A&A 531, A28 (2011)
DOI: 10.1051/0004-6361/201116990


Astronomy & Astrophysics

# A VLT/FLAMES survey for massive binaries in Westerlund 1

## III. The WC9d binary W239 and implications for massive stellar evolution*

J. S. Clark[1], B. W. Ritchie[1], I. Negueruela[2], P. A. Crowther[3], A. Damineli[4], F. J. Jablonski[5], and N. Langer[6]

[1] Department of Physics and Astronomy, The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK
[2] Departamento de Física, Ingeniería de Sistemas y Teoría de la Señal, Universidad de Alicante, Apdo. 99, E03080 Alicante, Spain
[3] Department of Physics & Astronomy, Hicks Building, University of Sheffield, Hounsfield Road, Sheffield, S3 7RH, UK
[4] Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo, Rua do Matão 1226, Cidade Universitária, 05508-090 São Paulo, SP, Brazil
[5] Instituto Nacional de Pesquisas Espaciais/MCT, Avenida dos Astronautas 1758, São José dos Campos, SP 12227-010, Brazil
[6] Argelander-Institut für Astronomie der Universität Bonn, Auf dem Hügel 71, 53121 Bonn, Germany

Received 31 March 2011 / Accepted 15 April 2011

### ABSTRACT

*Context.* There is growing evidence that a treatment of binarity amongst OB stars is essential for a full theory of stellar evolution. However the binary properties of massive stars – frequency, mass ratio & orbital separation – are still poorly constrained.

*Aims.* In order to address this shortcoming we have undertaken a multiepoch spectroscopic study of the stellar population of the young massive cluster Westerlund 1. In this paper we present an investigation into the nature of the dusty Wolf-Rayet star and candidate binary W239.

*Methods.* To accomplish this we have utilised our spectroscopic data in conjunction with multi-year optical and near-IR photometric observations in order to search for binary signatures. Comparison of these data to synthetic non-LTE model atmosphere spectra were used to derive the fundamental properties of the WC9 primary.

*Results.* We found W239 to have an orbital period of only ~5.05 days, making it one of the most compact WC binaries yet identified. Analysis of the long term near-IR lightcurve reveals a significant flare between 2004-6. We interpret this as evidence for a third massive stellar component in the system in a long period (>6 yr), eccentric orbit, with dust production occuring at periastron leading to the flare. The presence of a near-IR excess characteristic of hot (~1300 K) dust at every epoch is consistent with the expectation that the subset of persistent dust forming WC stars are short (<1 yr) period binaries, although confirmation will require further observations. Non-LTE model atmosphere analysis of the spectrum reveals the physical properties of the WC9 component to be fully consistent with other Galactic examples.

*Conclusions.* The simultaneous presence of both short period Wolf-Rayet binaries and cool hypergiants within Wd 1 provides compelling evidence for a bifurcation in the post-Main Sequence evolution of massive stars due to binarity. Short period O+OB binaries will evolve directly to the Wolf-Rayet phase, either due to an episode of binary mediated mass loss – likely via case A mass transfer or a contact configuration – or via chemically homogenous evolution. Conversely, long period binaries and single stars will instead undergo a red loop across the HR diagram via a cool hypergiant phase. Future analysis of the full spectroscopic dataset for Wd 1 will constrain the proportion of massive stars experiencing each pathway; hence quantifying the importance of binarity in massive stellar evolution up to and beyond supernova and the resultant production of relativistic remnants.

**Key words.** stars: evolution – stars: early-type – binaries: general

## 1. Introduction

Recently, there has been increasing recognition of the importance of binarity in the evolution of massive stars. The binary fraction of such objects is expected to provide an important observational test of current theories of star formation (e.g. Bonnell & Bate 2005; Zinnecker & Yorke 2007) and the early (rapid) dynamical evolution of young massive stellar clusters. As both binary components evolve it is thought that substantial quantities of mass may be lost in close binaries as the primary expands to (over)fill its Roche Lobe (e.g. Petrovic et al. 2005a). Such binary driven mass loss is also predicted to influence the nature of both subsequent supernova (e.g. Paczynski et al. 1967; Podsiadlowski et al. 1992) and resultant relativistic remnant (Wellstein & Langer 1999; Fryer et al. 2002). Moreover, recent evolutionary simulations suggest that in very compact binaries tidal interaction may drive homogeneous chemical evolution permitting the formation of very massive stellar mass black holes (de Mink et al. 2009) while it is also suspected that a proportion of Gamma Ray Bursts may result from binary evolution channels (Cantiello et al. 2007).

Powerful observational support for the importance of binary mediated mass loss and homogeneous chemical evolution has been provided by the dynamical determination of the masses of both components of galactic (4U1700-37 & GX301-2 – Clark et al. 2002; Kaper et al. 2006) and extragalactic (IC10 X-1 & NGC 300 X-1 – Crowther et al. 2010; Silverman & Filippenko et al. 2008) high mass X-ray binaries. However, the relative importance of these pathways depends on both the overall binary percentage amongst massive stars as well as the distribution of orbital separations and mass ratios (e.g. Kobulnicky & Fryer 2007). Consequently significant effort has been applied to the

* Based on observations made at the European Southern Observatory, Paranal, Chile under programs ESO 81.D-0324 & 383.D-0633 and OPD/LNA Observatory (Br).

determination of these properties via multiepoch (multiplexed) spectroscopic observations of massive stellar aggregates (e.g. Cyg OB2, NGC 6231 & 30 Dor – Kiminki et al. 2007; Sana et al. 2008; Bosch et al. 2009) whereby homogeneous stellar populations may be efficiently sampled. These studies reveal a uniformly high binary fraction for OB stars (≥40%), which, when corrected for the observational bias against long period systems results in a fraction consistent with unity for at least one region (Cyg OB2, Kobulnicky & Fryer 2007).

Another compelling target is the young (4–5 Myr) massive (~$10^5$ $M_\odot$) galactic cluster Westerlund 1 (Wd 1, Clark et al. 2005), which contains a significant (≫100) population of massive ($M_{\rm initial}$ > 30 $M_\odot$, Ritchie et al. 2010a) stars. Multiwavelength observations of the cluster revealed a number of indirect binary markers amongst the OB supergiants and Wolf-Rayets (WR), with a binary fraction for the latter inferred to be at least 70% (and potentially consistent with unity, Crowther et al. 2006a; Clark et al. 2008; Dougherty et al. 2010). Motivated by these findings we have undertaken a systematic radial velocity (RV) spectroscopic survey to identify and characterise the binary population of Wd 1; a detailed description of the project methodology, reduction technique and preliminary results may be found in Ritchie et al. (2009).

In this paper we present an analysis of the properties of the WC9d star W239 (=WR F, WR77n), for which binarity was suggested by the presence of a hard X-ray spectrum and a pronounced near-mid IR excess due to warm circumstellar dust (Skinner et al. 2006; Crowther et al. 2006a). Including W239, 7 of the 8 WCL (=WC8-9) stars within Wd1 demonstrate one or both of these observational properties. Such phenomena are typically attributed to the wind collision zone in a massive binary system where material is first shock heated to high temperatures, with the concommitant high densities subsequently permitting downstream dust condensation upon cooling (e.g. Prilutskii & Usov 1976; Allen et al. 1972; Usov et al. 1991; Williams & van der Hucht 1992).

We present a brief description of the spectroscopic and photometric datasets employed in this work in Sect. 2, as well as a full RV solution – to the best of our knowledge only the fifth for a dusty WC binary after WR 113, 137 & 140 (Massey & Niemela 1981; Williams et al. 1990; Lefèvre et al. 2005) and the LMC system HD 36402 (=Br31, Moffat et al. 1990; Williams 2011). The results of a tailored non-LTE atmospheric analysis of the WR component of the binary is also included in Sect. 2, while we discuss the implications of our findings in Sect. 3, before summarising them in Sect. 4.

## 2. Data reduction and analysis

### 2.1. Spectroscopy

Eleven epochs of spectra were obtained between 2008-9 with the Fibre Large Array Multi Element Spectrograph (FLAMES, Pasquini et al. 2002) mounted on VLT UT2, with the GIRAFFE spectrograph operated in MEDUSA mode (HR21 setup), resulting in a resolving power of ~16 200 between 8484–9001 Å. Full details of data reduction and analysis may be found in Ritchie et al. (2009).

While Clark et al. (2010) found that W239 was not subject to secular variability between 2001-9, Ritchie et al. (2009) report the presence of RV variations in the C III 8500 & 8664 Å lines in the 2008 spectra (e.g. Fig. 1). As a result RV measurements of all 11 epochs of observations were carried out using the Nelder-Mead simplex method to fit Lorentzian profiles to the strong

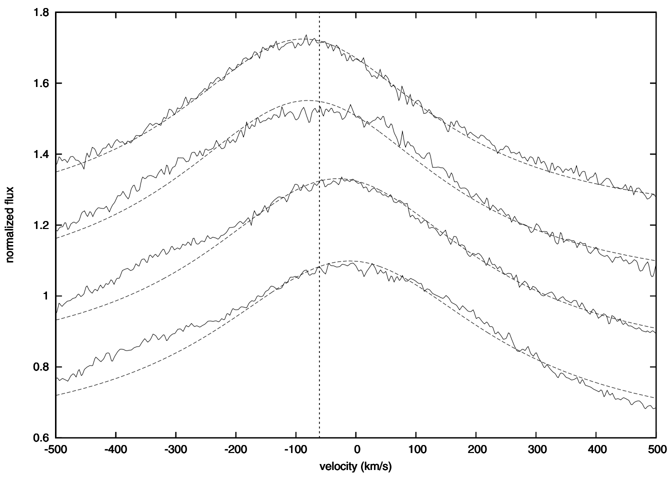


**Fig. 1.** *Top panel*: sample C III 8664 Å emission line profiles for W239 clearly indicating the binary induced radial velocity shift relative to the systemic velocity (dashed line). Lorentzian profile fit to emission line as utilised for the radial velocity determination overplotted. Note the presence of an additional C III emission feature in the blue wing at 8653.2 Å; this was found to have no effect on the RV determination.

**Table 1.** Journal of observations.

| MJD[a] | Phase (Orbits)[b] | RV(C III 8664) (km s$^{-1}$)[c] | O–C |
|---|---|---|---|
| 54 646.1846 | 0.000 | −47.4 | −1.0 |
| 54 665.0356 | 0.731 (3.73) | −31.1 | −0.5 |
| 54 671.1343 | 0.938 (4.94) | −29.2 | 5.8 |
| 54 692.0423 | 0.076 (9.08) | −62.1 | 1.4 |
| 54 713.0107 | 0.226 (13.23) | −87.9 | 4.6 |
| 54 724.0818 | 0.417 (15.42) | −89.8 | 2.0 |
| 54 728.0554 | 0.203 (16.20) | −91.0 | −1.8 |
| 54 734.0613 | 0.392 (17.39) | −85.5 | 9.3 |
| 54 965.1768 | 0.132 (63.13) | −92.6 | −16.6 |
| 54 969.3198 | 0.952 (63.95) | −22.2 | 15.0 |
| 55 063.0575 | 0.503 (82.50) | −87.1 | −10.5 |

**Notes.** [(a)] Modified Julian day at the midpoint of two 600 s integrations (2 × 500 s, 04/09/2008; 1 × 600 s + 1 × 700 s, 19/09/2008). [(b)] Phase taking $T_0$ = 54 646.1846, elapsed orbits for an orbital period of 5.053 d. [(c)] RV listed for the C III 8664 Å line, with fitting errors ≤4 km s$^{-1}$ at all epochs.

C III lines, providing a robust RV determination that is unaffected by small-scale line-profile variations due to wind effects. The results of this process are summarised in Table 1, with sample fits presented in Fig. 1.

An obvious explanation for the pronounced RV shifts is that they are due to reflex motion induced by an unseen companion to the WC9d primary. A period search of the RV data strongly favours a candidate period of 5.05 days. An alias of this period at 3.04 days may not be excluded from the current data but results in larger (O–C) residuals and appears further disfavoured because wind-driven mass loss in the WC phase acts to widen the orbit, implying that W239 would have had to have passed through a particularly compact configuration prior to its current state; we return to this point in Sect. 3.3.1. Consequently, we adopt a period of 5.05 days for the remainder of this paper and emphasise that the analysis explicitly excludes longer orbital periods (>6 days) and that any residual uncertainty in the period *does not* materially affect our conclusions.

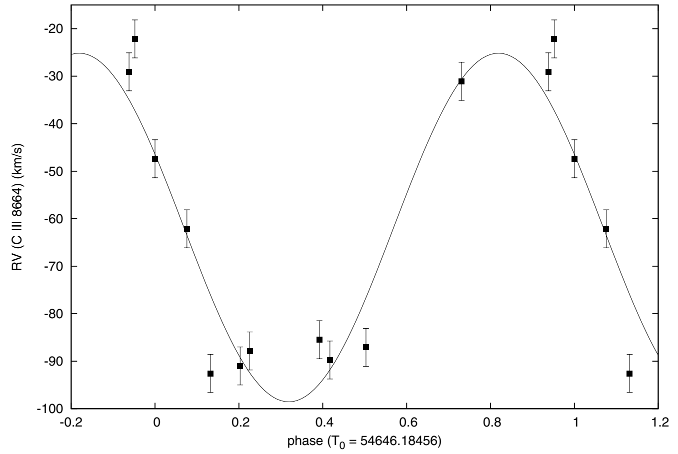


**Fig. 2.** Radial velocity curve for W239, phased on the orbital period. Velocity determined from the C III 8664 Å line.

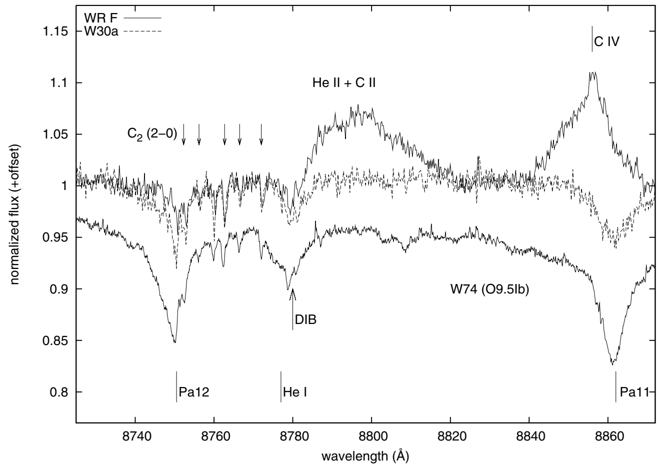


**Fig. 3.** Comparison of the 8700–8900 Å spectra of W239 (solid line) and the O+O SB2 binary W30a (dotted line). W239 appears to demonstrate a similar weak, broad Pa12 profile at ~8500 Å as W30a. The weakness of this feature is apparent upon consideration of the single O9.5 Ib cluster member W74.

**Table 2.** Orbital parameters.

| Parameter | Value |
|---|---|
| $P$ (days) | 5.053 ± 0.002 |
| $K_{WC}$ (km s$^{-1}$) | 39.7 ± 4.8 |
| $\gamma$ (km s$^{-1}$) | −60.5 ± 3.5 |
| $i$ | <30° |
| $e$ | 0 (fixed) |
| $a \sin i$ ($R_\odot$) | 3.97 ± 0.48 |

We show the resultant curve derived from a Levenberg-Marquardt fit to the RV data in Fig. 2, with an (orbital) period, $P_{orb}$ = 5.053 ± 0.002 days[1], and semi-amplitude $K_{WC}$ = 39.7 ± 4.8 km s$^{-1}$ (Table 2). Eccentricity was fixed at zero, due to the short period and expectation that binary interaction would have circularized the orbit. We note that deviations from the RV fit are greater in the 2009 data (~10–15 km s$^{-1}$), suggestive of either a small systematic error in the period determination or wind variability superimposed on the orbital motion. The systemic velocity derived from the C III 8664 Å line is −60.5 ± 3.5 km s$^{-1}$, with the C III 8500 Å line offset redwards as noted by Ritchie et al. (2009). While slightly higher than the mean derived from 10 supergiants by Mengel & Tacconi-Garman (2009) it is within the range found for other cluster members from our full FLAMES dataset (Ritchie et al. 2009, 2010b).

It might, however, be supposed that such line profile variability was the result of rotating global wind structures. Indeed, periodic spectral variability attributed to such a cause has previously been reported in the optical lines of the apparently single WRs WR1 & 6 (Morel et al. 1997; Chené & St-Louis 2010). However, we consider this unlikely for several reasons. Firstly, the RV line profile variability in W239 encompasses the whole profile. This contrasts to the behaviour of WR 1 & 6, where superposition of additional transient emission components on a stationary underlying profile leads to shifts in the line centre of gravity or "skewness". This is also the case for the apparently single WC8 star WR K within Wd1, for which we find line profile variability in the line core but no global RV shifts (Ritchie et al., in prep.). Secondly, the 5.05 day period present in W239 is coherent over ~83 cycles; in comparison, the quasi-period of WR 1, attributed to wind asymmetries, is only stable for ≤4 cycles (Chené & St.-Louis 2010). Finally, this wind variability is accompanied by photometric modulation with an identical period in both WR 1 & 6, but Bonanos (2007) demonstrate that such behaviour is absent in W239.

Moreover, phase resolved near-IR spectral analysis of 5 WR binaries reveals that variability due to wind-wind interaction driven asymmetries – rather than binary reflex motion – is in any event phased on their known orbital periods (Stevens & Howarth 1999). We are thus confident that the 5.05 day period identified in the RV curve of W239 reflects an underlying binary orbital period of the system.

Motivated by this finding we re-examined the FLAMES spectra of W239 to search for the signature of a companion(s), noting that the shorter wavelength data were of too low S/N and resolution to permit such an analysis and the longer wavelength data are dominated by a near-IR excess due to hot dust (Sects. 2.2 and 2.3). The FLAMES spectra cover Pa11-16, which are expected to be in absorption in late O/early B stars. Unfortunately Pa11 falls on the red wing of a C IV emission line from the WC9 primary, while Pa13 and Pa16 fall at the same wavelengths as strong C III lines. Given the decrease in the strength of the Paschen series to higher transitions, Pa12 (8750 Å) appears to be the best remaining binary diagnostic. Unfortunately, while this transition is clear of any WR emission lines it does overlap the interstellar $C_2$ Phillips (2–0) $R/Q$ bands, which are visible in our spectra of W239 and other cluster members, complicating analysis (cf. Ritchie et al. 2010a). This region of the spectra is presented in Fig. 3, and we note that W239 appears to share the weak, broad Pa12 profile found for this transition (and the wider Paschen series) in the O+O spectroscopic binary W30a (Clark et al. 2008; Negueruela et al. 2010b); we therefore regard this as *tentative* evidence for a hot massive companion(s). Unfortunately, the weakness and breadth of the line, combined with the low S/N and presence of interstellar features precludes a search for RV variability, although pre-empting Sects. 2.3 and 3.1 one might expect any reflex motion in a putative early type companion to be of low amplitude, such that it would be difficult to identify at the resolution of these data.

[1] Errors are internal to the fit.

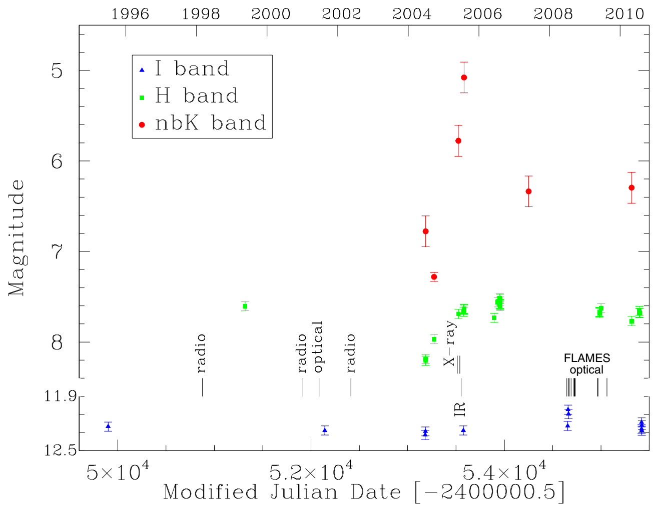


**Fig. 4.** Optical-near IR lightcurve for W239. The locations of optical and near-IR spectroscopic, radio and X-ray observations discussed in the text are also indicated.

**Table 3.** Summary of near-IR photometry.

| Date | *H* | *nbK* |
|---|---|---|
| 19/05/99 | 7.61 | – |
| 28/06/04 | 8.21 | – |
| 29/06/04 | – | 6.78 |
| 19/06/04 | 8.18 | – |
| 24/09/04 | 7.97 | 7.28 |
| 03/06/05 | 7.69 | 5.78 |
| 27/07/05 | 7.67 | – |
| 28/07/05 | 7.64 | – |
| 29/07/05 | 7.63 | – |
| 31/07/05 | 7.64 | 5.08 |
| 12/08/05 | 7.73 | – |
| 16/07/06 | 7.56 | – |
| 04/08/06 | 7.59 | – |
| 05/08/06 | 7.52 | – |
| 06/08/06 | 7.59 | – |
| 08/08/06 | 7.53 | – |
| 09/08/06 | 7.60 | – |
| 10/08/06 | 7.55 | – |
| 31/05/07 | – | 6.34 |
| 05/09/09 | 7.67 | – |
| 06/09/09 | 7.67 | – |
| 18/06/09 | 7.63 | – |
| 30/04/10 | 7.77 | 6.29 |
| 19/07/10 | 7.68 | – |
| 20/07/10 | 7.65 | – |
| 21/07/10 | 7.68 | – |
| 22/07/10 | 7.68 | – |

**Notes.** The errors on *H* band data of ±0.05 mag and on *nbK* band of ±0.17 mag, with the exception of the data from 24/09/04 where they are ±0.05 in both bands (Crowther et al. 2006a).

### 2.2. Photometry

Wd 1 has been the subject of a long term broad band $I, H$ & $K$ and narrow band $K$[2] continuum observational campaign since 2004, utilising the 0.6-m and 1.6-m telescopes at Pico dos Dias Observatory (LNA/Brazil). These were equiped with an Hawaii $1024 \times 1024$ pixel camera, which gave a field-of-view of $8 \times 8$ arcmin and $4 \times 4$ arcmin respectively. Standard image processing techniques were adopted (bias subtraction, flatfielding and sky subtraction) prior to data extraction via aperture photometry under IRAF. Finally, absolute $I$ band magnitudes were obtained via calibration to the data presented by Piatti et al. (1998), while the near-IR photometry was calibrated via comparison to 2MASS data.

Unfortunately, W239 was saturated in the broad $K$ band, leaving just 5 epochs of observations in the narrowband 2.14 $\mu$m filter. However 25 individual $H$ band observations between 2004-10 were viable; both datasets are plotted in Fig. 4 and summarised in Table 3, along with photometry from Crowther et al. (2006a). These are further supplemented with the $I$ band data from Piatti et al. (1998) and Clark et al. (2005) and 10 epochs of new observations. Unfortunately, archival 2MASS data were associated with large uncertainties and so were not employed.

These data provide no evidence for secular variability in the $I$ band between 1995–2010. However, dramatic near-IR variability is present, with a significant brightening observed between 2004-6 ($\Delta H \sim 0.6$ mag, $\Delta nbK \sim 2.2$ mag). This was also accompanied by the system becoming redder, with $(H - nbK) \sim 0.69 \pm 0.07$ on 2004 May 1 and $2.6 \pm 0.2$ on 2005 July 31. Subsequently, W239 appears to have faded in the *nbK* band, albeit to a higher quiescent flux than found during the initial phase of the outburst – with the inevitable corollaries that the data are both sparse and are associated with comparatively large uncertainties. In contrast the $H$ band luminosity was observed to increase by a smaller amount, but appears to have remained at the peak luminosity for the following 4 year period. This was also accompanied by a modest reduction to $(H - nbK) \sim 1.3 \pm 0.2$ by 2010. Unfortunately, lack of contemporaneous data did not permit us to determine if the outbursts peaked at the same time in both bands.

[2] Henceforth *nbK*, centred at 2.14 $\mu$m, $FWHM = 0.023$ $\mu$m.

Similar photometric behaviour – a transient outburst characterised by an increase in IR continuum excess with wavelength – is observed in other WC binary systems where dust production rates are modulated on the orbital period and peak during periaston passage (e.g. Williams et al. 1994, 2001; van der Hucht et al. 2001). Consequently, we infer the presence of an additional long period tertiary companion to W239, with the lack of a second outburst suggesting a period of at least ~6 yr for this component. However, the broadband near-IR colours *at all times* are clearly indicative of the continued presence of hot dust (e.g. Crowther et al. 2006a); in this respect W239 bears a close resemblance to WR48a, which also shows both persistent and episodic, enhanced dust emission. Williams et al. (2003) also interpret this as evidence for a triple system, with a short period binary ($P_{\rm orb} < 1$ yr) component responsible for continous dust formation and an interaction with a tertiary companion in a wide, eccentric orbit ($P_{\rm orb} > 30$ yr; Williams 2010, priv. comm.) leading to the outburst in 1980. We return to this in Sect. 3.

However, in this regard we highlight that despite the sparse sampling, the decay in flux from the outburst peak in the *nBK* band lightcurve appeared to occur more rapidly than that of the the $H$ band. In other periodic/episodic dust producing systems the opposite is observed, with more extended decays at progressively longer wavelenths due to the cooling of the dust as it is carried from the system by the stellar winds. Unfortuntely, given the limitations of our current dataset – in particular the lack of longer wavelength data – we cannot presently explain this apparent difference in behaviour.

Finally, optical observations by Bonanos (2007) between 2006 June 15–July 25 revealed no evidence for eclipses or ellipsoidal modulation in the lightcurve. We repeated the experiment

**Table 4.** Summary of physical properties of the WC9 primary of W239.

| Property | Value |
|---|---|
| $T_*$ (kK) | 52 |
| $\log(L/L_\odot)$ | 4.95 |
| $R_*/R_\odot$ | 3.8 |
| $\log(\dot{M}/\sqrt{f})$ ($M_\odot$ yr$^{-1}$) | −4.5 |
| $f$ | 0.1 |
| $v_\infty$ (km s$^{-1}$) | 950 |
| $X_C$ | 0.25 |

with a higher cadence – ∼1500 individual I band observations between 2008 July 8–17 – but again found no evidence for modulation on the orbital period although, as with Bonanos, intra-night variability of $\Delta I \leq 0.08$ mag. over short (∼h) timescales was observed.

### *2.3. The physical properties of W239*

In order to investigate the nature of the WC9 primary of W239 we have employed the non-LTE model atmosphere code CMFGEN (Hillier & Miller 1998, 1999). To accomplish this, in addition to the data described in Sect. 2.1 we also employed the spectra presented by Clark et al. (2002) and Crowther et al. (2006a) and we refer the reader to those works for a description of the observational and reduction procedures employed. While these data span a significant period of time, no secular spectral evolution is apparent (Sect. 2.1) and there is an excellent correspondence between regions of the spectrum that have been multiply sampled. The methodology adopted follows that of the analysis of the WC9 star WR103 by Crowther et al. (2006b). Given the significant reddening to W239 some of the UV/optical transitions utilised by Crowther et al. were unavailable to us; thus our primary diagnostics were C ii $\lambda\lambda$ 6678, 7230, 9900 Å, C iii $\lambda\lambda$ 6740, 8500, 9700, 21100 Å and C iv $\lambda$ 14300 Å which, when combined with local continuum levels enabled an estimation of temperature, wind properties and stellar luminosity.

One complication was the significant dilution of the spectrum at long (>1 $\mu$m) wavelengths by emission from hot dust, as well as a potential further contribution from a massive companion(s). The former was accounted for by the inclusion of a simple greybody model for the dust emission, assuming a single temperature of 1300 K. To represent the latter we utilised a Kurucz LTE model with $T$ ∼ 35 kK – corresponding to an O7 V star – and $\log g \sim 4$. We adopted an equal light ratio at 8500 Å for the WR and OB companion(s). The relative contribution of the O7 V star was determined from the analysis of Martins & Plez (2006) who found $M_V \sim -4.7$ and we adopted $(V-I)_0 \sim -0.47$ (appropriate for an O star, Cox et al. 2001) which yielded $M_I \sim -4.23$, while our WC9 model has $M_V \sim -4.3$ and $(V-I)_0 \sim -0.05$ leading to $M_I \sim -4.25$.

The results of this model are presented in Table 4. Encouragingly, they bear close resemblance to the parameters of other WC9 stars analysed in an identical manner (Crowther et al. 2002, 2006b). The resulting best fit synthetic spectrum (Figs. 5 and 6) provides an acceptable match to the spectrum from the optical to near-IR (∼0.6–2.2 $\mu$m) and photometry for $V$ through $K$ for a distance, $d$ = 5 kpc and reddening, $E(B-V)$ = 3. The resultant composite synthetic spectrum demonstrates no *pronounced* spectral features from the putative companion; consistent with the current observational data. Unfortunately, W239 is saturated and/or blended in both *Midcourse Source Experiment* (MSX) and *Spitzer* Galactic plane surveys; hence more sophisticated

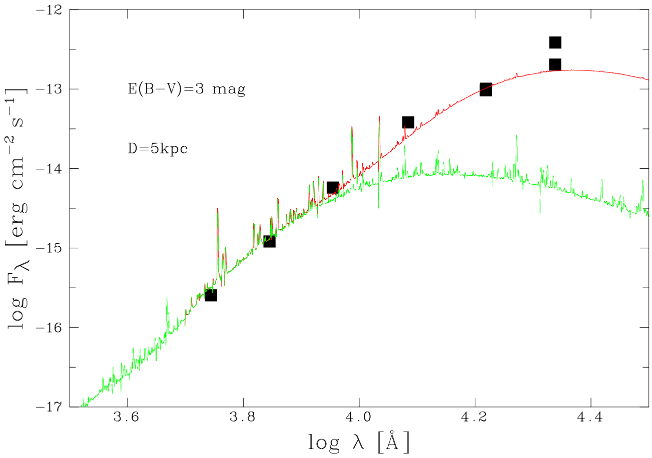


**Fig. 5.** Comparison between the broadband photometry of W239 and the reddened WC+O spectral energy distribution excluding (green dashed line) and including (red solid line) the simple 1300 K graybody dust model. Optical photometry from Clark et al. (2005, 2001 August 21) and the near-IR from 2005 June 3 & July 31 (this work).

modeling of the IR excess, although of considerable interest, appears unwarranted at this time. At longer wavelengths, the 3.6 cm radio flux predicted from the model is a factor ∼5 smaller than observed (∼0.3 mJy, Dougherty et al. 2010), suggesting the possibility of an additional contribution resulting from the wind collision. Finally, we note that our inability to *unambiguously* assign contributions to the continuum from the primary and companion(s) precludes us determining an accurate current mass for the WC9 star via the H-free mass-luminosity calibration of Schaerer & Maeder (1992), although we consider 10 $M_\odot$ to be a conservative *upper* limit.

## 3. Discussion

### *3.1. The nature of the W239 system*

The combination of cyclic RV variability, an IR excess, hard X-ray emission when single WC stars are not known to emit at such energies (e.g. Oskinova et al. 2003) and the tentative spectroscopic detection of the luminous companion(s) provides compelling evidence for the multiplicity of W239. Indeed, the mismatch between the 5.05 day RV periodicity and long term photometric behaviour is suggestive of a triple system. But what can be deduced about the putative companions from a synthesis of these observational datasets?

Unfortunately, the nature of the binary companion in the 5.05 day orbit is somewhat uncertain (in the absence of an RV curve from the putative Pa12 absorption line we may not assign it to either a binary or tertiary component with certainty). Nevertheless, assuming a mass for the WC9 component of ∼8–10 $M_\odot$ (Sect. 2.3), the combination of the observed RV semi-amplitude, $K_{WC}$, lack of eclipses and stellar radius derived from modeling imply a lower limit to the mass for the unseen companion of ∼2 $M_\odot$ (for an inclination of ∼45°). However based on evolutionary considerations – specifically the requirements placed on the system mass ratio for merger to be avoided during interaction (Sect. 3.3) – we suspect the actual companion mass is significantly larger, with the consequent constraint that the binary is observed at low inclination.

As an *illustrative* example, an hypothetical 10 $M_\odot$ (WC9) + 20–30 $M_\odot$ (B0 – O7 V) binary observed at ∼30–10° would replicate the observed $K_{WC}$ = 32 km s$^{-1}$. A putative O7 V companion

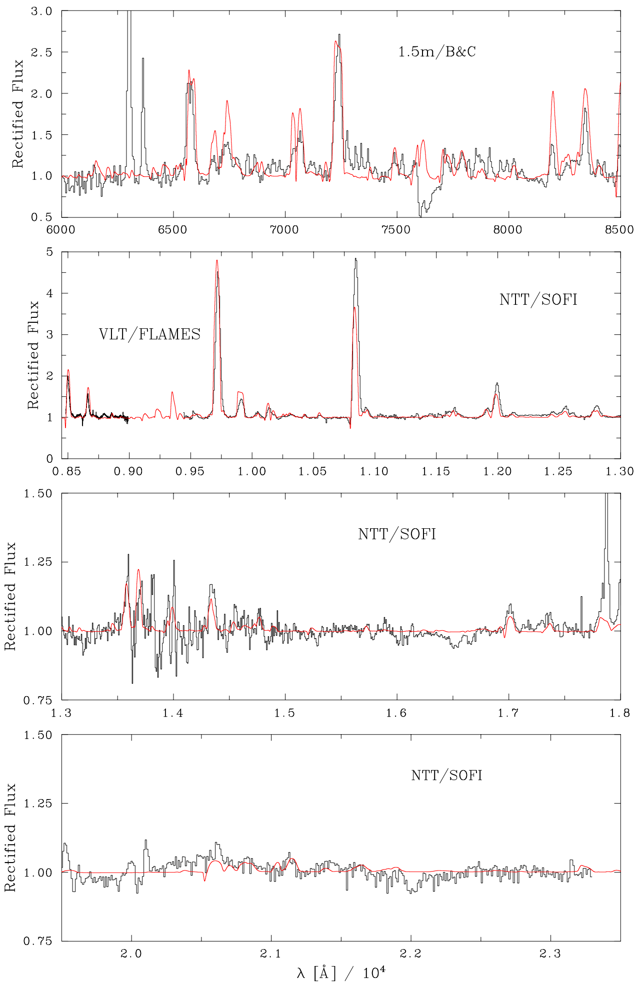


**Fig. 6.** Comparison of the rectified synthetic spectrum of W239 (red line) to observations (black line), acounting for the WC9 line dilution from the unseen companion and warm dust. Spectra were obtained in 2001 June (1.5 m/B&C), 2005 June (NTT/SofI) and 2008 July (VLT/FLAMES). Note the two emission features shortwards of 6500 Å are the result of incomplete sky subtraction; telluric contamination is also manifest in the observed spectrum beween ~7200–7400 Å, 1.35–1.50 $\mu$m and 1.77–1.8 $\mu$m.

would be consistent with our *assumption* that the WC9 primary and companion contribute equally at 8500 Å, while a fainter B0 V star would also satisfy this condition while also accommodating the presence of a tertiary companion of comparable spectral type. The resultant orbital separation of only ≤0.2 AU would then be an order of magnitude smaller than that of the archetypal dust producer WR140 ($P_{\rm orb}$ ~ 7.94 yr) during periastron. We emphasise that neither scenario represents an attempt to provide a fully self consistent model for the W239 system; a goal which must await future, stricter observational constraints.

Would such a putative binary be consistent with the current X-ray data for W239? In Table 5 we summarise the properties of known WC binary systems displaying phenomena associated with wind collision zones (X-ray and/or dust production). Unfortunately, no counterpart to an X-ray bright WC9 binary has yet been classified, although the WC8+O7.5 III binary WR11[3] suggests that companions of comparatively late spectral type may yield detectable X-ray emission in conjunction with WCL stars, although we note that this system in *not* a dust producer.

With $L_X$ ~ $2 \times 10^{32}$ erg s$^{-1}$, W239 is an order of magnitude fainter than WR11 (Clark et al. 2008), but is also a much more compact system. For the binary configuration described above, the orbital separation is only an order of magnitude larger than the stellar radii of the WC9 and O7 V stars (Martins et al. 2005); hence one would expect that neither wind will have reached terminal velocity at the position of the shock, likely reducing the resultant X-ray luminosity in comparison to WR11. Moreover, one might also expect radiative braking of the WR wind by the O star (cf. V444 Cyg, Owocki & Gayley 1995), further suppressing X-ray emission.

The X-ray observations of W239 were made in two blocks, one of 18 ks (~4% of orbit) on 2005 May 22 and 42 ks (~10% of orbit) on 2005 June 20, a separation of 5.8 cycles (Clark et al. 2008). No variability in flux was found within or between either observation. While X-ray variability as a function of orbital phase has been observed in WR11 (e.g. Schild et al. 2004) that system is observed at higher inclination, such that significant orbital variation in the wind properties and hence line of sight extinction are present, which would be absent for the putative low inclination configuration proposed here. Consequently, one can at least qualitatively understand the X-ray properties of W239, although quantitative confirmation would require a tailored hydrodynamical simulation, which currently appears unwarranted given the lack of observational constraints.

Finally, we briefly turn to the nature of the putative $P_{\rm orb}$ > 6 yr tertiary component suggested by the IR lightcurve. Unfortunately, the lack of contemporaneous spectroscopy over this period precludes any firm conclusions, save that a ≲O7 V or ~O9 III star are suggested by the twin constraints imposed by the age of Wd1 and the requirement of the star to support a substantive wind to permit dust production, noting that we might also expect such a star to contribute to the observed X-ray emission.

### 3.2. Dust production in close binaries

Our current IR observations are consistent with the hypothesis that hot dust is always present within the W239 system. Monnier et al. (1999) suggested that the subset of the persistently dusty WC stars were short orbital period (<1 yr) binaries, where dust formation occurs in long lived Archimedean spirals that result from high density material produced at the wind collision zone being carried outwards by a uniformly expanding wind until temperatures are low enough to permit condensation (Tuthill et al. 1999). With a ~5.05 day orbital period – comparable to that of HD 36402 in the LMC (Moffat et al. 1990; Williams 2011) and a factor of ~6 smaller than WR113[4], the next most

[3] The physical properties of the WC8 star in WR11 – $T_*$ = 57.1 kK, $\log(L/L_\odot)$ = 5.0, $\log(\dot{M}/\sqrt{f})$ = −4.53, $v_\infty$ = 1550 km s$^{-1}$ (De Marco et al. 2000) – are similar to those of W239, save for a faster wind. In contrast, earlier WC stars are significant hotter, more luminous and support winds with higher velocity and mass loss rates (Crowther et al. 2002).

[4] Two other dust WC9d stars – WR69 & 103 – have also been suggested to be short period binaries on the basis of periodic photometric variability. For the former star Marchenko et al. (1998) report a 2.29 day periodicity from Hipparcos data but are unable to determine its origin (binarity or NRP), although earlier observations by Balona et al. (1989) failed to identify this. Conversely, both the latter authors and Moffat et al. (1986) report a ~1.75 day photometric period for WR 103 which was not found in the Hipparcos dataset. Given the potentially transient nature of the periodicity in both stars and the lack of a confirmatory RV curve we regard the adoption of these periods as orbital in origin as premature.

**Table 5.** Summary of dusty WC binary properties (*upper panel*) and remaining X-ray detected binaries (*lower panel*).

| WR | Spectral type | $P_{orb}$ | $L_X$ ($10^{33}$ erg s$^{-1}$) | Period determinations | Reference |
|---|---|---|---|---|---|
| 77n/W239 | WC9vd+? | 5.053 ± 0.002 day | 0.4 | RV | This work |
| | | | | | Clark et al. (2008) |
| 19 | WC4pd + O9.6 | 10.1 yr | – | photometric | Veen et al. (1998) |
| 48a | WC8ed + ? | ~1 yr + >30 yr? | 100 | photometric (provisional) | Williams et al. (2003) |
| | | | | | Zhekov et al. (2010) |
| 65 | WC9d+? | "few years" | 0.1 | variable X-ray | Oskinova & Hamann (2008) |
| 70 | WC9vd + B0 I | 1045 ± 60 day | – | photometric | Williams et al. (2008) |
| 98a | WC8-9vd + ? | 564 ± 8 day | – | photometric + imaging | Monnier et al. (1999) |
| | | | | | Williams et al. (2003) |
| 104 | WC9pd + B0.5 V | 241.5 ± 0.5 day | – | imaging | Tuthill et al. (2008) |
| | | | | | Crowther (1997) |
| 112 | WC9d + ? | 24.8 ± 1.5 yr | – | imaging (provisional) | Marchenko et al. (2002) |
| 113 | WC8d+O8-9IV | ~29.707 day | – | RV | Massey & Niemela (1981) |
| 118 | WC9d + ? | ~60 day | – | imaging (provisional) | Millour et al. (2007) |
| 125 | WC7ed + O9 III | >4 yr | – | photometric (provisional) | Williams et al. (1994) |
| 137 | WC7ed + O9 | 13.05 ± 0.15 yr | – | RV + photometric | Williams et al. (2001) |
| | | | | | Lefevre et al. (2005) |
| 140 | WC7pd +O4-5 | 7.94 ± 0.03 yr | 5–12 | RV + photometric | Williams et al. (1990) |
| | | | | | Pollock et al. (2005) |
| | | | | | Zhekov & Skinner (2000) |
| HD 36402 | WC4(+O?)+O8 I | 3.03269 | – | RV | Moffat et al. (1990) |
| | | | | | Williams (2011) |
| 11 | WC8+O7.5III | 78.53 ± 0.01 day | 1.2–1.5 | RV | Schmutz et al. (1997) |
| | | | | | Schild et al. (2004) |
| 48 | WC5+O9.5/B0Iab | 19.138 ± 0.003 day | 1.0 | RV | Hill et al. (2002) |
| | (WC6+O6V) | | | | Oskinova (2005) |
| 79 | WC7+O5V | 8.8911 ± 0.0001 day | 0.05 | RV | Hill et al. (2000) |
| | | | | | Oskinova (2005) |

**Notes.** Column 5 summarises the origin of the orbital period, being derived from Radial Velocity data, periodicities in the photometric lightcurve, the motion of a pinwheel nebula (imaging) and/or a variable X-ray flux. In several cases (WR48a, 65, 112, 118 & 125) these are less robust and so are labeled as provisional. RV variations are also present in WR70 and are consistent with both short (~50 d) and long (~1200 d) periods. Note the discrepant classifications given for WR48 in Hill et al. (2002) and Oskinva (2005). Nazé (2009) report an X-ray detection of the WC7+O7/9 binary WR93 but no X-ray flux is given.

compact dust forming WC binary in the Galaxy – W239 potentially presents an ideal testbed for such a prediction.

Hydrodynamical simulations of the wind collision zones by Pittard (2009) indicate that coherent large scale Archimedean spirals may form in massive short period systems, although their properties are highly dependent on the binary separation. Specifically, the large scale wind structure of the most compact binary considered by Pittard (2009, $P_{orb}$ ~ 3 days) quickly fragmented, leading to a highly clumpy, inhomogeneous outflow. Could dust formation occur in such an environment? Unfortunately, ab initio simulations of such a process are not yet available and are certainly premature for W239. However, radiative transfer models of the wider ($P_{orb}$ ~ 241.5 day) binary WR104 of Harries et al. (2004) suggest that self shadowing from the dense inner regions of wind spiral strongly influences the temperature structure and hence location of dust condensation; it is unclear whether such a process would also operate in the fragmented wind spiral anticipated for W239, which in turn might be expected to affect dust production if the density at which the wind cooled to below the dust sublimation temperature was too low to permit dust grain growth.

In this regard we note with interest that a number of WC+O star CWBs with comparable periods are *not* dust producers[5] although these are all of earlier spectra type (WC4-7). One might speculate that the production of dust in W239 is a result of the softer radiation field of the WC9 primary when compared to these hotter stars, increasing the likelihood of survival of dust grains in this system, although the recent discovery of dust asociated with the LMC system HD 36402 (WC4(+O?)+O8 I, Williams 2011) potentially presents a counterarguement to this hypothesis.

### 3.3. W239 in an evolutionary context

#### 3.3.1. Possible binary pathways

With an orbital period of 5.05 days, W239 is one of the most compact WC binary system to have been unambiguously identified[6], although without dynamical mass estimates for both

[5] WR 9 (WC7+O5-8, $P_{orb}$ ~ 14.3 day; Niemela 1995), WR 42 (WC7+O7 V, $P_{orb}$ ~ 7.9 day; Hill et al. 2000), WR79 (WC5+O6, $P_{orb}$ ~ 8.9 day; Hill et al. 2000) and the LMC system HD 36521 (WC4+O6 V-III), $P_{orb}$ ~ 1.92 day; Moffat et al. 1990).

[6] In addition to those stars given in footnote 5, van der Hucht (2001) lists 3 further WC stars with shorter periods – WR 14, 50 & 86 – in all cases solely determined from photometry with no corrobarative RV data. As the author cautions, the dataset present by Shylaja (1990) for WR 14 is insufficient to derive a period and so its identification as a binary is highly uncertain. Likewise Veen & Wieringa (2000) cast serious doubt upon the photometric variability suggested for WR 50 by van Genderen et al. (1991). Finally, Paardekooper et al. (2002) show that the periodicity associated with WR86 is instead attributable to a $\beta$-Cephei companion.

components we may not yet produce a tailored evolutionary history for it. However following the arguements of Petrovic et al. (2005a), Cantiello et al. (2007) and De Mink et al. (2009) we may conclude that it must have been born in a particularly compact configuration, although none of the systems simulated by these authors have such a short orbital period when the primary becomes a WR star ($P_{orb} \geq 6$ days), still less once subsequent mass loss has led to a WC phase and caused the orbit to widen. Nevertheless, the WN7o+? $P_{orb} \sim 3.51$ day eclipsing binary WR B (Bonanos 2007) clearly demonstrates that suitable progenitor systems for W239 are present within Wd 1.

For evolutionary scenarios invoking non-conservative mass transfer (e.g. Petrovic et al. 2005a; Cantiello et al. 2007), increasing the initial orbital period of the progenitor O+O binary results in a progressively more compact WR+O MS configuration. However, above a critical period and after the transfer of ~50% of the envelope mass of the primary, the orbit widens and the mass transfer rate increases to the point where the secondary also expands to fill its Roche lobe (Wellstein et al. 2001). Adopting a standard common envelope prescription at this point, unpublished simulations by Wellstein (2000) found that a 16 + 15 $M_{\odot}$, $P_{orb} \sim 8$ day MS binary evolves to a 5+20 $M_{\odot}$, $P_{orb} \sim 1.8$ day configuration. Comparable simulations with improved input physics are currently being undertaken by Schneider et al. (in prep.), and although a higher mass progenitor would be required (e.g. 30...40 $M_{\odot}$ for a current mass of ~10 $M_{\odot}$) such a common envelope pathway appears promising for the production of W239.

As an alternative to binary evolution driven by mass transfer we also highlight the Case M(ixing) evolutionary pathway of De Mink et al. (2009). In this scenario – applicable to close, massive tidally locked binaries – rapid rotation leads to efficient rotational mixing and hence chemically homogeneous evolution. This results in the stars evolving directly to the WR phase, while remaining within their Roche Lobes. As with the above pathways, once the primary becomes a WR star, wind driven mass loss causes the initially compact orbit to widen. However, given that we anticipate progenitor and current masses of ~40 & 10 $M_{\odot}$ for the WC9 component of W239, we might expect the orbital period to have widened from an initial value of 1.5...2.5 days to beyond the observed ~5.05 days, although confirmation of this would require tailored modeling.

What implications do these scenarios have on the mass of the 5.05 day binary companion? Case B evolution leading to a common envelope phase leads to merger for low secondary masses, suggesting that it must be rather massive. From the unpublished thesis work of Wellstein (2000) a time averaged mass transfer efficiency of ~50% was found for the 16 + 15 $M_{\odot}$ binary considered. If this is applicable to higher mass systems such as W239 we estimate that a ~40 + 38 $M_{\odot}$ system would result in a current ~15 + 50 $M_{\odot}$ configuration, which we may exclude on observational grounds. For lower initial mass ratios one would expect the mass transfer efficiency to be reduced (e.g. Petrovic et al. 2005a) and so one could anticipate a ~40 + 20 $M_{\odot}$ system evolving into a ~15 + 25 $M_{\odot}$ WR+MS system, broadly consistent with our current observational data. Weaker constraints on the mass of the binary companion are obtained for a case M evolution, but are expected to be in the range ~10–38 $M_{\odot}$, although masses in the upper reaches of this range are again likely to be excluded on observational grounds. Nevertheless, while tailored numerical modeling is required to confirm these estimate, it appears highly likely that the binary companion of W239 is massive enough to generate a wind collision zone and support dust production.

#### 3.3.2. Evolutionary pathways in Wd1

Even if we are unable to provide a unique evolutionary scheme for W239, such pathways are of particular interest given that Wd 1 appears to host a number of compact WR binary systems; W239 being the third following WR B (WN7o+?) and W13 (WNVL+OB). To these we might also add, albeit with less certainty, W44 (WR L; WN9h) – which showed rapid, dramatic line profile variability for which binarity is the most compelling explanation (Clark et al. 2010) – as well as the progenitor of the magnetar CXOU J164710.2-455216 (Ritchie et al. 2010a).

However, Wd1 1 also contains a significant population of cool supergiants – 10 Yellow Hypergiants (YHGs) & Red Supergiants (RSGs) – and a further 3 cool B hypergiants transiting to/from such a phase (Clark et al. 2005, 2010). Due to their intrinsic luminosity, these stars have such a large physical extent (e.g. ~2000 $R_{\odot}$ for the RSG W26 assuming an intrinsic luminosity of $\log(L/L_{\odot}) \sim 5.8$) that any putative companion must be in such a wide orbit that it could not influence their evolution.

Consequently, given the apparent coevality of Wd 1, the twin hypergiant and short period WR binary populations provide compelling evidence for the presence of two distinct evolutionary pathways for ~30–40 $M_{\odot}$ stars. The first, experienced by single stars and long period binaries is predicted by current evolutionary theory (e.g. Meynet & Maeder 2003) and results in a post-Main Sequence red loop across the H-R diagram:

*Single channel:* O6-7 V → O8-9 III → O9-B1 Ia → B5-9 Ia$^{+}$/YHG → RSG → B5-9 Ia$^{+}$/YHG/LBV → WN → WC[7] → SN + production of black hole.

The second, experienced by short period binaries avoids the red loop due to binary driven mass transfer:

*Binary channel:* O6-7 V + OB V → WNLh + OB III-V (e.g. W13[8]) → WNo + OB III-V (e.g. WR B) → WC + OB III-V (e.g. WR F) → SN + production of neutron star.

where one would predict that the wider the initial binary separation, the further through a red loop the primary travels before the onset of mass transfer curtails it.

The pre-SN evolutionary pathway followed also plays a significant role in determining the nature of the post-SN relativistic remnant. If binary driven mass loss removes the H-rich mantle in – or shortly after – the main sequence, the He-rich core is exposed for a longer period of time than in single star evolution, allowing the enhanced WR mass loss rates to act for longer. This results in a lower pre-SN core mass and hence the likely formation of a neutron star rather than a black hole (Fryer et al. 2002) as appears to be the case in Wd1 (Clark et al. 2008; Ritchie et al. 2010a). In contrast, a single star will retain its H-rich mantle for longer, be subject to WR mass loss rates for a shorter period of time and will likely yield a Black Hole in the mass range considered here (e.g. Wellstein & Langer 1999).

Finally case M evolution, which occurs in very compact systems (1.5...2.5 days, De Mink et al. 2009) and proceeds without

[7] We note that the WC8 star WR K appears to be single, being amongst the faintest of the WRs within Wd1 and demonstrating no evidence of RV binary reflex motion, an IR excess from dust emission or X-ray emission. Hence it appears that single stars with progenitor masses ~40 $M_{\odot}$ (Ritchie et al. 2010a) can also evolve through a WC phase prior to SNe.

[8] With a period of ~9.27 days W13 will *not* evolve into a comparable configuration as WR B & F since stellar wind losses will drive it to longer periods.

significant binary driven mass-loss is thought to lead to rather massive pre-SNe core masses and the consequent formation of a high mass black hole.

#### 3.3.3. Wider implications

It therefore appears that in addition to initial mass, metallicity and rotational velocity, binarity plays a key role in the evolution of massive stars. If correct, what are the consequences of such an hypothesis? Firstly it may help to resolve the difficulties in reconciling the current post-MS stellar population of Wd 1 to evolutionary predictions. Crowther et al. (2006a) highlight this problem – specifically that the ratio of WC/WN and WN(H-rich)/WN(H-poor) WRs are discrepant – and indeed advance binarity as a possibly ammeliorative factor.

Secondly, the operation of two parallel evolutionary channels would suggest that extrapolating the cluster binary fraction from the Wolf-Rayet population may be in error. If this were the case then one might expect the binary fraction of the unevolved O Main Sequence/Giants to be lower than that inferred for the WRs; our full multiobject spectroscopic dataset (Ritchie et al. 2009) will allow us to test this assertion.

Beyond Wd 1, if proven, this hypothesis will have significant impact on the determination of ages and integrated masses of star forming regions. As an example we consider the star formation region recently detected at the base of the Scutum-Crux arm and delineated by at least four red supergiant clusters (Figer et al. 2006; Davies et al. 2007; Clark et al. 2009; Negueruela et al. 2010a). Given that extinction has prevented the identification of the Main-Sequence of each cluster, their masses have been determined via comparison of the number of RSGs to evolutionary predictions. If a proportion of massive stars instead avoid this phase via close binary evolution then integrated cluster masses and consequently star formation rates may be (substantially) underestimated (Davies et al. 2009). However, as a corollary one might also expect a population of (underluminous) WR stars produced via the binary channel, which have yet to be identified.

Indeed, the significance of a close binary pathway in massive stellar evolution has already been highlighted by a number of authors. Brinchmann et al. (2008) found that binary evoluton is necessary to replicate the observational properties of Wolf-Rayet galaxies at low metalicities. Moreover Smith et al. (2010) argue that the observed fraction of Type Ibc and IIb SNe requires a large proportion of their progenitors to have evolved via close binary evolution and mass stripping via Roche Lobe overflow, while Cantiello et al. (2007) demonstrate the role such a channel will play in the production of GRBs in lower metallicity environments. Finally, as implied by the discussion above, the prevalence of this pathway will also profoundly influence the production rate and properties of both intermediate- and high-mass X-ray binaries as well as binary pulsars (e.g. Kobulnicky & Fryer 2007).

## 4. Conclusions

We have analysed multi-epoch spectroscopy and photometry of the WC9d star W239, which reveal it to be a binary with a 5.05 day period. Non-LTE modeling indicates that the parameters of the primary are fully comparable to those of other Galactic WC9 stars. Inspection of the spectral energy distribution of W239 indicates the presence of hot (~1300 K) dust which, from the long term near-IR lightcurve appears to be present at all epochs. These observations reveal substantial variability, with a significant near-IR "flare" between 2004-6 that is best understood as a transient increase in the dust production rate resulting from the periastron passage of a massive tertiary companion in a wide, eccentric orbit.

The combination of the current stellar census of Wd1 and the requirement that they support strong stellar winds constrains both secondary and tertiary components to be stars of spectral type >O7-8 V or O8-9 III. Such classifications are consistent with the assumptions made during our non-LTE model atmosphere analysis, while our tentative identification of a Pa12 photospheric line suggests the presence of at least one O7-9 V-III star within the W239 system.

W239 has one of the shortest orbital periods yet determined for *any* WC star. This finding leads to several important conclusions. Firstly, it suggests that dust production in WC stars can occur over all binary separations and is not restricted to long period systems, fully consistent with the hypothesis that the persistent dust producing systems are all short period binaries. Future RV observations of the complete dusty WC population within Wd 1 will test this scenario.

Secondly, W239 is the third short period WR binary identified within Wd 1. The compact nature of these systems implies that they must have evolved from massive, short period progenitor systems; likely via non-conservative mass transfer while still on the main sequence, or shortly thereafter. In doing so they would have avoided the post-main sequence red-loop that results in the formation of the cool YHGs and RSGs that are present within Wd 1. We therefore conclude that there is compelling evidence for the presence of two parallel evolutionary pathways for massive ~30–40 $M_{\odot}$ stars within Wd 1, depending on their binary properties (specifically their orbital separation). In combination with our current RV survey on OB stars, an extention to include all remaining WRs with Wd 1 scheduled for summer 2011 will enable us to determine the relative weighting of each channel. *Consequently, the co-eval stellar population within Wd 1 may prove critical in determining whether binarity plays as significant a role in the evolution of massive stars as their initial mass, chemical composition and rotational velocity are thought to.*

If this is the case, it will have important consequences for the nature of both GRB and SNe progenitors as well as the subsequent production of relativistic objects – such as the Wd 1 magnetar – and X-ray binaries. Moreover, this evolutionary bifurcation will need to be incorporated into population synthesis codes used to infer the properties of stellar aggregates both in our own and external galaxies; for example, mass determinations for the RSG-rich clusters at the base of the Scutum-Crux arm may currently be significantly underestimated due to this omission. Finally, one might speculate that if binaries are predominantly formed via dynamical capture in stellar aggregates, rather than being primordial, then massive stellar evolution may be partially dependent on environment, with denser regions leading to higher capture probabilities and hence enhanced evolution via the close binary channel.

*Acknowledgements.* J.S.C. acknowledges support from an RCUK fellowship. This research is partially supported by the Spanish Ministerio de Ciencia e Innovación (MICINN) under grants AYA2008-06166-C03-03, AYA2010-21697-C05-05 and CSD2006-70 and based upon observations made at the Pico dos Dias Observatory (LNA/MCT). We wish to thank the referee, Peredur Williams, for his comments which greatly improved the paper and Julian Pittard for his valuable input into understanding the likely properties of the wind collision zone in W239.

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