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Radio emission from the massive stars in Westerlund 1

S.M. Dougherty[1,2], J.S. Clark [3], I. Negueruela[4], T.W. Johnson[1,5] and J.M. Chapman[6]

[1] NRC-HIA, Penticton, Canada
[2] Institute for Space Imaging Science, University of Calgary, Canada
[3] Open University, Milton Keynes, UK.
[4] University de Alicante, Alicante, Spain
[5] University of Victoria, Victoria, BC, Canada
[6] Australia Telescope National Facility, Sydney, Australia

Abstract: The diverse massive stellar population in the young massive cluster Westerlund 1 (Wd 1) provides an ideal laboratory to observe and constrain mass-loss processes throughout the transitional phase of massive star evolution. A set of high sensitivity radio observations of Wd 1 leads to the detection of 18 cluster members, a sample dominated by cool hypergiants, but with detections among hotter OB supergiants and WR stars. Here the diverse radio properties of the detected sample are briefly described. The mass-loss rates of the detected objects are surprisingly similar across the whole transitional phase of massive star evolution, at $\sim 10^{-5}$ M$_\odot$ yr^{-1}. Such as rate is insufficient to strip away the H-rich mantle in a massive star lifetime, unless the stars go through a period of enhanced mass-loss. The radio luminous star W9 provides an example of such an object, with evidence for two eras of mass-loss with rates of $\sim 10^{-4}$ M$_\odot$ yr^{-1}.

1 Introduction

Mass-loss rate is a fundamental property of stars with masses in excess of $\sim 30\ M_\odot$, important to stellar evolution and feedback to the ISM. Mass-loss rates of massive main sequence stars are insufficient to remove H-rich mantles to produce WR-type stars. There must be epochs of enhanced mass-loss rate in their evolution to WR stars, through phases that include hot supergiant B[e], Luminous Blue Variables (LBV), cool Yellow Hypergiant (YHG) and Red Supergiant (RSG) stars.

Westerlund 1 (Wd 1) is one of the most massive clusters in the Milky Way ($M_{\rm total} \sim 10^5\ M_\odot$), directly comparable to Super-Star Clusters in other galaxies such as M82. Hence Wd1 represents a nearby example of one of these clusters, providing a valuable opportunity to study the properties, evolution and interaction of massive stars.

Wd 1 contains a unique population of cool and hot supergiants, with a large population of post-MS stars that represent all phases of massive star evolution: OB supergiants and hypergiants, RSGs, YHGs, and WR stars (Clark & Negueruela 2002; Clark et al. 2005).

Radio observations are a long established tool for estimating mass-loss rates. Clark et al (1998) discovered two unusually radio luminous stars in Wd 1 - the supergiant B[e] star W9 and the RSG

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W26. Motivated by the possibility of detecting emission from stars across a broad range of evolutionary stages, more sensitive radio observations of Wd 1 were obtained with the Australian Telescope Compact Array to establish radio characteristics of cluster members, particularly their mass-loss rates. These observations have been used in conjunction with optical, IR and X-ray observations from the literature to elucidate the nature of the radio sources.

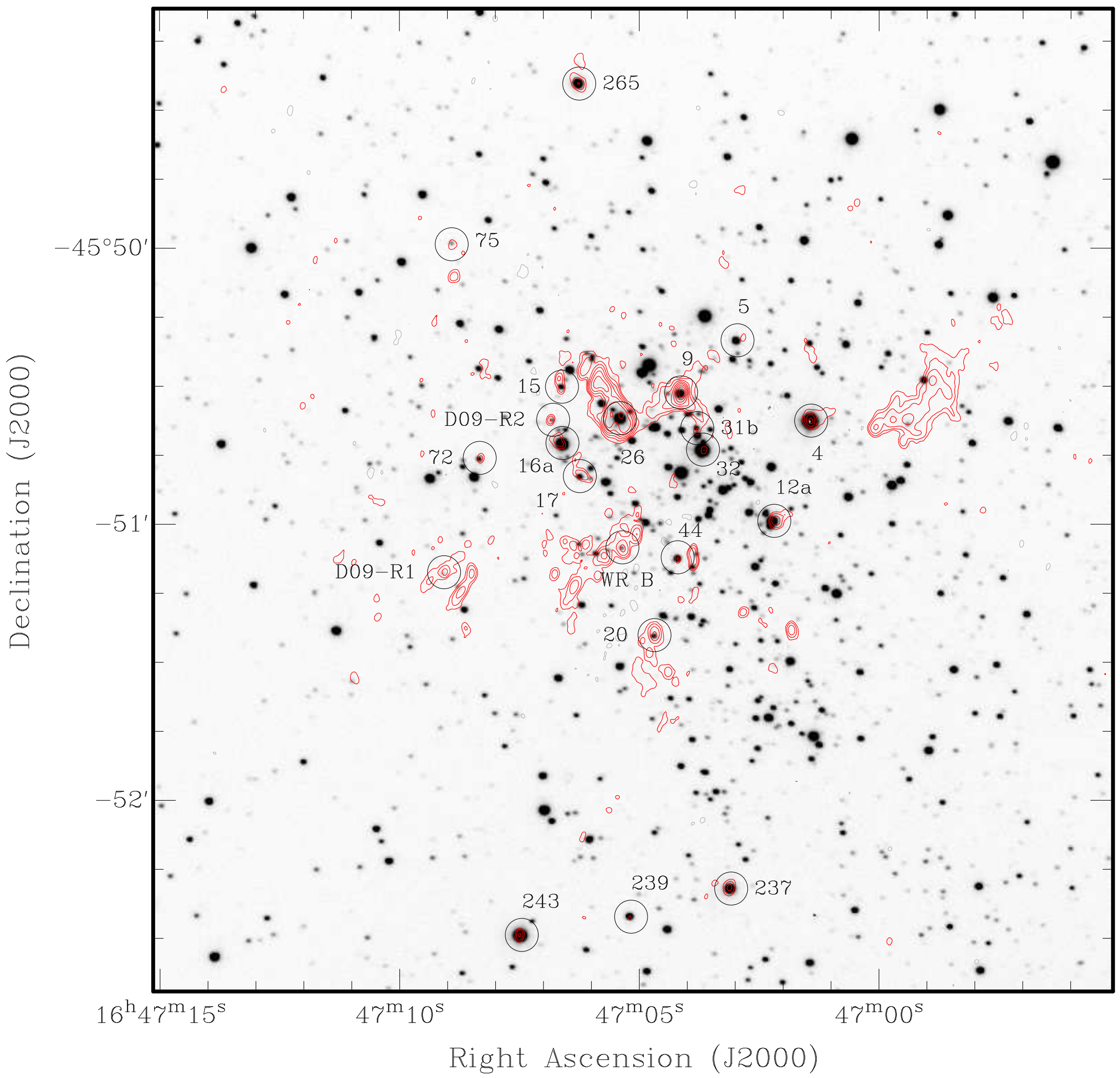

Figure 1: 8.6-GHz of Wd 1 overlaid on a FORS R-band image, with limiting magnitude 17.5 mag. The radio sources with putative optical counterparts are identified by circles and Westerlund numbers

2 Results

- 18 cluster members were detected, dominated by cool hypergiants, though with detections among hotter OB supergiants and WR stars (see Table 1).
- The sources are a diverse population of point-like, unresolved sources and extended, resolved sources with spectral indices corresponding to thermal, non-thermal and composite thermal and non-thermal emission.

Table 1: Number of radio emitters of given spectral type

Spec. Type	No. radio emitters	Source ID	Cluster total
OB SGs	3(4?)	15, 17, D09-R1, (D09-R2?)	∼150
sgB[e]	1	9	1
BHGs	1	243	4
YHGs	4(5?)	4, 12a, 32, 265 (16a?)	6
RSGs	4	20, 26, 75, 237	4
WN9-10	1 (2?)	44, (5?)	2
WN5-8	3	WR B, 31b, 72	14
WC	1	239	8

- The radio observations in conjunction with X-ray and IR observations provide striking evidence for a high fraction of binaries among the massive stars in Wd 1, strongly supporting previous estimates of high binary fractions, in excess of 40% (Clark et al, 2008; Ritchie et al. 2009).

- The derived mass-loss rates determined for YHG W4, LBV W243 and WR L, which form an evolutionary sequence in some schemes, are all closely the same.

- Mass-loss rates of $\leq 10^{-5}$M$_\odot$yr^{-1} are likely insufficient to remove the H-rich mantle unless stars remain in the transitional phase for significantly longer than expected. This implies an additional mechanism is required to shed the requisite mass, with short-lived episodes of greatly enhanced mass loss. Indeed mass-loss rates $> 10^{-4}$M$_\odot$yr^{-1} have already been inferred for RSGs e.g. VY CMa (Smith et al. 2001) and directly observed for the YHG ρ Cas (Lobel et al. 2003). The nebulae around the RSGs W20, 26 and 236 already indicate that significant mass loss has occurred for some stars within Wd 1, while the mass-loss rate inferred for W9, over a magnitude greater than any other transitional star in Wd 1, is of obvious interest.

2.1 W9 - a luminous radio source

W9 is the brightest radio source in Wd 1, with a total flux at 8.6 GHz of 55.4 mJy, which implies a luminosity of 1.6×10^{21} erg s^{-1}. This makes W9 one of the most luminous radio stars, being a factor of a few less luminous than the extreme LBV η Car at radio minimum (Duncan & White 2002).

The radio structure of W9 is a compact radio source surrounded by an extended emission region. The spectral index of the compact source ($+0.68 \pm 0.08$) is consistent with thermal emission from a stellar wind. The extended region is essentially flat ($+0.16 \pm 0.07$) and arguably consistent with optically-thin thermal emission. Assuming a radial ion distribution in the extended region goes as r^{-2}, the lack of a turnover in its continuum spectrum implies that the region is optically-thin down to at least 1.4 GHz, with an inner radius to the region larger than the $\tau_\nu = 1$ surface at 1.4 GHz. We believe this is from an earlier epoch of mass loss, prior to the start of the current stellar wind phase.

Modelling the envelope as a stellar wind surrounded by an optically thin shell-like wind from an earlier phase of mass loss gives mass-loss rates of $9.2 \pm 0.4 \times 10^{-5}(v_\infty/200\ \mathrm{km\,s^{-1}})f^{1/2}$ and $33 \pm 10 \times 10^{-5}(v_\infty/200\ \mathrm{km\,s^{-1}})f^{1/2}$ M$_\odot$ yr^{-1} respectively, where f is the volume filling factor (see Dougherty et al. 2010 for modelling details).

The structure of the envelope is similar to some LBVs, with W9 having a current mass-loss rate similar to galactic examples e.g. Pistol star. The rate deduced for the extended shell is close to the limit expected for line-driven winds (Smith & Owocki, 2006), and comparable to several other galactic LBV's during outburst, though orders of magnitude less than for P Cygni and η Car during outburst (Clark et al. 2009). Nevertheless, the question of whether W9 is undergoing an 'eruptive' event remains.

The X-ray properties imply W9 is a binary system, being too hard ($kT \sim 3$ keV) and bright ($L_x \sim 10^{33}$ erg s^{-1}) to come from a single star. However, it is not possible to constrain the properties of a putative companion star from current observations. Given the unusually high radio luminosity and concomitant high mass-loss rates, W9 is clearly an object for further study.

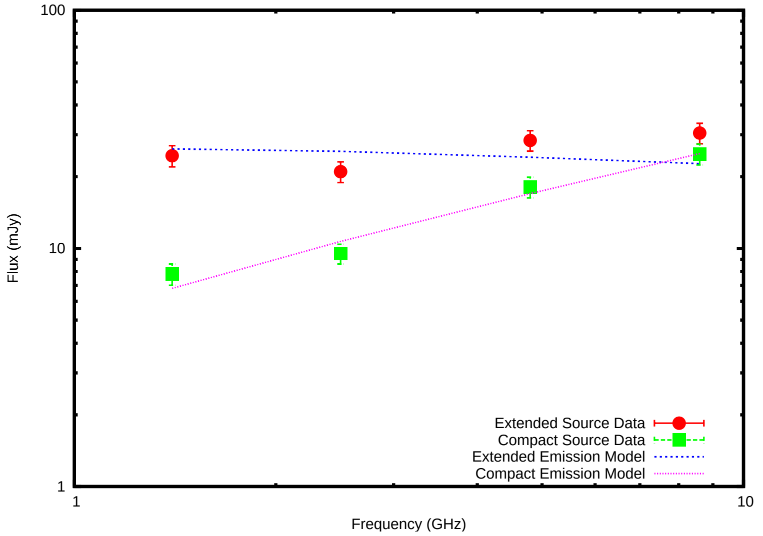

Figure 2: Model fits to the observations of W9, using a partially optically-thick compact source from a current stellar wind, and a flat spectrum extended region due to optically-thin emission from an earlier epoch of mass loss via a stellar wind.

2.2 OB stars

Surprisingly, three of the > 100 evolved OB stars are detected, with radio fluxes larger than an order of magnitude higher than expected for stellar winds in these types. These may be colliding-wind binaries based on potentially composite spectra (both thermal and non-thermal components) but there are neither X-ray emission nor RV variations associated with these three objects to support the claim. Alternatively, the high level of radio emission maybe influenced by extended radio emission in which they are embedded.

2.3 Red Supergiants

All four RSGs are detected, three of them associated with large nebulae with masses up to $\sim 0.3\ M_{\odot}$. The nebulae around W20 and W26 have a pronounced cometary morphology, suggesting significant interaction with either the intracluster medium or cluster wind.

W237 shows less evidence for such interaction and has a kinematic age of ~3,600 yr and a *time averaged* mass-loss rate of $2 \times 10^{-5} (\mathrm{v}_{\infty}/30 \mathrm{km\,s}^{-1}) f^{1/2}$ M$_{\odot}$yr^{-1}. This is consistent with other field RSGs, although it is substantially lower than inferred for NML Cyg and VY CMa during the formation of their nebulae.

2.4 Yellow Hypergiants

The YHG W4 has a stellar wind with a mass-loss rate of $10^{-5}(\mathrm{v}_\infty/200\mathrm{km\,s^{-1}})f^{1/2}$ $\mathrm{M_\odot yr^{-1}}$, consistent with the few estimates available for other field YHGs. The extended nebulae associated with W4, W12a and W265 are significantly less massive than those associated with the RSGs in Wd 1, and likely arise from quiescent mass loss rather than during outburst episodes.

Neither the YHGs nor RSGs are hot enough to ionize their own stellar winds and/or more extended nebulae, and the requisite ionizing photons must arise from either an unseen companion or the cluster radiation field.

2.5 B Hypergiants

Of the extreme B-type hypergiants, only LBV W243 was detected, with a spectral index consistent with thermal emission. The corresponding mass-loss rate is comparable to YHG W4, as expected given the similarity in current spectral type and radio flux. Upper limits for the three other B hypergiants were found to be $2\times10^{-6}(\mathrm{v}_\infty/200\mathrm{km\,s^{-1}})f^{1/2}$ $\mathrm{M_\odot yr^{-1}}$, consistent with mass-loss rates amongst field stars of these types

2.6 Wolf-Rayets

Five of the 24 WRs in Wd 1 were detected. WR L has a partially optically-thick wind, with a mass-loss rate consistent with stars of identical spectral type in the Galactic Centre cluster and the general field population ie. $\dot{M} = 2\times10^{-5}(\mathrm{v}_\infty/1000\mathrm{km\,s^{-1}})f^{1/2}$ $\mathrm{M_\odot yr^{-1}}$. The remaining three (WR A, B and V) are identified as having composite spectra from a CWB. The optical and X-ray properties of WR A and WR B have previously indicated these to be binaries, while this is the first hint of binarity in WR V.

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References

Clark, J. S., Crowther, P. A., Larionov, V. M., et al. 2009, A&A, 507, 1555
Clark, J. S. & Negueruela, I. 2002, A&A, 396, L25
Clark, J. S., Fender, R. P., Waters, L. B. F. M., et al. 1998, MNRAS, 299, L43
Clark, J. S., Negueruela, I., Crowther, P. A., & Goodwin, S. P. 2005, A&A, 434, 949
Clark, J. S., Muno, M. P., Negueruela, I., et al. 2008, A&A, 477, 147
Duncan, R. A. & White, S. M. 2002, MNRAS, 330, 63
Lobel, A., Dupree, A. K., Stefanik, R. P., et al. 2003, ApJ, 583, 923
Ritchie, B. W., Clark, J. S., Negueruela, I., & Crowther, P. A. 2009, A&A, 507, 1585
Smith, N., Humphreys, R. M., Davidson, K., et al. 2001, AJ, 121, 1111
Smith, N. & Owocki, S. P. 2006, ApJ, 645, L45