A 3mm ALMA census of the massive cluster Westerlund 1

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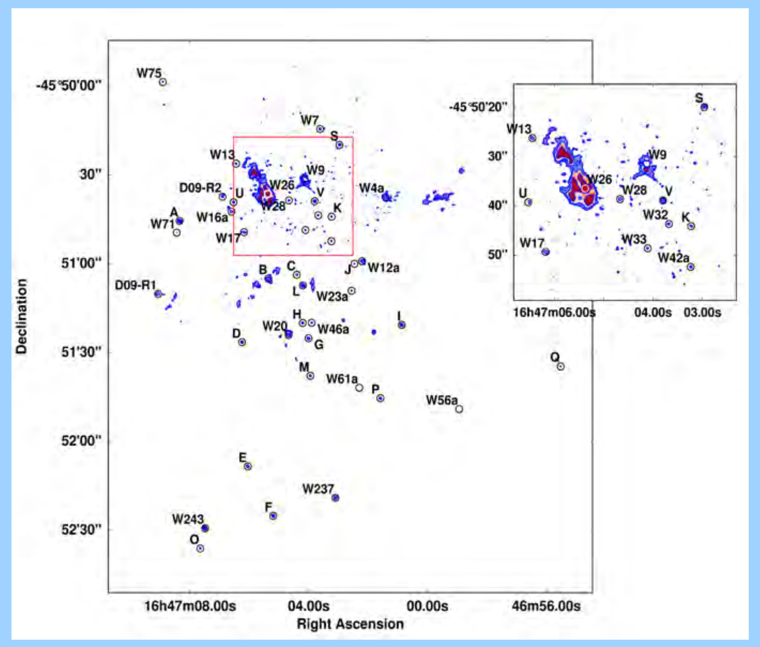
Westerlund 1

Westerlund 1 (Wd1) is one of the first examples of a super star cluster within our Galaxy and contains a population of co-eval massive stars. Located at a distance of ~5 kpc, Wd1 was discovered by Westerlund in 1961 (Westerlund, 1961,PASP, 73, 51). However, the large extinction towards Wd1 (Av~11 mag) meant that few observations were made of the cluster until relatively recently when radio images revealed a large number of radio sources (Dougherty et al. 20010, A&A, 511,58). Alongside the earlier spectroscopic observations (Westerlund 1987, A&AS, 70, 311), this confirmed a rich population including Wolf-Rayets (WRs), cool super/hyper-gaints and evolved OB stars.

In order to better understand the nature of the massive single and binary populations in Wd1 we undertook ALMA Band 3 (100GHz) observations. ALMA was used to observe Wd1 on the 30th June and 1st July 2015 covering the central ~3.5 sq. arcmin area with 27 pointings.



ALMA 3mm colour-scale (0.15-1.2 mJy/bm) and contour map (0.16,0.29,0.52,0.96,1.74,3.16 mJy/bm). Stellar source s identified in these ALMA observations are labelled.

Massive stars

Despite their rarity, massive stars play a major role in galactic evolution. They deposit large amounts of chemically enriched material, energy and ionising radiation into their environment and dominate the integrated galactic spectra in the UV and IR regimes (via re-radiation). However, the lives of massive stars are still poorly understood.

Mass-loss is considered a critical factor in the evolutionary pathway of massive stars and consequently the nature of their eventual demise (e.g. core-collapse supernova or gamma-ray burst). Mass-loss will therefore also determine the nature of the remnant, black hole (BH) or neutron star (NS).

For single massive stars, line-driven radiative winds are the main mechanism of mass-loss. However, recent studies have measured observational mass-loss rates for OB stars that differ by up to a factor of 10 (Puls et al. 2006, A&A, 454, 625; Sundqvist et al. 2011, A&A, 528, 64), believed to be a result of structure or clumping in the wind (e.g. Prinja and Massa 2013, A&A, 559, 15).

Given the recent recognition that ~70% of massive stars are found within binary systems (de Mink et al. 2014, ApJ, 782, 7), it is equally important to consider this evolutionary channel as well. Interaction between the stellar components may lead to extreme mass-loss from the primary allowing for the formation of WRs and favouring the production of NSs instead of BHs, of particular importance given the recent detection of gravitational waves and multiwavelength emission from the NS-NS merger SSS17a/GW170817A (LVC GCN Circ. 21505, 21509; Blackburn et al. 2017, LVC GCN Circ. 21506; Yang et al. 2017, LVC GCN Circ. 21531).

Young massive stellar custers provide ideal places to study massive stars courtesy of their single metallicity, co-eval stellar populations. Given their potential to shape their environment through the collective effect of stellar winds and supernovae, studying YMCs is also important for understanding the effect on the cluster and galactic evolution as a whole. Courtesy of its proximity and diverse stellar population, Wd1 provides an excellent opportunity to observe such a YMC in detail.

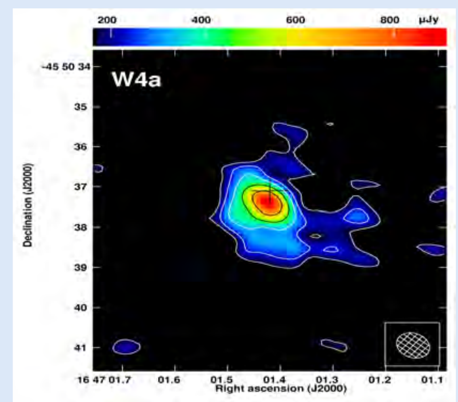
Cool super-/hypergiants

Yellow hypergiants (YHGs) and red supergiants (RSGs) are of particular interest as they are believed to shed mass at suffucent rates to profoundly affect a stars evolution in spite of spending relatively little time in this phase.

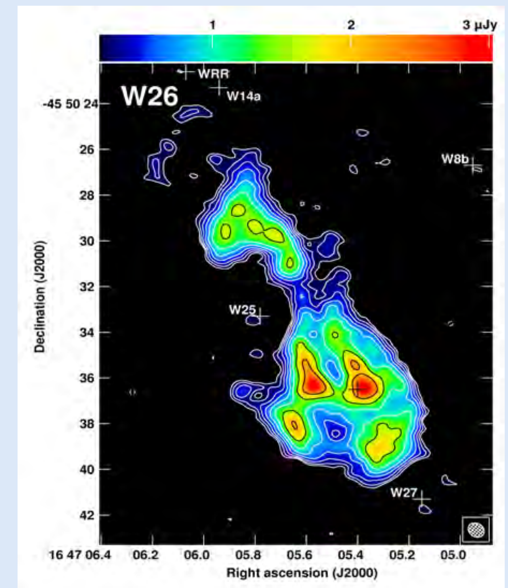
We detect four of the six YHGs in Wd1, the missing Wd1-265 lying outside of the ALMA field and Wd1-8a which is not seen in either these or radio observations.

Wd1-32 (F5 Ia+) appears unresolved, however, Wd1-4a (F3 Ia$^+$), 12a (F1 Ia$^+$) and 16a (A5 Ia$^+$) are revealed for the first time a eak of emission at the apex of a compact nebula with an arc-head like morphology directed towards the central region of the cluster.

All four of the RSGs are resolved in these ALMA observations. Wd1-75 (M4 Ia) & 237 (M3 Ia) show compact emission, though recent radio observations suggest the latter has a much more extended nebula (see Andrews et al, these preceedings). As with the previous radio observations (Dougherty et al. 2010, A&A, 511, 58) Wd1-20 & 26 show pronounced cometary nebula, believed to be the result of shaping by interaction with the wider cluster environment



ALMA image of the YHG Wd1-4a in contours and color-scale. Contours are plotted at -1,1,1.4,2,2.8,4,5.7,8,11.3,16 x 55 μJy/beam.



ALMA image of the RSG Wd1-26 in contours and color-scale. Contours are plotted at -1,1,1.4,2,2.8,4,5.7,8,11.3,16 x 64 μJy/beam.

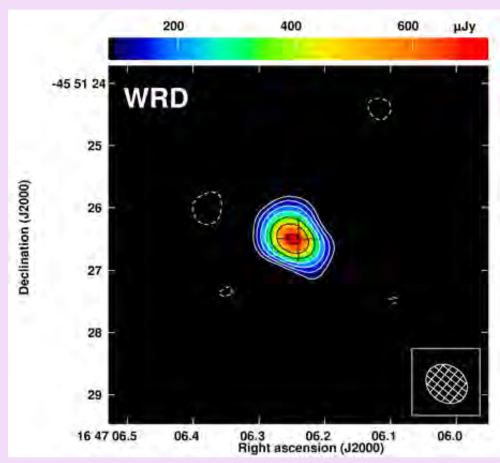
Wolf-Rayet population

One of the major findings of our survey is that almost half of the sources revelaed by ALMA are Wolf Rayet stars and importantly raises the possibility of measuring their mass-loss rates. We detect 21 of the 22 WR stars within the field of view identified in the censusby Crowther et al. (2006, MNRAS, 372, 1407). This includes 15 of the 16 WN stars ranging in sub-type from WN5o (WRJ) to the WNVLh/B hypergiant hybrids (WRS and Wd1-13). We also detect all six of the WC stars which are of WC8 and WC9 sub-types.

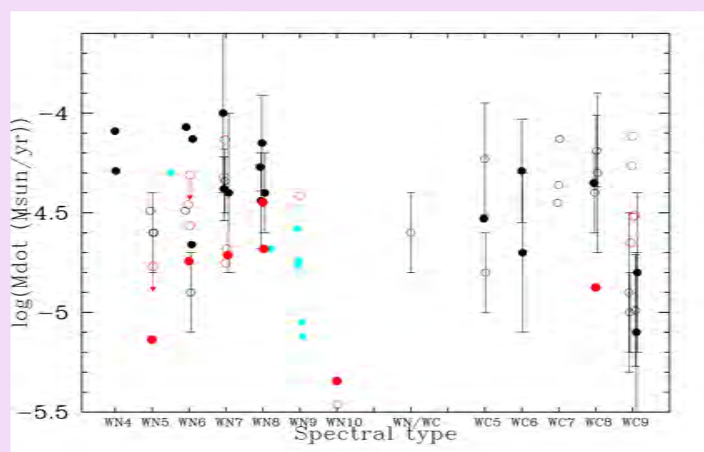
Comparison of the measured 3 mm flux densities with those from the previous radio survey (Dougherty et al. 2010, A&A, 511, 58) allows estimation of the spectral indices for seven of these sources and upper limits for the remaining 14. In spite of the known binary nature of eight of the WN and five of WC stars, we find that the spectral indices are completely consistent with partially optically-thin thermal emission consistent with stellar-wind emission with the exception of WR V and WR S.

Assuming therefore the emission to be from the stellar wind we calculated mass-loss rates using the equation from e.g. Wright & Barlow (1975, MNRAS, 170, 41) assuming a gaunt factor as described by e.g. Leitherer & Robert (1991, ApJ, 377, 629). We assumed an electron to ion density ratio (Z) of 1 and mean number of electrons (γ) of 1. The mean molecular weight (μ) is taken to be 4.0 for WN6 or earlier, 2.0 for later and 4.7 for WC8 & 9. We also assume a clumoing gradient of 1.0 (i.e. a smooth wind). This results in a mean mass-loss for the population of ~3.3±1.0 x 10^{-5} $M_{\odot}yr^{-1}$.

Furthermore both the WN and WC mass-loss rates are completely consistent with previous radio determinations (e.g. Leitherer et al. 1997, ApJ, 481, 898; Cappa et al. 2004, AJ, 127, 288) as well values derived from spectroscopic model-atmosphere analysis (Sander et al. 2012, A&A, 540, 144). The advantage of these measurements being the large percentage of WR stars detected. These observations therefore provide a single-look survey of mass-loss rates for the WR population.



Contour and colour-scale of WRD. Contours plotted at -1,1,1.4,2,2.8,4,5.7,8,11.3,16 x 29 μJy/beam.

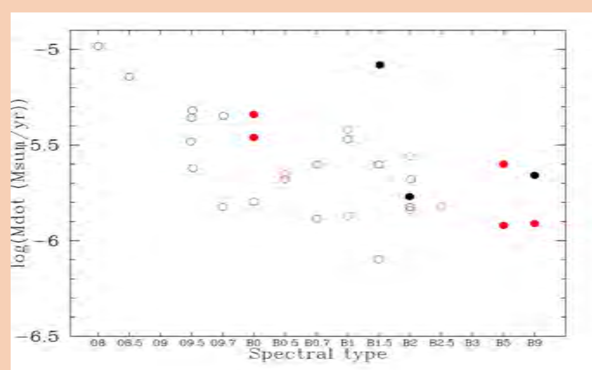


3-mm mass-loss rates versus spectral sub-type for the WRs in Wd1: red open - binary, red filled - single stars. Errors are ~ 0.2 dex. Also plotted are field-star radio mass-loss rates in black (Willis et al. 1991,, IAUS, 143; Leitherer et al. 1997, ApJ, 481, 898; Cappa et al. 2004, AJ, 127, 2885) and Galactic centre in blue (Yusef-Zadeh & Morris 1991, ApJ, 371, 59)

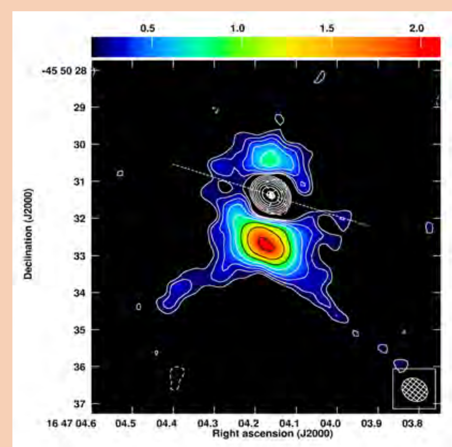
OB stars

We detect a total of 16 mm continuum sources coincident with cluster members. Subject to the classification of two objects (D09-R1 & R2) only one star of spectral type O9 was detected, with the remainder being highly luminous B super-/hyper-giants (BSG/BHG), the sgB[e] star Wd1-9 and the luminous blue variable (LBV) Wd1-243. All three mid-late BHGs and a further nine of BSGs with spectral types B0.5 Ia - B2.5 Ia. Three of the sources (D09-R1, R2 & Wd1-17) have radio properties suggestive of non-thermal emission (Dougherty et al. 2010, A&A, 511, 58) and the mm data is consistent with this conclusion. The LBV Wd1-243, the BHG Wd1-7 and the BSGs Wd1-28 & 46a appear distinctly thermal. The radio upper limits for the remaining six sources don't allow a for a sufficient conclusion. Only one of these sources, Wd1-23a, is known to be a binary (B2 Ia+ OBIa; Neguerela et al. 2010, A&A, 516, 78), but does not appear to be significantly bright at mm wavelengths.

As for the WR stars we calculate mass-loss rates for the OB population detected, again utilising the equations for mass-loss and gaunt factor from Wright & Barlow (1975, MNRAS, 170, 41) and Leither & Robert (1991, ApJ, 377, 629) assuming a smooth wind. For the OB stars, we take the electron to ion density ratio (Z) and mean number of electrons (γ) to be 1 and a mean molecular weight (μ) of 1.4. Comparing these to previous radio studies of field stars (e.g. Puls et al. 2006, A&A, 454, 625; Scuderi et al. 1998, A&A, 332, 251) shows our measurements to be in agreement with those of comparable spectral type.



Mass-loss rate versus spectral type for OB stars in red (open: supergiants; filled - hypergiants). Also shown are radio field-star mass-loss rates in black (Benaglia et al. 2007, A&A, 467, 1265; Leitherer et al. 1995, ApJ, 450, 289). Mean errors in all cases are approximately 0.2 dex.



ALMA image of the sgB[e] star Wd1-9 in contours and color-scale. Contours are plotted at -1,1,1.4,2,2.8,4,5.7,8,11.3,16 x 30 μJy/beam. The compact source emission (~153 mJy) is also displayed in white contours plotted at 0.14,0.2,0.28,0.4,0.57,0.8 x 1.4mJy/beam. The dashed line shows the orientation of line emission centroids (see Fenech et al. 2017, MNRAS, 464,75 for further details).

Resolved Stars

Surprisingly, a large number of the stellar sources appear to be resolved in these ALMA observations. In some cases this is anticipated e.g. the extended nebulae associated with the YHGs & RSGs.

However, Gaussian fitting performed on the compact emission associated with both the WRs and evolved OB stars have revealed a number of them to be spatially resolved. Specifically, 16 of the WR stars appear extended with major axes ranging from ~ 0.1 - 0.6 arcsec. There appears to be no obvious correlation between spectral sub-type or binary status for either the resolved or unresolved objects.

Utilising the mm flux densities and adopting the equation of Wright & Barlow (1975, MNRAS, 170, 41) we can infer the radius of the mm photosphere, which range from 0.1 - 3.8 mas. As a result, it would appear unlikely that we are resolving the stellar wind. However, the observed emission from both WRs and OB stars does appear completely consistent with thermal emission from a stellar wind.

Furthermore, integrated annular profile fitting of these sources also appears to suggest a potential internal structure with a possible composite nature. That of an unresolved core with a halo of emission.

Given the known cometary nebulae around the cool super-/hypergiant stars, this would suggest that these stellar winds are also being confined and shaped by the cluster enviornment leading to potentially smaller-scale compact wind-blown bubbles surrounding the WR and OB stars.