectroscopic binaries (see Ritchie et al. 2010 and refs. therein).

The B0 Ib supergiant W3003 (Ritchie et al. 2009a), located to the north-east of the cluster, appears a similar system to W43a. Our RV data find a period of 11.12 ± 0.01 days and a slightly eccentric orbit ($e \lesssim 0.05$), with a systemic velocity of -39 ± 8 km s^{-1} and a semi-amplitude of 38 ± 5 km s^{-1}. Once again, no indications of binarity are found in other observations[3]. These two supergiants are therefore of interest as the first examples that previous estimates of the binary fraction of Wd1 based on the signature of colliding-wind systems (in which *both* components must be sufficiently massive to support a powerful stellar wind) are incomplete. In the case of W43a, assuming a $\sim$35M$_\odot$ primary and an inclination of $\sim$35–45° implies a main sequence secondary with a mass $\sim$15–21M$_\odot$; lower inclinations would suggest a higher-mass secondary that should be directly visible in our spectra, while higher inclinations would result in a detectable eclipsing system. Similarly, the low semi-amplitude of W3003 suggests either a very low inclination and/or a low-mass companion. The intrinsic X-ray luminosity of individual OB supergiants in Wd1 ($L_x \lesssim 10^{32}$ erg s^{-1}; Clark et al. 2008) is insufficient for direct detection, and unequal-mass OB supergiant+main sequence binaries such as W43a and W3003 will lack the strong wind interaction required to significantly raise their X-ray luminosities. Neither system is expected to have begun strong binary interaction, but once shell burning commences the primary will rapidly lose its Hydrogen envelope via Case B mass transfer, leaving a WR+O binary with an orbital period of a few weeks (Petrovic et al. 2005).

4 Evolutionary implications

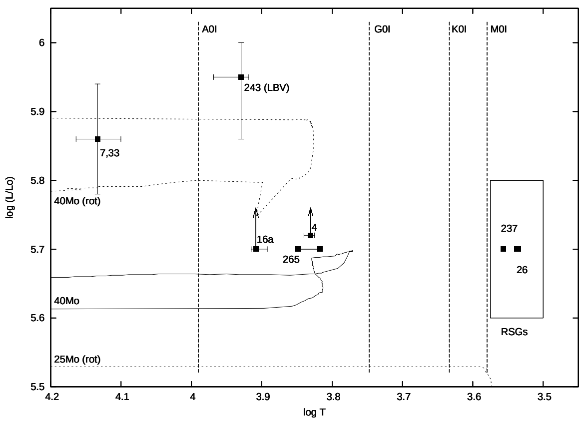

Figure 3: Location of luminous hypergiants and red supergiants in Wd1 compared to evolutionary tracks with and without rotation (Meynet & Maeder 2003).

The OB supergiant population of Wd1 suggests a single burst of star formation lasting less than 1 Myr and a cluster age of $\sim$5 Myr (Negueruela et al. 2010). The $\sim$40M$_\odot$ main sequence mass of the emission-line object in W13 and lack of evidence for significant non-coevality in the cluster therefore suggests that the ten highly-luminous B5-F8 Ia$^+$ hypergiants in Wd1 all evolved from progenitors with $M_{\rm ini} \gtrsim$35M$_\odot$. Although these objects appear to be in good agreement with evolutionary tracks

[3]Both W43a and W3003 are identified as aperiodic variables in the photometry of Bonanos (2007), but this likely reflects pulsational instability seen in all stars later than $\sim$B0 in Wd1 (Ritchie et al. 2009a).

including rotation (Meynet & Maeder 2003), these models do not predict further evolution to the red supergiant (RSG) phase for stars in this mass range. In contrast, the transitional population in Wd1 also contains four RSGs (see Figure 3), while the early-A LBV W243 (Ritchie et al. 2009b) also displays nitrogen enrichment and oxygen and carbon depletion suggestive of CNO-processed material 'dredged up' during a previous RSG phase.

Lack of contemporaneous spectroscopy and photometry means that the luminosities of the Wd1 RSGs are somewhat uncertain, although the spectral types, derived from TiO bandhead strengths, are secure. Estimates of the luminosity of the RSG W26 (M1–6 Ia) suggest log($L/L_{\odot}$)$\sim$5.8, and a consequent radius possibly as large as $\sim$2000 $R_{\odot}$, while non-LTE modelling of the LBV W243 yields $R \sim 450(d/$4.5kpc) $R_{\odot}$. Such objects are clearly incompatible with close binary evolution channels in which stars are separated by $\lesssim 100$ $R_{\odot}$, and the distribution of Wolf-Rayets and cool hypergiants in Wd1 therefore hints at a split evolutionary sequence in which the close binary population undergo strong interaction as the primary evolves off the main sequence, becoming WR+O binaries like W13 and W239, while isolated (or long-period binary) stars become B–F hypergiants en route to the RSG phase. Further observations of the transitional hypergiant, RSG and Wolf-Rayet populations will allow this hypothesis to be tested directly, and this topic is explored further in Clark et al. (2010).

Acknowledgements

We thank the referee for a thorough reading of this manuscript and helpful comments. JSC acknowledges support from an RCUK fellowship. IN has been funded by grants AYA2008-06166-C03-03 and Consolider-GTC CSD-2006-00070 from the Spanish Ministerio de Ciencia e Innovación (MICINN).

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