

A VLT/FLAMES survey for massive binaries in Westerlund 1

VI. Properties of X-ray bright massive cluster members[★]

J. S. Clark¹, B. W. Ritchie^{1,2}, and I. Negueruela³

¹ School of physical sciences, The Open University, Walton Hall, Milton Keynes MK7 6AA, UK
e-mail: s.clark@open.ac.uk

² Lockheed Martin Integrated Systems, Building 1500, Langstone, Hampshire PO9 1SA, UK

³ Departamento de Física Aplicada, Facultad de Ciencias, Universidad de Alicante, Carretera San Vicente del Raspeig s/n, 03690 San Vicente del Raspeig, Spain

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ABSTRACT

Context. X-ray emission from massive stars was first reported four decades ago, but the precise physics governing its formation as a function of stellar properties and binarity remains not fully understood. With the recent suggestion that such objects may be important sites of cosmic ray production, a better understanding of their high-energy properties is particularly timely.

Aims. The young massive cluster Westerlund 1 provides an ideal testbed for understanding this emission, with over 50 cluster members detected in historical X-ray observations. In the decade since these data were obtained, significant new multi-epoch observations of the cluster have been made, allowing a fundamental reappraisal of the nature of both X-ray bright and dark stars.

Methods. Optical spectroscopy permits accurate classification of cluster members, while multi-epoch observations of a sub-set allow identification and characterisation of the binary population.

Results. A total of 45 X-ray sources within Wd1 now have precise spectral classifications. Of these, 16 have been identified as candidate or confirmed massive binaries. X-ray emission is confined to O9-B0.5 supergiants, Wolf-Rayets and a small group of highly luminous interacting/post-interaction OB+OB binaries. Despite their presence in large numbers, no emission is seen from earlier, less evolved O stars or later, cooler B super-/hypergiants. A total of 22 stars have X-ray properties that are suggestive of a contribution from emission originating in a wind collision zone.

Conclusions. We suppose that the lack of X-ray emission from O giants is due to their comparatively low intrinsic bolometric luminosity if, as expected, they follow the canonical L_X/L_{bol} relation for hot stars. The transition away from X-ray emission for OB supergiants occurs at the location of the bistability jump; we speculate that below this limit, stellar wind velocities are insufficient for internal, X-ray emitting shocks to form. Our results are consistent with recent findings that massive binaries are not uniformly brighter than single stars of comparable luminosity or spectral type, although it is noteworthy that the brightest and hardest stellar X-ray sources within Wd1 are all either confirmed or candidate massive, interacting/post-interaction binaries.

Key words. binaries: general – stars: early-type – stars: Wolf-Rayet – stars: winds, outflows – X-rays: stars

1. Introduction

Since the advent of X-ray astronomy hot, massive stars have been recognised as important sources of emission (e.g. Seward et al. 1979), with the realisation that O stars obeyed an empirical X-ray/bolometric luminosity relation – $L_X \sim 10^{-7} L_{\text{bol}}$ – quickly following (Long & White 1980; Seward & Chlebowski 1982). The consensus view holds that this emission arises in hot shocked material embedded in a cooler bulk stellar wind as a result of the line driving instability inherent in radiatively driven winds (Lucy & White 1980; Feldmeier et al. 1997), with the temperature of shocked material consistent with the soft ($kT \sim 0.6$ keV) X-ray spectra of the majority of hot stars. A sub-set of hot stars are found to be significantly brighter and/or harder than these canonical sources; such emitters are typically found to be massive binaries, where it is thought that additional emission arises in shocked material in a wind collision zone (WCZ; cf. Stevens et al. 1992; Pittard & Dawson 2018 and references therein).

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However the L_X/L_{bol} relationship appears to break down for stars of spectral type B0-2 and later, which are found to be significantly fainter than predicted (Cassinelli et al. 1994; Berghöfer et al. 1997). Likewise Wolf-Rayet (WR) stars also diverge from this correlation, with (moderate) emission dependant on sub-type and binarity (e.g. Oskinova 2016a; Sect. 3). Unfortunately, the physical basis for the L_X/L_{bol} relationship is currently uncertain, making such observational findings difficult to interpret. Analysis by Owocki & Cohen (1999) suggests that X-ray emission driven by shocks should be sensitive to the wind density parameter (\dot{M}/v_{wind}) rather than to L_{bol} (although in practice the former will be somewhat sensitive to the latter). Sciortino et al. (1990) show a correlation between X-ray luminosity and the total wind momentum flux, while Nebot Gómez-Morán & Oskinova (2018) also find that emission scales with wind properties for main sequence and giant O stars.

Given that the X-ray flux may change the ionisation balance of the wind and hence affect mass loss determinations, an understanding of the production mechanism and its relation to underlying wind and stellar parameters is clearly required; especially since determination of the wind properties of massive stars

is essential if one it to constrain their evolution and feedback into their immediate environment. Moreover it has been suggested that the (interacting) winds of massive single and binary stars may serve as sources of cosmic rays, accelerating protons to PeV energies (e.g. [Cesarsky & Montmerle 1983](#); [Bednarek et al. 2014](#); [Aharonian et al. 2019](#)); consequently understanding the physics and prevalence of such wind interaction zones via the X-rays they emit is important if we are to verify this hypothesis.

2. Motivation, methodology and results

The above empirical results derive from surveys of ensembles of field stars (e.g. [Berghöfer et al. 1997](#); [Oskinova 2005](#); [Nebot Gómez-Morán & Oskinova 2018](#)) and targeted observations of star clusters and star forming regions ([Sana et al. 2006](#); [Nazé et al. 2011](#); [Rauw et al. 2015](#)). The former benefits from large sample sizes that span a range of spectral types but fundamental stellar properties and evolutionary status can be difficult to determine. Conversely, while the distance to, and ages of, stars within clusters can be well constrained, sample sizes are typically relatively small; this may be alleviated by studying OB associations, although such aggregates demonstrate complex, extended star formation histories.

The young, massive cluster Westerlund 1 offers a uniquely rich and co-eval population of massive stars which, unlike galactic centre clusters such as the Quintuplet and Arches, may be readily resolved by extant X-ray instrumentation ([Clark et al. 2005](#); [Negueruela et al. 2010](#); [Kudryavtseva et al. 2012](#)). Moreover, it has been identified as the source of highly energetic γ -rays (GeV and TeV; [Ohm et al. 2013](#) and [Abramowski et al. 2012](#), respectively) and consequently has been implicated in the production of cosmic rays (e.g. [Bykov et al. 2015](#); [Aharonian et al. 2019](#)), providing a powerful motivation for understanding of the nature of the X-ray emitting stellar cohort.

[Clark et al. \(2008\)](#) found a total of 53 X-ray sources that appeared to be associated with the massive stars and presented spectral classifications for half of these. However, since this study, classifications have become available for 166 cluster members (cf. [Negueruela et al. 2010](#), [Clark et al.](#), in prep.) and so it seems opportune to revisit this dataset. In total we are now able to provide classifications for 45 X-ray detections, in part comprising 19 new objects and reclassification of a further 13 stars. Moreover the binary status of 22 X-ray bright cluster members have been investigated via our VLT/FLAMES radial velocity (RV) survey ([Ritchie et al. 2009a, 2010a](#), [Clark et al.](#), in prep.), with VLT/UVES observations available for two further stars (Wd1-27a and WR L; [Clark et al. 2019](#), and in prep.); relevant data reduction and analysis techniques are described in these works.

These yield binary RV periods for Wd1-13, WR F and L, while [Bonanos \(2007\)](#) reports photometric periods for Wd1-6a, -36, -53 and WR A and B¹; these eight systems therefore appear to be unambiguous binaries (Table A.1). The optical spectrum of Wd1-10 in [Clark et al. \(2008\)](#) demonstrates a double-troughed He I 7065 Å photospheric line that is indicative of a SB2 classification and one epoch of our *I*-band observations clearly confirms this hypothesis (Fig. 1). Intriguingly, in

the remaining epochs Wd1-10 has the appearance of a single star, suggesting that it may be a highly eccentric system with the double lined spectrum fortuitously obtained at periastron. For the purpose of this paper we therefore consider it a bona fide binary (cf. Fig. 2).

Wd1-24, -30a and W1040 are found to be RV variable at a level indicative of binarity, although no unique period may be identified for any object in the current datasets ([Clark et al. 2010, 2019](#), and in prep.). Additional variability is observed in the C III 8500 Å/Pa-16 blend of the first two systems, suggesting the presence of a second O star of similar luminosity ([Clark et al. 2010](#)). W1041 demonstrates very broad, flat-bottomed photospheric Paschen-series lines that are indicative of an unresolved blend of two stars of comparable luminosities, an hypothesis bolstered by the morphologically identical spectra of the photometrically confirmed binaries Wd1-36 and -53a (Fig. 1; [Bonanos 2007](#)). We therefore conclude that all four stars are compelling binary candidates, although not yet unambiguous classifications in the manner of the preceding nine systems.

Several authors have suggested that supergiant B[e] stars are massive (post-) interacting binaries ([Kastner et al. 2010](#); [Clark et al. 2013a](#)) and two additional lines of evidence suggest that this is the case for Wd1-9. Specifically radio- and mm-continuum observations reveal the presence of a bipolar outflow with a velocity and mass-loss rate that is inconsistent with expectations for a radiatively driven wind from a single supergiant or Wolf-Rayet ([Fenech et al. 2017, 2018](#)). However the mass-loss rate is comparable to predictions for mass-transfer from the primary in a compact binary undergoing rapid case-A evolution ([Petrovic et al. 2005](#)). Likewise, the presence of forbidden [O IV] emission in the mid-IR spectrum of Wd1-9 requires either stellar temperatures in excess of those expected for single OB supergiants (≥ 60 kK; [Clark et al. 1998, 2013b](#)) or shock excitation, which would naturally arise in the WCZ of a massive interacting binary. The non-thermal radio continuum spectrum of Wd1-17 and the association of hot dust with the WC9 star WR N are likewise indicative of binarity for these stars ([Clark et al. 2008](#); [Dougherty et al. 2010](#)). Hence we conclude that these three cluster members are likely to be binaries, yielding a total of 16 confirmed and candidate binaries associated with X-ray emission.

Finally we briefly consider Wd1-65 and -232. Wd1-65 (O9 Ib) appears to be a low level RV variable with an *I*-band spectrum suggestive of binarity; while the Paschen lines are typical of lower-luminosity O9 stars, the C III/Pa-16 blend appears anomalously broad and weak (cf. Fig. 1). Likewise, the star seems rather too luminous for its implied early spectral type ([Clark et al.](#), in prep.). Erroneously listed as W234 in [Ritchie et al. \(2009a\)](#) Wd1-232 (O9.5 Ib) is a clear RV variable, albeit of low amplitude. As a consequence period fitting failed to yield a unique value, with multiple possible short periods (<10days) returned. However, significant scatter is present in the RV curve when folded onto any of these periods and hence the nature of this object remains unclear, with either complex pulsational modes or a combination of pulsational and orbital periodicities possible explanations for the RV variability ([Ritchie et al. 2009a](#), [Clark et al.](#), in prep.). We therefore refrain from listing these stars as strong binary candidates at this time, pending further observations.

We present the new and revised spectral classifications for the 45 X-ray sources in Table A.1, along with information on binarity and basic X-ray properties. Following [Clark et al. \(2008\)](#), Fig. 2 summarises the spectral properties and fluxes of these sources as a function of spectral type and binarity. Using the Portable

¹ For reasons of space and legibility we have abbreviated the Simbad recognised nomenclature; the formal forms being Cl* Westerlund 1 Wxx for those stars listed in [Westerlund \(1987\)](#) and Cl* Westerlund 1 CN x for the Wolf-Rayet cohort. Star designated W1xxx are new cluster members presented in [Clark et al.](#) (in prep.) and are ordered by increasing right ascension.

Table 1. Stellar demographics of X-ray sources within Wd1.

Spectral type	Cluster population	X-ray detected
O9-9.5 III	27	1
O9-9.5 II,II-III	12	1
O9-9.5 Iab,Ib	30	19
B0-0.5 Ia,Iab,Ib	23	6
B1-1.5 Ia,Iab	10	0
B2-4 Ia	7	0
B5-9 Ia ⁺	4	0
LBV	1	0
YHG+RSG	10	0
O4-8 Ia ⁺	2	2
B0-2Ia ⁺ /WNVL	4	2
sgB[e]	1	1
OB SB2	2	2
WN5-8	14	8
WC8-9	8	3

Notes. Summary of X-ray detections by spectral type. The top panel reflects the expected evolutionary pathway for single stars, the second the possible products of binary interaction and the third WRs – a structure chosen to reflect the discussion in Sect. 3. We note that the marginal X-ray detections discussed in Sect. 3.4 are not included here. The X-ray detections Wd1-13, W1033 and Wd1-232 are included with the B0-2Ia⁺/WNVL, O9-9.5 II-III and B0-0.5 Ia,Iab,Ib sub-sets, respectively. The OB2 SB2 grouping comprises the optically and X-ray luminous systems Wd1-36 and -53a. A further ten optically faint O+O binaries of uncertain spectral type and luminosity class are excluded from the table, as is the sole Be star; none of these are X-ray detections.

Multi-Mission Simulator (PIMMS)² and XSPEC, we simulated the colours and fluxes produced by a thermal plasma spectrum absorbed by a column equivalent to $2 \times 10^{22} \text{ cm}^{-2}$ of H - appropriate for the mean extinction to the cluster (Negueruela et al. 2010), following the relationship of Predehl & Schmitt (1995) – for a range of temperatures and intrinsic luminosities (0.5–8.0 keV, assuming a distance of 5 kpc). The resulting grid is overplotted on Fig. 2 to aid in the interpretation of individual sources. Finally Table 1 summarises the stellar demographics of the X-ray emitting cluster population.

3. The nature of the emitters

Table 1 clearly summarises the first of two major findings of this work; X-ray emitters are found to be confined to very limited sub-sets of cluster members. The lack of emission amongst the cool stellar cohort had already been recognised (Clark et al. 2008), but despite the increase in numbers of B5-9 Ia⁺ and B2-4 Ia stars (11 versus 6) and the identification of ten new B1-1.5 Ia,Iab stars, none are detected; consistent with the findings of e.g. Cassinelli et al. (1994) and Berghöfer et al. (1997)³. Instead emission appears concentrated amongst the O9-O9.5 Iab,Ib and B0-0.5 Ia,Iab,Ib supergiants (25 from 53) with earlier spectral types within this range clearly favoured (Table 1). Of the 39

² <https://heasarc.gsfc.nasa.gov/docs/software/tools/pimms.html>

³ Cazorla et al. (2014) and Oskinova et al. (2017) report strong X-ray emission for the B3-4 Ia⁺ star Cyg OB2 #12 (Clark et al. 2012), which they attribute to putative binarity. None of the six B3-9 super/hypergiants within Wd1 are found to be X-ray detections, nor do any show signs of binarity.

lower luminosity O9-9.5 II,II-III,III stars only W1033 (O9-9.5 I-III) and W1050 (O9 III) are detected (with the former having an uncertain luminosity class). The remaining X-ray emitters appear to comprise a number of interacting/post-interaction OB+OB binaries and a sub-set of the cluster WRs; we anticipate a significant overlap between these latter cohorts, in the sense that a number of WRs are likely post-interaction systems.

3.1. O9-B0.5 supergiants

We expect individual OB supergiants within Wd 1 to have $\sim 30\text{--}40 M_{\odot}$ progenitors and hence $L_{\text{bol}} \sim 3\text{--}5 \times 10^5 L_{\odot}$ after ~ 5 Myr (Clark et al. 2005; Negueruela et al. 2010; Ritchie et al. 2010b). Assuming $L_X \sim 10^{-7} L_{\text{bol}}$ this would imply $L_X \sim 1.2\text{--}2 \times 10^{32} \text{ erg s}^{-1}$. The OB supergiant detections have X-ray fluxes broadly consistent with this prediction (Fig. 2)⁴. Due to the low count rates, uncertainties on the hardness colour are large for photon fluxes $< 10^{-6} \text{ cm}^{-2} \text{ s}^{-1}$. Nevertheless, eight of the 27 OB SG detections have a hardness colour deviating from ~ -0.5 by $\geq 1\sigma$; appropriate for shock-heated material within single O star winds ($\sim 0.6 \text{ keV}$; Feldmeier et al. 1997).

An obvious explanation for these harder sources would be emission from hot shocked gas in a WCZ in a massive binary (but see below). Of the eight, Wd1-24 and W1041 are strong binary candidates, with tentative evidence for binarity for Wd1-65. W1036 and W1055 show no indication for binarity in our RV data, while Wd1-47, -56b and W1064 have yet to be subject to RV monitoring, but are not SB2s. If future observations were to confirm binarity for Wd1-65 and the latter three objects, one would suspect that W1036 and W1055 are also binaries seen at an unfavourable inclination for identification via RV shifts.

Given their less evolved status, and hence lower bolometric luminosities, one might suppose that both W1051 (O9 III) and W1033 (O9-9.5 I-III) might also be (X-ray overluminous) binaries, but no evidence for this has been found in our RV data. While we cannot rule out binarity, Nebot Gómez-Morán & Oskinova (2018) find a large scatter in the L_X/L_{bol} relation and, if their classifications are correct, these two stars may simply be the brightest examples of their evolutionary phase within Wd1.

It is notable that a number of binaries with primaries spanning spectral types O9-B4 and luminosity class I-III – for example Wd1-43a (B0 Ia +? and $P_{\text{orb}} \sim 16.27\text{d}$; Ritchie et al. 2010a) and Wd1-52 (B1.5Ia +? and $P_{\text{orb}} \sim 6.7\text{d}$; Bonanos 2007) – are not detected as X-ray sources. Moreover, binaries such as Wd1-6a (B0.5 Iab +? and $P_{\text{orb}} \sim 2.20\text{d}$; Bonanos 2007) and Wd1-10 (B0.5 I +OB; Negueruela et al. 2010) have X-ray luminosities and hardness colours that are directly comparable to those of apparently single stars of similar spectral type (e.g. Wd1-62a (B0.5 Ib) and W1005 (B0 Iab); Fig. 2). These findings are consistent with a number of recent observational studies which indicate that, contrary to historical expectations, the majority of binaries do not generate excess hard X-ray emission (e.g. Oskinova 2005; Nazé 2009; Rauw et al. 2015; Nebot Gómez-Morán & Oskinova 2018). Instead, they follow the same canonical $L_X \sim 10^{-7} L_{\text{bol}}$ relation as single stars, suggesting that the bulk of the emission arises in the stellar winds of the individual stars, rather than in WCZs.

The lack of X-ray detections amongst the non-supergiant O-star binary population of Wd1 (Clark et al., in prep.) would

⁴ Unfortunately, the 90% completeness limit for a 0.6 keV emitter is $2 \times 10^{32} \text{ erg s}^{-1}$ (assuming $d = 5 \text{ kpc}$ and $N_{\text{H}} = 2 \times 10^{22} \text{ cm}^{-2}$), hence we are likely incomplete for emission from single OB supergiant stars.

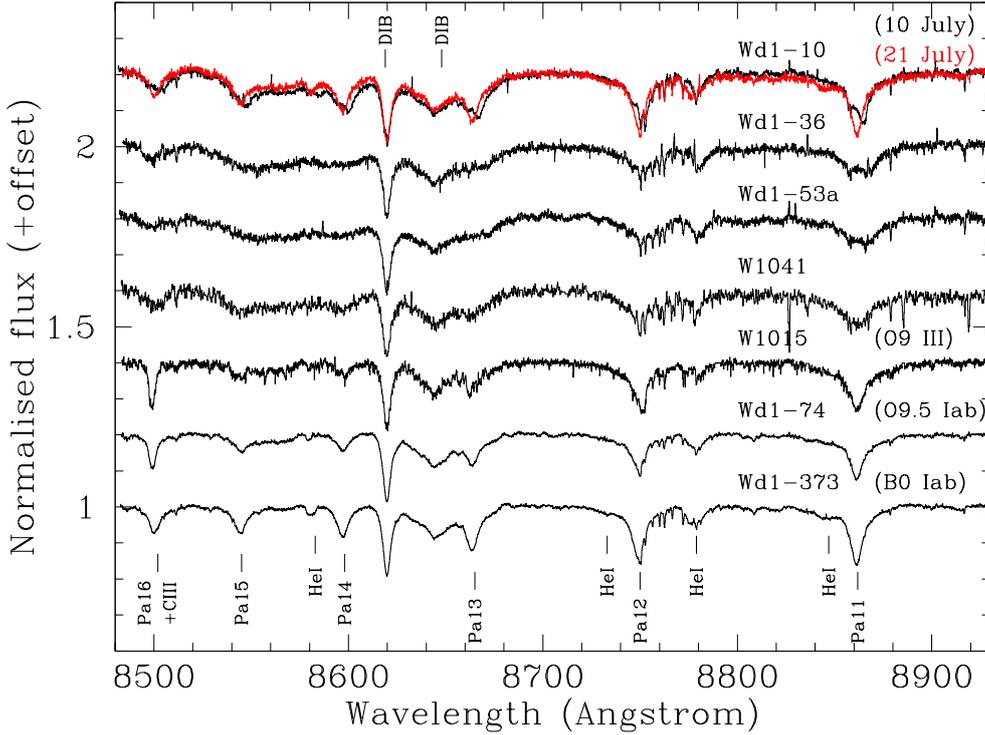


Fig. 1. Montage of classification spectra (Wd1-74, -373 and W1015) and apparent SB2 binaries. Note the shallower, flat-bottomed photospheric profiles for Wd1-36, 53a and W1041 in comparison to the templates, indicative of unresolved SB2 systems. Two spectra are presented for Wd1-10 to demonstrate the pronounced line profile variability in the Paschen-11 and -12 photospheric lines, which transition from doubled- to single-troughed in the 11 days between the observations.

be consistent with this hypothesis; presumably both components in such systems support rather weak winds in comparison to the supergiant cohort, such that they are neither intrinsically X-ray luminous nor can generate excess emission in a WCZ. Similarly, an obvious explanation for the absence of spectral features from the secondary in SB1 binaries such as Wd1-6a, 43a and -52 is that they are less luminous and evolved stars supporting comparatively weak winds. Consequently a WCZ is either weak or absent, resulting in the detectability of the system being solely dependant on the nature of the primary. This would naturally explain the similarity of Wd1-6a to X-ray bright single O supergiants such as Wd1-38 and -62a (see also Sect. 4.2), while the lack of detections for Wd1-43a and -52 (and single stars of comparable spectral type and luminosity class) would result from a combination of the significant intrinsic scatter in the L_X/L_{bol} relation (Nebot Gómez-Morán & Oskinova 2018) and incompleteness (cf. footnote 4). Clearly, deeper observations would help resolve this issue.

However, the properties of Wd1-10 are more challenging to interpret, given that the presence of double troughed He I and Paschen series lines (Fig. 1; Negueruela et al. 2010) clearly requires the secondary to be of comparable luminosity to the B0.5 Ia primary. As such it appears similar to a number of other SB2 binaries within Wd1 (e.g. Wd1-13, -24, -36 and -53a); however these are brighter and/or harder X-ray sources than Wd1-10 (Sect. 3.2). The most obvious explanation for this discrepancy is that Wd1-10 is a highly eccentric system (cf. Sect. 2) yielding an orbital dependence for X-ray luminosity and spectral shape and that our X-ray observations happened to catch the binary at a phase where emission from a WCZ is minimal/absent.

3.2. Interacting and post-interaction OB binaries

As summarised in Rauw & Nazé (2016), the weight of observational evidence increasingly suggests that the X-ray properties of many massive binaries do not deviate from those of single stars. However this conclusion does not hold for all binaries,

with η Carina being an exemplar in which orbital modulation of the WCZ leads to substantial variability in the X-ray spectrum and overall luminosity (e.g. Corcoran et al. 2017 and references therein). Indeed Wd1 contains a number of massive interacting and post-interaction systems that are found to be anomalously hard and/or luminous in comparison to the late-O/early-B supergiants discussed in the preceding section (Fig. 2).

Of these, both Wd1-9 and -30a are amongst the sub-set of sources that have enough counts for tailored spectral analyses; Clark et al. (2008) report fluxes of $\sim 3.6 \times 10^{33} \text{ erg s}^{-1}$ and $\sim 1.6 \times 10^{33} \text{ erg s}^{-1}$ respectively and, critically, harder spectra than expected for single stars ($kT \sim 2.3^{+0.5}_{-0.3}$ and $\sim 1.3^{+0.1}_{-0.1}$). Individual absorption columns were determined for both stars, contrasting with the single global value adopted for all cluster members following the methodology outlined in Sect. 2; this leads to a minor discrepancy between the flux estimates for Wd1-9 determined by the two approaches (cf. Fig. 2). Any such evaluation is complicated by the fact that significant differential extinction exists across the cluster and the form of the reddening law is uncertain (Clark et al. 2019). Given this uncertainty and the quality of the X-ray spectra, re-analysis of extant data appears premature.

However the overall conclusion – that these stars appear anomalously bright and hard relative to the majority of cluster OB supergiants – remains valid under either methodology, even if the absolute flux is uncertain by a factor of a few. Indeed, both Wd1-9 and -30a have X-ray fluxes that would place them amongst the most luminous 20% of known O+O binaries (Gagné et al. 2012)⁵, with Wd1-9 $\geq 6\times$ times brighter than expected for canonical OB supergiants within Wd1.

Since the stellar components of Wd1-9 are entirely veiled by circumstellar material (Clark et al. 2013b) there has been some ambiguity regarding the nature of the system – colliding wind or accreting binary. Recent observations of the sgB[e] X-ray binaries CI Cam and NGC 300 ULX-1 in quiescence reveal a

⁵ We caution that the majority of such binaries consist of two mid-late O dwarfs and hence may be expected to be intrinsically faint.

not possible due to the blending of the Paschen series lines but the absence of cool N I photospheric lines precludes a spectral type of B2 or later and by comparison to other spectra we suspect they are substantially earlier. By contrast Wd1-27 is similar to Wd1-30a, showing evidence for substantial mass accretion in a binary, leading to a classification of O7-8 Ia⁺ and $\log(L_{\text{bol}}/L_{\odot}) \sim 5.97^{+0.15}_{-0.10}$ (Clark et al. 2019). No RV motion has been detected for this object; hence we cannot distinguish between, for example, a binary with an extreme current mass ratio observed under an unfavourable inclination or the product of binary merger (Clark et al. 2019).

It is therefore of interest that the soft X-ray emission of Wd1-27 is consistent with expectations for a single star, while the flux is only $\sim 2\times$ greater than one would predict for a star of its extreme luminosity. Berghöfer & Schmitt (1995) analysed the short period ($P_{\text{orb}} \sim 4.39\text{d}$) O8 Iaf + O9 I binary UW CMa, finding the X-ray emission arose from a summation of the individual contributions from the stellar winds of both components, with no need to invoke a WCZ. Given the apparent similarity of UW CMa to Wd1-36 and -53a and after consideration of Wd1-27, one might wonder whether a similar scenario could also account for their X-ray properties.

To summarise; the multi-wavelength properties of Wd1-9, -13, -24 and -30a reveal them all to be massive, evolved and interacting binaries, with their hard spectra revealing that emission from WCZs likely dominates their X-ray flux. Conversely, despite Wd1-36 and -53a being short period systems and the potential for (current) binarity for Wd1-27, we find no unambiguous evidence for emission from a WCZ in these systems; we discuss these latter systems further in Sect. 4.2.

3.3. Wolf-Rayets

Oskinova (2016a) provides a review of the observational properties of WRs, reporting that they are diverse X-ray emitters, with fluxes ranging over several orders of magnitude. Broken down by sub-type, single WNL stars are relatively weak emitters ($L_X \sim 10^{32} \text{ erg s}^{-1}$; Oskinova 2005) with WNE stars found to be more luminous ($L_X \sim 2 - 6 \times 10^{32} \text{ erg s}^{-1}$; Oskinova 2016b). Likely due to the opacity of their dense, metal-rich winds, WC stars are significantly fainter, with only one example of an apparently single star, WR144 (WC4), detected to date ($L_X \sim 10^{30} \text{ erg s}^{-1}$; Rauw & Nazé 2016). Intriguingly, single WR stars do not conform to the L_X/L_{bol} relation of O stars and, on average, binaries are found to be brighter (Pollock 1987), with fluxes ranging up to $L_X \sim 10^{35} \text{ erg s}^{-1}$ (the WC8d star WR48a; Zhekov et al. 2011).

The X-ray properties of the WR population of Wd1 appear consonant with these expectations. The distribution of the spectral sub-types of the X-ray emitters is formally identical to the underlying distribution they are drawn from (Table 1; Clark et al. 2008). As can be seen from Fig. 2, with the notable exception of WR E, detected systems are on average harder and/or more luminous than the OB supergiant cohort, overlapping the region of the hardness/flux diagram that the interacting OB supergiants occupy (Sect. 3.2)⁷. The brightest stars, WR A and WR B are long-known compact binaries with WN7 primaries ($P_{\text{orb}} \sim 7.63\text{d}$ and $\sim 3.51\text{d}$ respectively; Bonanos 2007). Our

VLT/FLAMES data shows the WC9d star WR F to be a similar short-period binary ($P_{\text{orb}} \sim 5.05\text{d}$), with long term IR variability suggesting the presence of a tertiary component (Clark et al. 2011); as a consequence it is not obvious which components contribute to the WCZ responsible for the X-ray emission. Recent RV monitoring reveals the WN9h star WR L (=Wd1-44) to be a longer period binary ($P_{\text{orb}} \sim 54\text{d}$; Clark et al., in prep.); as such four of the five brightest and hardest X-ray detected WRs within Wd1 are unambiguously confirmed to be massive binaries (cf. Skinner et al. 2006).

Unfortunately, due to the combination of high interstellar extinction towards Wd1 and the capabilities of VLT/FLAMES, a lack of appropriate spectral diagnostics prevents an RV survey for binarity amongst the WN5-8 stars within Wd1. Nevertheless we strongly suspect binarity for WR U given its luminosity and spectral similarity to WR A and B (Clark et al. 2008), while the hard but fainter sources WR D (WN7o), G (WN7o) O (WN6o), R (WN5o) and W (WN6h) all appear strong binary candidates. The dusty nature of the hard but comparatively X-ray faint WC9d WR N also implies binarity (cf. Williams et al. 2005). The binary status of the WC9 star WR E is unclear at this time but it is unique amongst the WRs as being a rather faint and soft X-ray source co-located with the OB supergiants in the hardness/flux diagram (Fig. 2).

While the binary nature of the remaining undetected WN stars is uncertain, the presence of an IR-excess due to hot dust in the WCL stars WR C, H and T implies that they are binaries. Since binary induced dust production and X-ray emission in WRs modulate on the orbital period, one might suppose that these stars were observed at an unfavourable phase.

3.4. Marginal detections

Finally we discuss the handful of massive cluster members that are found in a post-supergiant evolutionary phase and are marginal X-ray detections at the $\sim 90\%$ level of significance (Clark et al. 2008). Assuming a 0.5 keV thermal plasma appropriate for a single early-type star, such sources have fluxes $\sim 10^{31} - 10^{32} \text{ erg s}^{-1}$; as such WR Q (WN6o), S (=Wd1-5; WN10h), V (WN8o) and X (WN5o) would appear to represent the low brightness tail of the luminosity distribution observed for WRs (Sect. 3.3). Of these WR S is of interest since it appears to be the product of binary-induced mass-stripping although, presumably following the explosion of its putative companion, it now appears to be single (Clark et al. 2014). In terms of gross properties WR S is similar to the primaries of Wd1-13 and WR L; both of which are hard and luminous X-ray sources (Fig. 2 and Table A.1). As such it appears likely the presence of a WCZ in the latter two system is the cause of the discrepant X-ray properties.

Surprisingly, the last two objects for which tentative detections were made are the luminous blue variable (LBV) Wd1-243 and the yellow hypergiant Wd1-8a, with the former in a cool phase when the X-ray observations were undertaken (spectral type $\sim \text{A3 Ia}^+$; Clark & Negueruela 2004; Ritchie et al. 2009b). Nazé et al. (2012) investigated the X-ray properties of LBVs, finding emission to be rare and potentially associated with binarity. With the X-ray flux of Wd1-243 being fully consistent with cluster OB supergiants, emission from an unseen companion would seem an obvious explanation for its properties. Indeed, the strong H I and He I emission lines in the spectrum of Wd1-243 led Ritchie et al. (2009b) to infer the presence of a hot, luminous companion, since the temperature of the LBV “primary” is insufficient to ionise its wind.

⁷ Upon individual modelling, the absorption columns found for WR A and B (WR L) imply an excessively high (low) visual extinction in comparison to optical determinations (Negueruela et al. 2010), resulting in a likely over- (under-) estimate of the relevant X-ray fluxes determined via this methodology (Clark et al. 2008 and Sect. 3.2).

A similar explanation would appear appropriate for Wd1-8a although, since it is located within the crowded core of Wd1, it is not obvious if it is a bona fide binary or instead if the putative OB supergiant is simply located along the same line-of-sight.

4. Interpretation and concluding remarks

Significant progress has been in the spectral classification of cluster members and the determination of their binary status in the decade since the publication of the X-ray point source catalogue. These new data allow a more accurate and concise characterisation of the nature of the massive X-ray emitting population of Wd1. We may draw two fundamental conclusions from this; that X-ray emitters are confined to very well delineated stellar sub-sets and that binarity plays an important role in the emission properties of some, but not all, of these stars.

4.1. Influence of luminosity and spectral type

X-ray emission is confined to three sub-sets of stars: WRs, interacting binaries and O9-B0.5 Ia,ab,b supergiants and, of the latter cohort, it is biased towards earlier (O9-9.5) spectral types (Table 1). The properties of the WRs appear broadly consistent with empirical expectations (Sect. 3.3) and hence we defer discussion of these and the (post-) interacting OB binaries until later, concentrating here on the (single) OB supergiants. The lack of emission from the less evolved O9-9.5 II-III stars is most likely due to their lower bolometric luminosity, since they are expected to follow the L_X/L_{bol} relation (cf. Nebot Gómez-Morán & Oskinova 2018). However, one cannot appeal to a low bolometric luminosity to account for the absence of emission in super-/hypergiants of spectral type B1 and later, since supergiants of $M_{initial} \sim 30\text{--}40 M_{\odot}$ should evolve to cooler temperatures at constant luminosity (e.g. Ekström et al. 2012). As a consequence if the L_X/L_{bol} relation were to apply for all B supergiants, we would not expect emission within Wd1 to abruptly cease at spectral type B0.5.

Our results mirror those of Berghöfer et al. (1997), who find X-ray emission to abate at spectral type B1 for stars of luminosity class I and II. While the physics resulting in the L_X/L_{bol} relation is uncertain, Berghöfer et al. (1997) suggest that beyond this point the wind velocity drops to such a degree that it is too low to produce the strong shocks required to yield X-ray emission. Prinja et al. (1990) and Lamers et al. (1995) report a discontinuity in wind properties around spectral type B1, with winds of high (low) velocity and low (high) mass-loss rate above (below) this point. Vink et al. (1999) attribute this discontinuity to a change in the ionisation balance of iron in the wind, which modifies the efficiency of line driving. Intriguingly, circumstantial evidence for the bistability jump is seen in mm-continuum observations of Wd1, where stars are only detected at spectral types B0 and later; on the cool side of this transition. Since thermal continuum emission from the stellar wind is sensitive to its density (scaling as $(\dot{M}/v_{wind})^{4/3}$; Wright & Barlow 1975), it is tempting to attribute this finding to an abrupt increase in this parameter for such stars (cf. Fenech et al. 2018).

One might therefore suppose that at temperatures above the bistability jump, wind velocities are high enough to permit X-ray emission via wind-shocks while, at temperatures below this transition, wind densities are sufficient to yield strong thermal continuum emission, but velocities are insufficient to generate post-shock temperatures high enough to produce X-ray emission.

4.2. The influence of binarity

As implied by Rauw & Nazé (2016), the role of binarity in determining the properties of the X-ray emission from cluster members appears complex. Clark et al. (in prep.) infer the presence of a large number of massive binaries within Wd1, but many are not detected at X-ray energies. This result is consistent with recent studies that suggest that in many binaries the WCZ, if present, does not yield excess, hard X-ray emission (Sect. 3.1). This behaviour is observed for the sub-set of binaries containing luminous OB star primaries within Wd1, with the X-ray properties of e.g. Wd1-6a and -10 being indistinguishable from those of single supergiants of comparable spectral type. Nevertheless, emission from a WCZ clearly plays a role in a sub-set of cluster binaries which are both harder and brighter than expected for single stars. Four of the five brightest and hardest WR X-ray detections are unambiguously binary (WR A, B, F and L), while the interacting and post-interaction systems Wd1-9 and -30a have emission that also appears to be dominated by a WCZ. A number of fainter WR and O supergiant detections also appear anomalously hard, including the confirmed short-period binary Wd1-13.

However, while the short period OB+OB binaries Wd1-36 and -53a are also anomalously bright, they are unexpectedly soft; properties that are potentially consistent with the summed emission from the stellar components with no contribution from a WCZ, despite their apparent similarity to e.g. Wd1-13 (see also Wd1-24; Sect. 3.2). Notwithstanding this finding, we may conclude that while binarity does not lead to all binaries being more luminous than single stars, the hardest and most luminous stellar X-ray sources within Wd1 are either interacting binaries comprising stars of high bolometric luminosity or post-interaction systems containing either a WR or rejuvenated binary product (cf. Wd1-30a).

Unfortunately interpreting this diverse behaviour is difficult. The contribution of a WCZ to the intrinsic emission of the binary components will depend on the cooling efficiency for shocked material and the attributes of both outflows at the location of the interaction (Stevens et al. 1992). The properties of the stellar winds in turn depend on the nature of the driving stars as well as binary separation and eccentricity (i.e. will the winds have time to reach their terminal velocity and is radiative braking important?). While beyond the scope of this paper, tailored hydrodynamical simulations will be required to fully understand the physical effects leading to the manifold X-ray properties of apparently similar binary systems (e.g. Pittard & Dawson 2018).

Nevertheless, it is of interest to consider Wd1-6a, -36 and 53a, for which emission from a WCZ appears absent and photometric periods are available. Following the analysis of Wd1-13 by Ritchie et al. (2010b) we adopt a current total mass of $\sim 60 M_{\odot}$ for such systems and stellar radii for the constituent late O/early B supergiants of $\gtrsim 20 R_{\odot}$ (see also Martins et al. 2005). Given these values, the 2.20d photometric period for Wd1-6a implies an orbital separation of $\sim 28 R_{\odot}$; two such supergiants could barely be accommodated in such a system, although the situation would be improved if the secondary were a less luminous $\sim O8$ V or $\sim O9$ III star ($\sim 8.5 R_{\odot}$ to $\sim 13.7 R_{\odot}$; Martins et al. 2005), as suggested by its SB1 classification (Sect. 3.1). One might also suppose that the true orbital period is twice this value; such a conclusion appears inescapable for Wd1-53a, where a 1.30d period implies a separation of only $\sim 20 R_{\odot}$ and the double-lined nature of the spectra requires comparable bolometric luminosities for both components. The eclipsing nature of Wd1-36 implied by its lightcurve morphology requires an orbital

separation of $\sim 36 R_{\odot}$, implying that the stars are essentially in contact. As a consequence one might reasonably conclude that the stellar winds in such compact binary configurations cannot accelerate to their terminal velocities and hence WCZs do not readily form. Moreover even if one assumed a smaller, less evolved companion for e.g. the single-lined binary Wd1-6a, such a star would support a weaker wind which might be expected to lead to reduced X-ray emission from the WCZ (cf. Sect. 3.1).

4.3. Conclusions and future perspectives

Wd1 appears to be an ideal laboratory for the study of X-ray emission from massive single and binary stars. Although significant interstellar reddening is present, it is not so high that soft emission is undetectable and its proximity means that individual stellar sources may be spatially resolved. This can be contrasted with the Arches and Quintuplet, which are located within the Galactic centre region and where only a handful of hard X-ray sources may be discerned (Wang et al. 2006). Moreover, at 5 Myr old, Wd1 hosts a rich co-eval population of massive evolved stars that straddles the wind bistability limit, allowing the dependence of X-ray emission on wind parameters to be probed (cf. Owocki & Cohen 1999).

In order to exploit this potentiality, further multi-epoch optical and near-IR spectroscopy will be required to fully constrain the binary population and determine stellar and wind properties via model-atmosphere analysis (cf. Clark et al. 2019). Deeper multi-epoch X-ray observations will also be needed in order to (i) reach currently undetected stellar cohorts, in particular the O giants (to further test the L_X/L_{bol} relation) and the B1-4 supergiants (to determine the nature of X-ray emission below the wind bistability limit) and (ii) search for orbital modulation in known binaries. Finally, these data will need to serve as input into individually tailored hydrodynamical simulations of the binary cohort in order to quantify the role of the WCZ and physics governing it.

Such an analysis will lead to a better understanding of the stellar winds which mediate evolution for massive stars and the conditions under which a WCZ forms and dominates the high energy emission of massive binaries. At this epoch at least 22 of the >166 massive evolved stars within Wd1 appear strong candidates to host detectable WCZs (comprising the eight O stars with hardness colours > -0.5 at $>1\sigma$, the (post-) interacting binaries Wd1-9, 13 and 30a and all WR detections with the exception of WR E; Sect. 3). These systems are of particular relevance for understanding the role colliding wind binaries play in the production of cosmic rays and the significance of this process relative to other mechanisms, such as shocks in the winds of single stars, generation in SNe remnants and pulsar winds and the interaction between cluster winds and SNe (Bednarek et al. 2014; Aharonian et al. 2019 and references therein).

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Appendix A: Summary of the X-ray properties of massive cluster members

Table A.1. Summary of spectrally classified cluster members associated with X-ray emission (adapted from Clark et al. 2008).

Opt. ID	Spectral type	X-ray identifier	Counts	Hardness ratio	Flux (10^{-7} ph cm $^{-2}$ s $^{-1}$)	Notes
W1	O9.5 Iab	164659.3-455046	11.3 $^{+3.6}_{-3.6}$	-0.27 $^{+0.32}_{-0.31}$	4.9	
W6a	B0.5 Iab + ?	164703.0-455023	11.1 $^{+3.9}_{-3.3}$	-0.47 $^{+0.31}_{-0.29}$	4.7	P(2.20d)
W9	sgB[e]	164704.1-455031	462.2 $^{+22.7}_{-22.4}$	0.23 $^{+0.05}_{-0.05}$	241.2	Interacting binary
W10	B0.5Ia+OB	164703.3-455034	10.2 $^{+3.8}_{-3.5}$	-0.43 $^{+0.34}_{-0.32}$	4.2	SB2, RV variable
W13	B0.5 Ia $^+$ /WN10h + OB Ia	164706.4-455026	18.9 $^{+4.1}_{-5.2}$	0.14 $^{+0.24}_{-0.24}$	13.1	SB2, E(9.27d)
W15	O9.5 Ib	164706.6-455029	10.2 $^{+3.7}_{-3.3}$	-0.62 $^{+0.30}_{-0.28}$	4.5	Not RV variable
W17	O9 Iab	164706.2-455048	7.2 $^{+4.0}_{-3.8}$	-1.00 $^{+0.63}_{-0.63}$	2.4	Non-thermal radio, not RV variable
W24	O9 Iab+O?	164702.1-455112	19.3 $^{+5.4}_{-5.2}$	0.14 $^{+0.27}_{-0.27}$	11.9	SB2? RV variable
W25	O9 Iab	164705.7-455033	11.2 $^{+4.0}_{-3.6}$	-1.00 $^{+0.36}_{-0.36}$	4.9	
W27	O7-8 Ia $^+$	164705.1-455041	32.9 $^{+5.8}_{-6.9}$	-0.72 $^{+0.15}_{-0.14}$	13.4	Not RV variable, Overluminous merger product?
W30a	O4-5 Ia $^+$	164704.1-455039	552.2 $^{+24.9}_{-24.5}$	-0.15 $^{+0.04}_{-0.04}$	253.4	RV variable, Overluminous binary interaction product?
W36	OB Ia + OB Ia	164705.0-455055	43.4 $^{+7.2}_{-7.4}$	-0.79 $^{+0.13}_{-0.11}$	19.0	SB2, E(3.18d)
W38	O9 Iab	164702.8-455046	9.0 $^{+4.2}_{-3.6}$	-0.39 $^{+0.41}_{-0.43}$	3.3	Not RV variable
W41	O9 Iab	164702.7-455057	14.1 $^{+4.6}_{-4.0}$	-0.21 $^{+0.30}_{-0.31}$	6.1	
W47	O9.5 Iab	164702.5-455117	18.0 $^{+4.8}_{-6.0}$	0.22 $^{+0.30}_{-0.29}$	10.1	
W53a	OB Ia + OB Ia	164700.3-455131	56.7 $^{+7.6}_{-8.2}$	-0.58 $^{+0.12}_{-0.11}$	24.0	SB2, P(1.30d)
W56b	O9.5 Ib	164658.8-455145	14.5 $^{+3.9}_{-4.2}$	-0.02 $^{+0.28}_{-0.28}$	6.8	Not RV variable
W61b	O9.5Iab	164702.5-455142	3.4 $^{+2.7}_{-3.0}$	-1.00 $^{+0.8}_{-0.8}$	1.5	
W62a	B0.5 Ib	164702.5-455137	15.3 $^{+4.5}_{-4.3}$	-0.51 $^{+0.27}_{-0.26}$	6.5	
W65	O9 Ib	164703.8-455146	12.6 $^{+3.5}_{-4.0}$	0.47 $^{+0.26}_{-0.28}$	6.8	Low level RV variable
W74	O9.5 Iab	164707.0-455012	9.3 $^{+3.4}_{-3.2}$	-0.75 $^{+0.29}_{-0.24}$	4.0	Not RV variable
W84	O9.5 Ib	164659.0-455028	10.4 $^{+3.4}_{-3.5}$	-1.00 $^{+0.30}_{-0.30}$	3.9	Not RV variable
W232	O9.5-B0 Iab	164701.4-455235	11.9 $^{+3.1}_{-4.2}$	-0.25 $^{+0.30}_{-0.29}$	5.4	RV variable, C07-X6
W1005	B0 Iab	164654.2-455154	9.7 $^{+3.0}_{-3.6}$	-0.54 $^{+0.32}_{-0.29}$	6.4	Not RV variable, C07-X7
W1018	O9.5 Iab	164658.2-455056	12.7 $^{+3.5}_{-4.1}$	-0.18 $^{+0.30}_{-0.29}$	6.5	
W1027	O9.5 Iab	164701.0-455006	14.5 $^{+3.9}_{-4.1}$	-0.43 $^{+0.26}_{-0.25}$	6.2	
W1033	O9-9.5 I-III	164702.3-455233	9.9 $^{+2.8}_{-3.8}$	-0.54 $^{+0.31}_{-0.28}$	4.9	Not RV variable, C07-X5
W1036	O9.5 Ib	164702.7-455212	12.3 $^{+3.8}_{-3.7}$	-0.02 $^{+0.30}_{-0.31}$	5.6	Not RV variable, C07-X4
W1040	O9.5 Iab/b	164704.5-455008	14.2 $^{+4.2}_{-3.9}$	-0.42 $^{+0.27}_{-0.25}$	6.3	RV variable, C07-X3
W1041	O9.5 Iab + ?	164704.4-455109	13.9 $^{+3.8}_{-4.8}$	0.02 $^{+0.31}_{-0.31}$	6.6	Broad Paschen lines, SB2?
W1051	O9 III	164706.9-454940	12.6 $^{+3.6}_{-4.0}$	-0.33 $^{+0.29}_{-0.28}$	5.4	Not RV variable
W1055	B0 Ib	164707.8-455147	14.5 $^{+3.9}_{-4.2}$	0.40 $^{+0.25}_{-0.27}$	7.2	Not RV variable
W1064	O9.5 Iab	164711.5-455000	5.1 $^{+3.1}_{-2.5}$	1.00 $_{-0.49}$	2.3	
WR A	WN7b	164708.3-455045	743.7 $^{+27.3}_{-27.3}$	0.19 $^{+0.04}_{-0.04}$	380.7	P(7.63d)
WR B	WN7o	164705.3-455104	237.5 $^{+16.1}_{-16.5}$	0.21 $^{+0.06}_{-0.07}$	133.2	E(3.51d)
WR D	WN7o	164706.2-455126	14.3 $^{+4.7}_{-4.6}$	1.00 $_{-0.19}$	16.6	
WR E	WC9	164705.9-455208	8.0 $^{+4.0}_{-3.3}$	-0.57 $^{+0.39}_{-0.40}$	3.7	RV binary?
WR F	WC9d	164705.2-455224	109.6 $^{+10.9}_{-11.3}$	0.63 $^{+0.08}_{-0.08}$	65.7	RV(5.05d), possible trinary?
WR G	WN7o	164704.0-455124	19.2 $^{+5.5}_{-5.1}$	0.55 $^{+0.25}_{-0.25}$	17.5	
WR L	WN9h:	164704.1-455107	80.8 $^{+9.6}_{-10.3}$	0.34 $^{+0.11}_{-0.11}$	48.8	RV(~54d)
WR N	WC9d	164659.8-455525	11.3 $^{+3.7}_{-3.6}$	0.57 $^{+0.25}_{-0.29}$	19.7	Dust producing CWB?
WR O	WN6o	164707.6-455235	54.5 $^{+7.7}_{-8.1}$	0.07 $^{+0.14}_{-0.14}$	27.0	
WR R	WN5o	164706.0-455022	30.8 $^{+5.9}_{-6.8}$	0.27 $^{+0.20}_{-0.20}$	20.5	
WR U	WN6o	164706.5-455039	161.2 $^{+13.6}_{-13.2}$	-0.14 $^{+0.08}_{-0.08}$	81.4	
WR W	WN6h	164707.6-454922	21.1 $^{+5.2}_{-4.8}$	0.72 $^{+0.16}_{-0.19}$	15.9	

Notes. Columns 1 and 2 present optical IDs and spectral classifications derived from Clark et al. (2005; 2013b; 2019, and in prep.), Crowther et al. (2006), Negueruela et al. (2010) and Ritchie et al. (2009a, 2010b). X-ray designations are given in Col. 3 and corresponding physical data from Clark et al. (2008) in Cols. 4–6. Additional information is presented in Col. 7, including Eclipsing or Periodic photometric modulation (Bonanos 2007), the presence or absence of periodicity in the Radial Velocity data derived from the 2008–9 observing seasons (Ritchie et al. 2009a, 2010a, Clark et al., in prep.), apparent SB2 binaries (Clark et al., in prep.) and non-thermal radio emission (Dougherty et al. 2010). W1041 has been observed as part of our RV variability survey but the breadth of the Paschen series lines prevents analysis of RV variability (Fig. 1; Clark et al., in prep.).