Dissecting the Galactic Super Star Cluster Westerlund 1 — A Laboratory for Stellar Evolution

Simon Clark[1]
Ignacio Negueruela[2]
Ben Ritchie[1]
Paul Crowther[3]
Sean Dougherty[4]

[1] Department of Physics and Astronomy, The Open University, Milton Keynes, United Kingdom
[2] Departamento de Física & Ingeniería, Universidad de Alicante, Spain
[3] Department of Physics and Astronomy, University of Sheffield, United Kingdom
[4] National Research Council, Herzberg Institute for Astrophysics, Penticton, Canada

Westerlund 1 is the first example of a super star cluster identified within the Galaxy. As such, its proximity allows us to resolve directly and study individual stars down to sub-solar masses, as well as their complex interactions. This in turn permits advances in our understanding of the physics of these stellar powerhouses, which drive evolution in starburst galaxies near and far. Here we provide a brief overview of our current understanding of this cluster, both in terms of its stellar constituents — and the constraints they place on the evolution of massive stars from cradle to grave — and its global properties.

Figure 1. The central region of the vigorous starburst galaxy NGC 1313 is shown in this colour image from VLT FORS data (from Release eso0643). Note the numerous shells of ionised gas excited by young massive clusters similar to Wd1.

Starburst galaxies and super star clusters

Images of starburst galaxies such as the Antennae, M82 and NGC 1313 (see Figure 1) reveal that the process of star formation appears hierarchical, with stars forming within massive clusters, which in turn are located within larger complexes that reflect the underlying structure of the natal giant molecular clouds. The impact of both these super star clusters (SSCs) and complexes on the wider galactic ecology is immense: the OB stellar population contained within dominates both the ultraviolet (UV) and, via dust reprocessing, the infrared (IR) radiative output of the host galaxy, while their post-supernovae (post-SNe) relativistic remnants — neutron stars and black holes within binary systems — are responsible for the high energy emission.

Moreover, the same population of massive stars provides significant input of mechanical energy and chemically processed material via their stellar winds and SNe. Indeed, the combination of both radiative and kinetic feedback is thought to be responsible for the initiation of superwinds that may promote or suppress subsequent generations of star formation, as well as enrich the intergalactic medium. Nevertheless, despite their pivotal role in galactic evolution the small physical extent of SSCs in external galaxies means that they must be studied via comparison of their integrated spectral and photometric properties.

But such an approach is based on two unproven hypotheses: (i) that the Initial Mass Function (IMF) of stars within such clusters (and complexes) is identical to that determined locally; and (ii) that stars within such clusters follow comparable evolutionary paths to those within the Local Group, such that we understand their radiative output, lifetimes and post-SNe endpoints. Without such assumptions we cannot accurately calibrate the population synthesis codes used to determine cluster ages and integrated masses (and hence star formation rates), nor constrain the degree of mechanical and radiative feedback that yields galactic-scale superwinds.

Unfortunately, through the 20th century it had been supposed that the Galaxy lacked spatially-resolved examples of SSCs, with the integrated masses of young (< 20 Myr) massive open clusters typically being less than $10^3\ M_\odot$ compared to 10^5–$10^7\ M_\odot$ for the former. Targeted near-IR observations of the centre of the Galaxy had revealed the presence

Figure 2. Optical image of Wd1 obtained with the Wide Field Imager mounted on the MPG/ESO 2.2-metre telescope. Note the high degree of reddening to the cluster in comparison to the foreground B supergiant (lower right). Image from Release eso1034c.

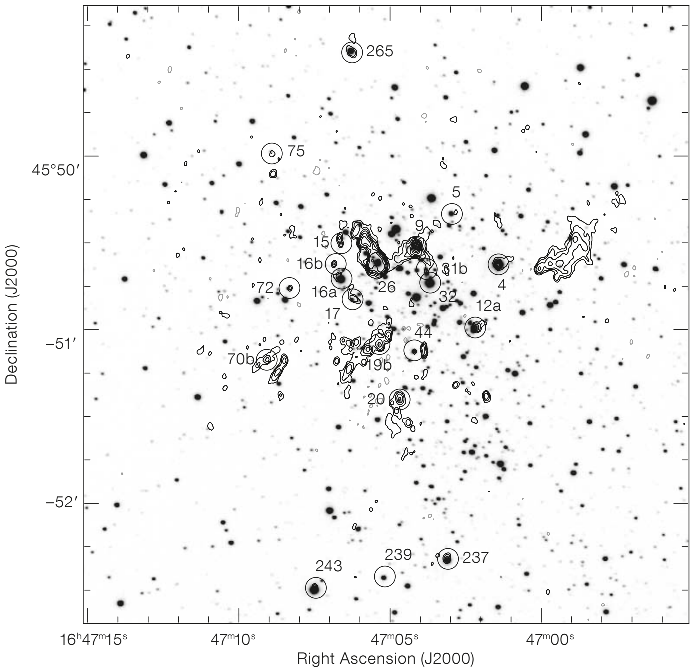

Figure 3. Overplot of radio observations (contours) on an optical image of Wd1. Note the emission associated with the cool hypergiants (Wd1-4, 12a, 16a, 32 & 265 — YHGs; Wd1-20, 26 & 237 — RSGs) indicative of significant ongoing mass loss.

of the Arches, Quintuplet and Galactic Centre clusters with masses ~ 10^4 $M_\odot$; still an order of magnitude smaller than known SSCs. In fact the first known example of a SSC had been identified fully 40 years earlier — indeed before their widespread recognition in external starburst galaxies! — but had subsequently remained in relative obscurity.

Westerlund 1

Located within the constellation of Ara (the Altar) Westerlund 1 (Wd1; see Figure 2) was simply described by Bengt Westerlund in 1961 as a very young, "heavily reddened cluster". Indeed the high extinction towards Wd1 (A_V ~ 11 mag) hampered spectroscopic investigation, with the first such survey following over a quarter of a century later (Westerlund, 1987). Despite revealing an unprecedented population of high luminosity supergiants of both early and late spectral types, Wd1 once again sank back into obscurity until radio observations of the B[e] supergiant Wd1-9 serendipitously detected a large number of radio sources amongst the evolved stellar population (Figure 3; see Clark et al., 1998 and Dougherty et al., 2010). Unexpectedly, a number of the cool red supergiants (RSGs) and yellow hypergiants (YHGs) were found to be strong radio sources, despite lacking the requisite UV flux to ionise their ejecta.

Prompted by these results we undertook spectroscopic and photometric observations of cluster members between 2001–2; firstly with the ESO 1.52-metre telescope and the Boller & Chivens spectrograph, and subsequently at higher signal-to-noise ratio (S/N) and resolution with the New Technology Telescope and EMMI spectrograph (Clark et al., 2005). Given the reddening towards Wd1, classification spectra were obtained from 600–900 nm, rather than the more common 400–600 nm window. An appropriate classification scheme, based on the occurrence and strength of H I, He I and He II lines in the OBA stars and the presence of low excitation metallic and molecular features for cool objects, was constructed from both real and synthetic spectra (Clark et al., 2005; Negueruela et al., 2010). As well as confirming the classifications of Westerlund (1987), these observations also identified large additional populations of OB supergiants and Wolf–Rayet stars (WRs), which had previously escaped detection due to a combination of comparatively low optical luminosity and heavy reddening. Indeed, subsequent observations revealed a population of 25 WRs, composed of both WN and WC subtypes; the richest haul detected within a Galactic cluster at this time (Crowther et al., 2006).

These observations enabled us to determine that Wd1 has an age of ~ 4–5 Myr and appears to be co-eval; conclusions confirmed by later observations (e.g., Negueruela et al., 2010). Moreover, utilising these spectra to calibrate our photometry, we were able to estimate that >> 100 stars within the cluster must have evolved from progenitors with initial masses ≥ 30 $M_\odot$. Such a census has two implications. Firstly, it offers an explanation for the anomalous radio emission associated with the YHGs and RSGs, whereby the diffuse UV radiation field from the hot stellar population (OB stars and WRs) provides the ionising photons. Secondly, using this population to normalise a Kroupa-type IMF we were able to infer a total (initial) mass for Wd1 of ~ 10^5 $M_\odot$, making it the most massive Galactic cluster yet discovered by an order of magnitude and hence the first SSC within the Milky Way.

Therefore, Wd1 is the first example of an SSC for which its relative proximity permits the resolution and study of individual stars to sub-solar masses — enabling the ecology of such an agglomeration to be decoded for the first time.

Massive stellar evolution — a tale of two pathways

A key driver in massive stellar evolution is mass loss, which strips away the H-rich mantle of O stars to yield H-depleted WRs. Indeed the rate at which this proceeds not only governs the precise evolutionary path trodden by the star, but also its ultimate post-SNe fate. Radio observations had already revealed the characteristic signature of heavy mass loss associated with many stars (Clark et al., 1998; Dougherty et al., 2010), while our new spectroscopy reveals a rich post-main sequence (post-MS) population. Thus Wd 1 presents a unique opportunity to investigate the physics of stellar evolution for some of the largest stars to be found within the Galaxy.

Nevertheless, such a goal is challenging for three reasons. Firstly, sophisticated modelling with non-local thermodynamic equilibrium (non-LTE) atmospheric codes is required to determine accurately physical properties such as stellar luminosity, temperature, mass-loss rate and chemical abundances; all of which are essential to determine accurately the precise evolutionary state of an individual star (see Figure 4; Ritchie et al., 2009b). Secondly, as such stars transit from the MS to H-depleted WR phase they pass through a dizzying variety of short-lived evolutionary states that include the luminous blue variables (LBVs) and the closely related P Cygni supergiant/B hypergiant, supergiant B[e] stars, YHG and RSG stages. It is thought that mass loss in such phases may play a dominant role in the removal of hydrogen and subsequent formation of WRs, but it appears likely that this process is accomplished via transient outbursts in which mass-loss rates increase by several orders of magnitude over their quiescent values. A prime example of this behaviour in LBVs is the 19th-century eruption of η Car, while similar behaviour has also been inferred for YHGs and RSGs such as ρ Cas and VY CMa. However, such outbursts are rare, with none subject to modern day observational and analytical techniques, meaning that the physical mechanism leading to the extreme mass-loss events has yet to be identified.

Finally, a synthesis of our multi-wavelength observations of Wd1 suggests a very high binary fraction amongst the WR population (Crowther et al., 2006; Clark et al., 2008). Binary-mediated mass loss through Roche-lobe overflow in short period systems offers an additional evolutionary pathway for massive stars, which leads to significantly lower pre-SNe core masses than expected for single stars. The importance of this pathway was dramatically demonstrated by the discovery of a magnetar (a class of neutron star with magnetic field strengths ~ 10^{15} G) within Wd1 (Muno et al., 2006). Conventional wisdom assumes that stars with initial masses in excess of ~ 25 $M_\odot$ give rise to the post-SNe formation of black holes rather than neutron stars. Consequently, with a current MS turnoff mass in excess of ~ 30 $M_\odot$ (Clark et al., 2005; Negueruela et al., 2010), it had been expected that only black holes should currently be forming within Wd1. Indeed, given that the pre-SNe mass loss required to yield a neutron star rather than a black hole is greatly in excess of that expected for single star evolution, significant binary driven mass loss appears mandatory to allow for the formation of the Wd1 magnetar.

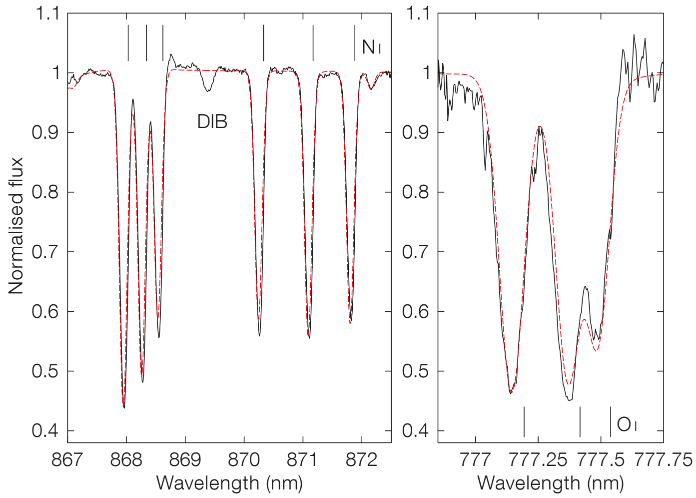

Figure 4. Comparison of observed (black) and synthetic (red) spectra of the LBV Wd1-243, focusing on the N I and O I triplets and indicating significant chemical evolution of N and O (respectively 12 and 0.1 times solar abundances).

Quantitative analysis via VLT follow-up

The existing spectral data were insufficient to address these issues, being of too low S/N and resolution to enable non-LTE-model atmosphere analysis and only at a single epoch, thus preventing the identification of either intrinsic (instabilities) or extrinsic (binary) variability. Consequently, throughout the period 2004–9 we obtained multiple epochs of high quality, 600–900 nm spectroscopic data of ~ 100 members of the evolved stellar population of Wd1 with both FORS and FLAMES on the VLT. Full details of the target selection, experimental setup and reduction techniques employed may be found in Ritchie et al. (2009a) and Negueruela et al. (2010). These data enabled us to address each of the challenges described above.

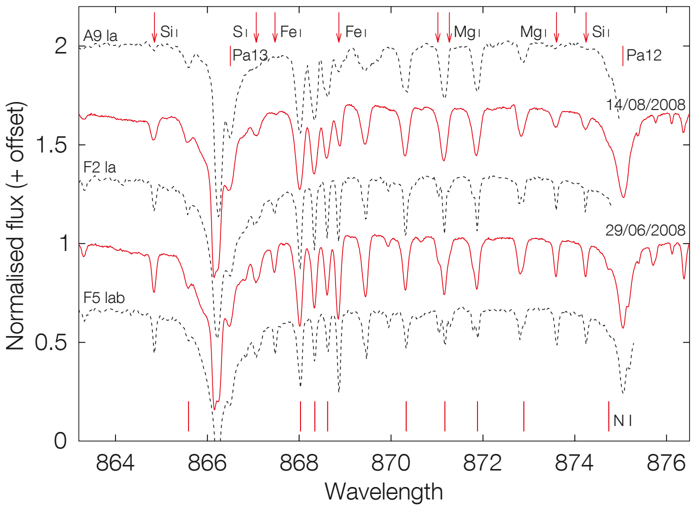

Figure 5. Time-resolved spectra of the pulsating YHG Wd1-265. Comparison with classification spectra (dotted lines) indicates significant variability in spectral type over a period of only 46 days.

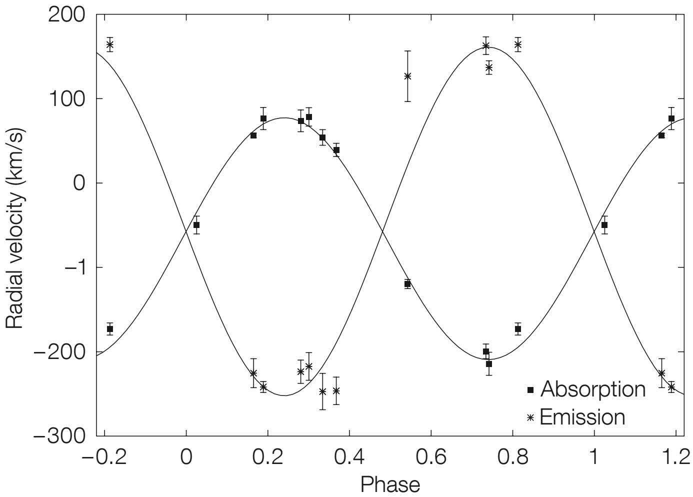

Figure 6. Radial velocity curve for both components of the WNL+OB binary Wd1-13 folded on the ~ 9.27-day orbital period.

Firstly, the data permit quantitative atmospheric modelling of individual stars in order to determine their stellar parameters. An example of such an analysis is presented in Ritchie et al. (2009b; see Figure 4). By constraining the chemical abundances for the LBV Wd1-243 it was possible to demonstrate unambiguously that it is a highly evolved, likely post-RSG, object. The use of elemental abundances to place the panoply of post-MS stars — LBVs, B/YHGs, RSGs, etc. — in a precise evolutionary scheme is a powerful technique, with mass loss systematically driving down the H/He ratio while simultaneously exposing the products of nuclear burning at the stellar surface. We aim to extend this approach to the remaining population of transitional stars within Wd1 in the immediate future.

Secondly, in combination with existing historical observations, the data enabled a search for variability amongst the subset of bright evolved stars over a ~ 50-yr baseline. Such an approach had previously allowed for the classification of Wd1-243 as an LBV, while radio observations of the B[e] star Wd1-9 showed an episode of enhanced mass loss that likely ended within the last 200 years (Dougherty et al., 2010). Intriguingly, while significant wind variability and pulsational instability appeared to be ubiquitous for all subtypes of evolved stars observed within Wd1, no further examples of LBVs have yet been identified within the hot super-/hyper-giant population.

However dramatic variations in spectral type, likely reflecting pulsation-driven changes in the stellar photosphere, were identified amongst the Blue-/YHG and RSG populations (c.f. the YHG Wd1-265 shown in Figure 5; Clark et al., 2010); indeed all stars of spectral types later than B1 appear to be pulsationally unstable. Amongst the cool super-/hypergiants this occurrence is of considerable importance since identical behaviour has been observed in field YHGs such as ρ Cas, where it has been associated with episodes of dramatically enhanced mass loss (~ 5×10^{-2} $M_{\odot}$ yr^{-1}; Lobel et al., 2003). When coupled with quantitative modelling, continued spectral monitoring of these stars raises the prospect of both determining the duty cycle of such mass-loss events as well as providing stringent constraints on the underlying physics driving these instabilities. Likewise, high cadence observations of the hotter supergiants potentially open up their internal structure to scrutiny via asteroseismology studies, while also probing the origin of their highly structured stellar winds.

Finally, we turn to the main science driver for our intensive spectrographic survey — comprising multi-epoch observations of ~ 100 evolved stars over a 14-month baseline utilising the VLT Fibre Large Array Multi Element Spectrograph (FLAMES) — the identification of radial velocity variables resulting from binary motion. While analysis of the full dataset is currently underway, preliminary results for the first year of observations of the brightest quarter of targets imply a binary frequency of > 40 % amongst the OB-supergiant population (Ritchie et al., 2009a). This finding suggests that single and binary channels *may* be of comparable importance in the evolution of massive stars, although a determination of the period distribution of the binary population will be necessary to quantitatively confirm this assertion.

A second critical result from this analysis was the identification of Wd1-13 — which had previously been identified as an eclipsing system — as a *double-lined* WNL+OB supergiant binary (Figure 6). This combination of properties enabled us to determine dynamical masses of 23 ± 3 and 35 ± 5 $M_\odot$ for the WNL and OB supergiant components respectively (Ritchie et al., 2010). Comparison to theoretical models of WR binary evolution suggest that the WNL component had an initial mass of ~ 40 $M_\odot$, which immediately places a firm lower limit on the mass of the magnetar progenitor. Given that magnetars are also present in clusters with comparatively low-mass MS turnoffs (< 20 $M_\odot$; Clark et al., 2008), their progenitors clearly span a range of masses, implying that an additional "ingredient" such as rapid rotation or a high natal magnetic field must be required for their formation.

Moreover, we may also place quantitative constraints on the location of the bifurcation in the canonical "Conti scenario" for stellar evolution, whereby the most massive stars evolve via:

O MS → WNLh → LBV → WNL → WNE → WC → SNe

thus avoiding a cool hypergiant phase, and less massive stars via

O MS → OB SG → RSG → LBV/YHG? → WNL → WNE(→WC?) → SNe

(where the WNLh designation means that the star shows hydrogen emission lines in its spectrum). Given the both YHGs and RSGs are currently present within Wd1, the masses implied for the progenitors of these stars by Wd1-13 reveals that the division must occur at > 40 $M_\odot$.

Future prospects

In the last decade of study Wd1 has yielded many of its secrets, enabling us to confirm that it is the first SSC to be identified within the Galaxy, as well as permitting us to place powerful observational constraints on the evolution of massive stars in their natural environment for the first time. However, what does the future hold? Our immediate goal is to fully determine the physical properties of the binary population of Wd1 in terms of frequency, orbital separation and mass ratio, which will be accomplished by comparison of the complete RV dataset to Monte-Carlo simulations. It is hard to overestimate the importance of such a goal — in addition to constraining the relative weighting of single and binary evolutionary channels accurately, such information will also constrain the physics of massive star formation (e.g., Ritchie et al. [2009a] and references therein) as well as the production efficiency of both high- and low-mass X-ray binaries, binary pulsars — a major source of gravitational radiation — and potentially the production of gamma-ray bursts.

Looking further ahead, the presence of RSGs within Wd1 permits a clear and unequivocal test of current theories of massive stellar evolution, which do not permit such stars to exceed $\log(L/L_\odot) \geq 5.6$ (e.g., Meynet & Maeder, 2005). Unlike field stars, the well-determined distance to Wd1 permits an accurate determination of the luminosity of the cluster RSGs once an appropriate bolometric correction has been determined via model atmosphere analysis.

Turning to Wd1 as a whole, we have a unique opportunity to investigate the interaction between individual massive stars within an SSC. The motivation for such a study is vividly illustrated by the cometary nebulae associated with the RSGs Wd1-20 & 26 and which are visible in mid-IR and radio images (Figure 3; Dougherty et al., 2010). These appear to be the result of the ablation and entrainment of the outer stellar layers/winds of these stars by the incipient cluster wind driven by the mechanical and radiative feedback from individual stars and SNe. But how do such winds work? Comparison of radio, mid-IR and X-ray data indicate that the intercluster medium appears to be multi-phase, composed of cool, neutral and dust-laden clumps shadowing warmer ionised gas in close proximity to the core, which, in turn, are imbedded in an X-ray-bright component, emitting via both thermal and non-thermal mechanisms. How is momentum imparted to this material to yield a cluster wind and what is the efficiency of this process? Answers to both questions are essential if we are to understand the impact of SSCs on their wider (extra-)galactic environments.

And finally regarding Wd1 in a wider context — did it form alone? Examination of star-forming regions suggests that such clusters do not form in isolation, but currently there is no evidence for ongoing star formation closely associated with Wd1. Was it born with other siblings which have since dispersed, or did it instead form monolithically in a single starburst event — and if so, why? How many other examples lurk in the Galactic plane? Systematic spectroscopic follow-up of candidates identified via current and future surveys such as the VISTA Variables in the *Via Lactea* survey will enable us to place and understand Wd1 in the context of the recent star formation history of the Milky Way. Clearly the discovery and analysis of Westerlund 1 has answered many questions, but has raised many more.

References

Clark, J. et al. 1998, MNRAS, 299, L43
Clark, J. et al. 2005, A&A, 434, 949
Clark, J. et al. 2008, A&A, 477, 147
Clark, J. et al. 2010, A&A, 514, 87
Crowther, P. et al. 2006, MNRAS, 372, 1407
Dougherty, S. et al. 2010, A&A, 509, 79
Lobel, A. et al. 2003, ApJ, 583, 923
Meynet, G. & Maeder, M. 2005, A&A, 429, 581
Muno, M. et al. 2006, ApJ, 636, L41
Negueruela, I., Clark, J. & Ritchie, B. 2010, A&A, 516, A78
Ritchie, B. et al. 2009a, A&A, 507, 1585
Ritchie, B. et al. 2009b, A&A, 507, 1597
Ritchie, B. et al. 2010, A&A, 520, 48
Westerlund, B. 1987, A&AS, 70, 311