An Astrophysical Laboratory: Understanding and Exploiting the Young Massive Cluster Westerlund 1

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Westerlund 1 provides a unique opportunity to probe the physics of massive stars, from birth to death and beyond, as well as the formation and evolution of a super star cluster that appears destined to evolve into a globular cluster. We highlight the result of current studies of this cluster, its diverse stellar constituents and immediate environment, concluding with a summary of future research avenues enabled by ESO facilities.

Massive stars play a central role in the evolution of galaxies, from the early Universe through to the current epoch, via their intense radiation fields and the deposition of chemically enriched gas and solid-state material into the interstellar medium. Moreover they are ultimately responsible for the most energetic, transient high-energy phenomena in the Universe: supernovae, gamma-ray bursts and X-ray binaries. It is therefore somewhat unsettling that the mechanisms of their birth, the processes governing their subsequent evolution on and beyond the main sequence (MS) and the nature of their deaths and ultimate fate — neutron star or black hole — are shrouded in uncertainty.

Nevertheless, our current understanding is sufficient to enable us to identify the physical agents driving massive stellar evolution. A central theoretical tenet is that the evolutionary pathway of a star is dependent on its initial mass, but, for the most massive stars, powerful stellar winds and, in their latter evolutionary stages, violent instabilities act to continuously strip their hydrogen-rich outer layers away. The efficiency of such processes is likely to contribute to the dichotomy between type II (H-rich) and type Ibc (H-poor/depleted) supernovae (SNe). Since stellar winds are driven by radiation pressure, this in turn introduces an additional explicit metallicity dependence into massive stellar evolution.

Moreover, the internal dynamics of such stars, and hence the degree of mixing of chemically processed and unprocessed material they experience, will also play a profound role in their evolution. Since it is likely that both the (differential?) rotation of such stars and the presence (or absence) of an internal magnetic field will play key roles in determining the efficiency of such processes, these too must be incorporated into theoretical models.

Finally, it has recently been recognised that a large proportion of massive stars are born in binary systems, and that in many cases these are close enough to permit interactions on or beyond the MS (e.g., Sana et al. 2013; de Mink et al., 2014). Since this can lead to the removal of the outer layers of a mass donor, the rejuvenation/growth of the mass recipient and, in extreme cases, their merger, it is apparent that both the binary fraction as well as the physical properties (e.g., mass ratio and orbital separation) also profoundly impact stellar evolution.

One can thus readily envisage how the endpoints of the stellar lifecycle depend on the interplay of these parameters. At a given stellar mass, do these factors combine to drive sufficient mass loss to permit a type Ibc rather than a type II SN? Is the pre-SN core rotating rapidly enough to permit a gamma-ray burst? Indeed, is the core massive and compact enough to form a black hole rather than a neutron star, and, if the latter, is it powered by the extraction of rotational or magnetic energy?

Observational tests

How, then, may one quantify the roles played by these various evolutionary agents? Ideally, one would like to study a homogeneous stellar population where the competing physical effects might be distinguished. An obvious solution is to employ massive stellar clusters or associations as laboratories, since both the age and metallicity of the stars may be expected to be well constrained and furthermore they furnish a statistically robust sample size.

With a mass likely > 10^5 $M_\odot$, the 30 Doradus star-forming complex (R136) within the Large Magellanic Cloud is a compelling target (Figure 1, bottom), more so because the low foreground extinction permits observations of traditional "blue-end" (400–500 nm) spectral diagnostics for massive stars. These factors drove the development and implementation of the VLT/FLAMES Tarantula survey (Evans et al., 2011), which encompasses ~ 800 O and B stars and, to date, has resulted in about 20 refereed publications on the properties and evolution of its members. Given this undoubted success, what is the motivation for additional studies?

We may identify a number of factors. Most importantly one would wish to study differing metallicity environments in order to determine the effect of chemical composition on stellar evolution. Secondly, star formation across the ~ 200 pc extent of 30 Dor appears to have proceeded in multiple bursts over ~ 10 Myr (Walborn & Blades, 1997). Therefore, identifying the co-eval populations ideally required to most effectively investigate stellar evolution is non-trivial, especially since the most likely locations to host them — dense individual clusters such as

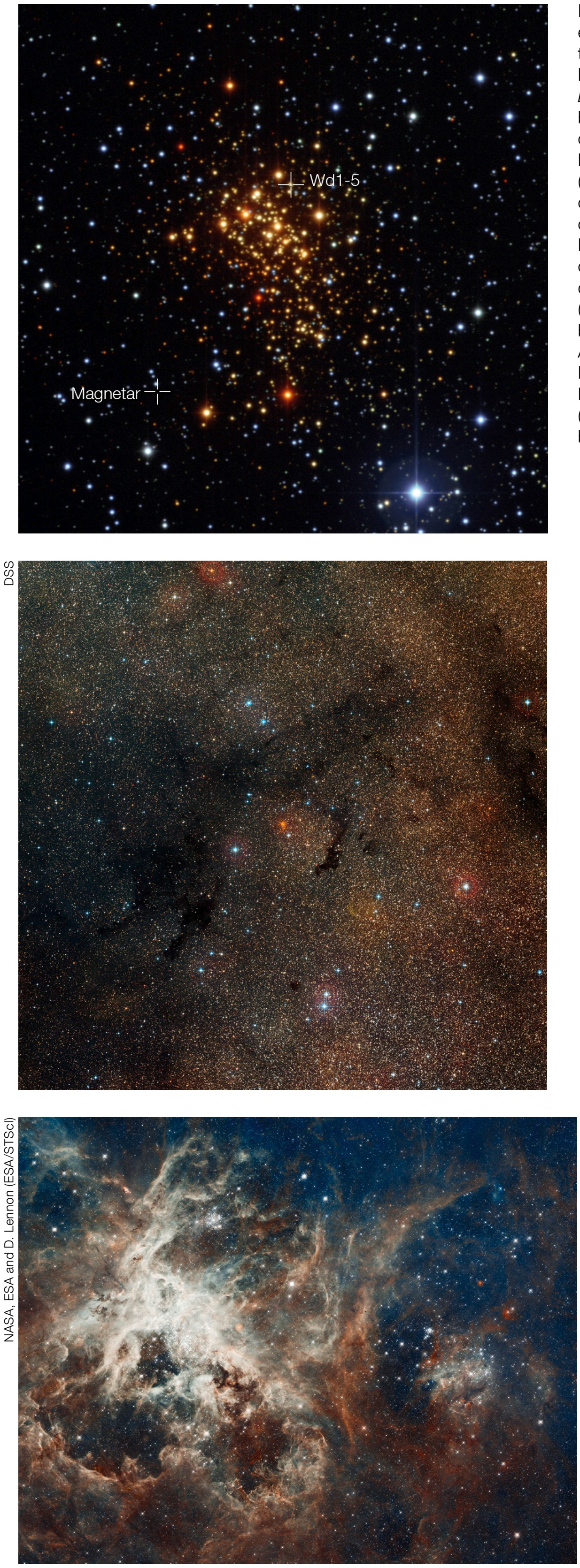

Figure 1. Top: Optical image of Westerlund 1 (~ 7.3 pc on a side) taken with the Wide Field Imager (WFI) on the MPG/ESO 2.2-metre telescope, with *BVR* filters, showing the position of both the magnetar and putative binary companion Wd1-5.
Middle: Wide-field optical image (~ 175 pc on a side) of the field centred on Wd1 (the fuzzy orange blob in the centre).
Bottom: HST composite-colour image of the star-forming complex 30 Doradus in the Large Magellanic Cloud (size 185 pc by ~ 146 pc), from a combination of Hubble Space Telescope Advanced Camera for Surveys/Wide Field Channel (ACS/WFC) and Wide Field Camera 3 (WFC3/UVIS) images (*i*-band) and WFI ([O III] and Hα narrowband filters).

R136 — are difficult to probe due to crowding. Despite this extended star formation history, 30 Dor appears to lack the cool hypergiants which help drive the extensive mass loss required to facilitate the formation of H-depleted Wolf–Rayet stars (WRs). Finally one might also wish to explore whether the environment in which the stars form affects their life cycle, e.g., via the dynamical formation, modification and disruption of binaries.

Historically, it was thought that the massive stellar aggregates required to enable such studies were absent from the Galaxy. However the advent of near- and mid-infrared surveys revealed an ever-expanding population of heavily obscured young massive clusters, alleviating this apparent deficiency. Nevertheless, given the effort expended in uncovering this population, it is frustrating that possibly the most massive cluster in the Galaxy appears to have been hidden in plain sight: in 1961 Bengt Westerlund simply characterised his discovery as a very young "heavily reddened" cluster, with Westerlund 1 (Wd1; Figure 1, top and middle) languishing in relative obscurity for the next forty years.

In retrospect the detection of an unprecedented cohort of cool, short-lived yellow hypergiants (YHGs) and red supergiants (RSGs) in the earliest observations of Wd1 obviously required a substantial population of massive progenitors; a clear indication that the cluster was worthy of follow-up observations. Motivated instead by the unusual radio properties of Wd1, the discovery that it hosted unprecedented numbers of both blue super- and hypergiants (BSG/BHGs) and WRs came as a complete surprise (Clark et al., 2005). Analysis of these populations implied a distance of ~ 5 kpc, a radius of < 2 pc (in comparison to the 200 pc extent of 30 Dor; Figure 1, bottom) and an apparent integrated mass of ~ 10^5 $M_\odot$, revealing that Wd1 was the first direct Galactic analogue of the super star clusters that characterise the young stellar population of starburst galaxies.

Intriguingly, the simultaneous presence of both WRs and RSGs was unexpected, suggesting that we either view Wd1 at a privileged point in its evolution, or that it comprises two or more stellar

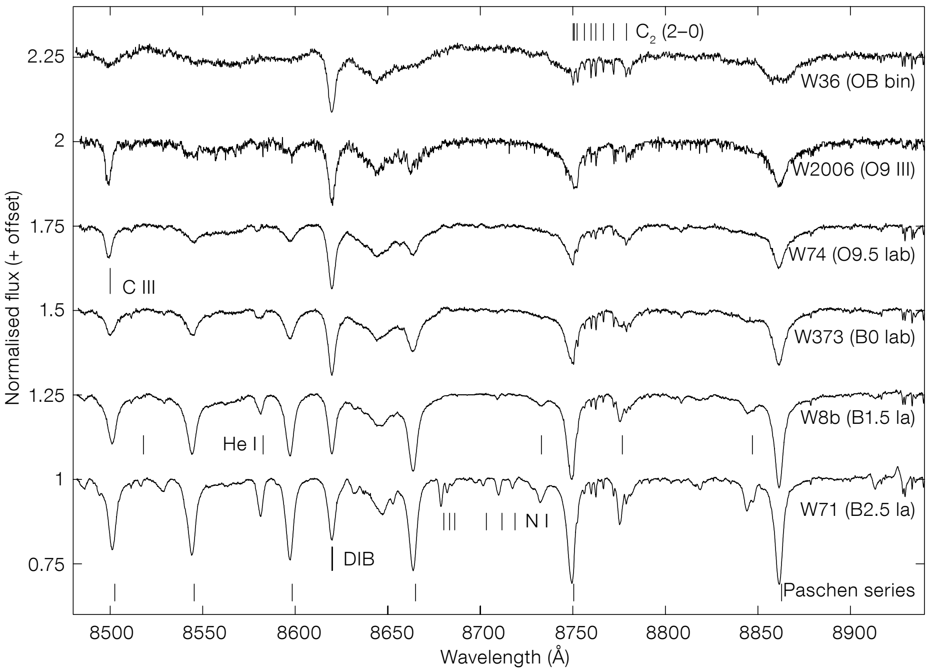

Figure 2. Montage of representative red-end optical spectra of evolved OB stars in Wd1 showing the smooth progression in both spectral type and luminosity class expected for a coeval stellar population (from Clark et al., in prep.).

populations. In order to investigate this issue, follow-up observations of the evolved OB star population were made with the suite of Very Large Telescope (VLT) instrumentation. These revealed a highly uniform population, with the spectral type and luminosity class of stars evolving continuously from O9 III to B2.5 Ia (see Figure 2; Negueruela et al. [2010] and Clark et al. in prep.). This behaviour is exactly that expected for a simple homogeneous and co-eval stellar population at an age of ~ 5 Myr, exactly the time for which one might expect the co-existence of WRs and RSGs. Critically, these observations would have detected a population of either younger or older supergiants if present within Wd1, the absence of such stars implying that it formed in a near instantaneous starburst. Such a conclusion was independently reached via observations at the other extreme of the mass function, with an age spread of < 0.4 Myr suggested for Wd1 via the properties of stars at the MS turn-on (Kudryavtseva et al., 2012).

How did Wd1 form?

The deduction of a nearly instantaneous burst immediately begs the question of how Wd1 formed. Observations of other star-forming regions in the Galaxy, and beyond, appear to show an additional level of hierarchy, whereby star clusters themselves form in larger complexes embedded within the remains of their natal giant molecular clouds. Exemplars include 30 Doradus, which hosts a number of clusters distributed throughout its confines (Figure 1, bottom), and the G305 complex, comprising a number of apparent proto-clusters embedded on the periphery of a wind-blown bubble driven by the young massive clusters Danks 1 and 2 (Clark & Porter, 2004; Davies et al., 2012). A further, diffuse population of massive stars is distributed across both regions, which taken together are indicative of ongoing star formation activity over several Myr.

However wide-field optical imaging of Wd1 reveals no such ongoing star formation activity, nor satellite clusters (Figure 1, top and middle); a conclusion supported by inspection of near- and mid-infrared data (e.g., the Two Micron All Sky Survey [2MASS] and the Spitzer Galactic Legacy Infrared Mid Plane Survey [GLIMPSE] and Multi Band Imaging Photometer Galactic [MIPSGAL] surveys). Mindful that it might be surrounded by a diffuse halo of isolated massive stars (either OB stars or RSGs; c.f., Negueruela et al., 2011), we obtained AAOmega multi-object spectroscopic observations of photometrically selected targets, but no such population was identified. Entirely unexpectedly, Wd1 appears to have formed in splendid isolation. Given both its coevality and the absence of additional, contaminating populations it thus serves as a "gold-standard" laboratory for the analysis of massive stellar evolution.

This, however was not the only surprise. Ostensibly designed to search for binary candidates, a multi-epoch radial velocity (RV) survey of the OB star population of Wd1 was undertaken with VLT/FLAMES (Ritchie et al., 2009). However the resultant dataset also permitted a determination of the cluster velocity dispersion, once the intrinsic RV variables, which would artificially inflate this measurement, were removed from the sample. Such an analysis of the pre-2010 dataset returns a velocity dispersion of < 4.6 km s^{-1} (Clark et al., 2014). This implies that Wd1 is sub-virial, which is difficult to explain since, in conjunction with its radial extent, one would instead expect it to be dynamically relaxed and hence in virial equilibrium. One potential solution to this apparent paradox might be that Wd1 formed, or is in the process of forming, via the merger of a number of discrete sub-clumps. However no statistical evidence for such spatially distinct co-moving groups was found within the RV data.

Our new observations appear to raise more questions than answers. Why is Wd1 currently in a sub-virial state? How was so much mass accumulated in such a small volume of space? What was the nature of the physical agent that led to its apparently instantaneous formation in an otherwise unassuming region of the Galaxy before quenching any further activity? The pronounced differences between Wd1 and other massive galactic stellar aggregates demand answers to such questions, even before one considers that it represents the outcome of the dominant mode of star formation in starburst galaxies and, that, given its sub-virial nature, we are witnessing the formation of a proto-globular cluster in the local Universe.

Binary evolution in action

Despite the uncertainty in the mode of its formation, the highly coeval nature of Wd1 makes it an ideal laboratory to study the effects of binarity on stellar evolution. Binary systems may be identified via a number of methodologies, from the RV survey described above and periodic (eclipsing or ellipsoidal) photometric modulation, to indirect diagnostics such as hard, over-luminous X-ray emission and/or the presence of host dust, both forming in the wind collision zones of massive binaries (Clark et al., 2008). A synthesis of these disparate criteria has to date resulted in the identification of over 70 confirmed and candidate binaries within Wd1 (Ritchie et al., in prep.), with the Monte Carlo simulations required to return an unbiased binary fraction underway.

The central role that binarity plays in stellar evolution is clearly illustrated by contrasting the homogeneous population of OB giants and supergiants to the remarkably diverse cohort of further-evolved transitional and WR stars within Wd1 (Clark et al., 2005; Crowther et al., 2006). Binary interaction in compact systems has the effect of prematurely removing the outer H-rich mantle of the primary and hence modifying evolution, by both preventing a subsequent transition through a cool hypergiant phase and initiating the extreme mass-loss that characterises WRs earlier than anticipated. Subject to limits imposed by its rapid spin-up, the secondary accretes some of the material lost by the primary, while some is lost to the system. This is well illustrated by Wd1-9, where the central binary appears completely veiled by a dense dusty circumstellar torus, resulting in the rich emission-line spectrum and infrared excess that characterises such supergiant B[e] stars (Figure 3; Clark et al., 2013).

The subset of early (Wd1-5, -13 and -44) and late (Wd1-7, -33 and -42a) BHGs apparently represents the immediate outcome of both pathways. Showing no indication of binarity, the latter group forms a natural extension of the sequence of B0-2Ia supergiants as predicted by evolutionary theory. Conversely the properties of the former are consistent with binary-driven mass loss; indeed RV data for both Wd1-13 and -44 reveal them to be short-period systems (Ritchie et al., 2010 and in prep.).

The WC9+O star binary Wd1-239 (P_{orb} ~ 5.05 days; Clark et al., 2011) is consequently of interest since its properties are consistent with expectations for the pre-SN endpoint of such a pathway. Under this scenario, the early onset of the WR phase leads to significant additional mass loss, a low pre-SN core mass and the production of a neutron star. However the current compact configuration of Wd1-239 accommodates an even more exciting scenario: the rapid rotation induced in massive, tidally locked binaries naturally leads to highly efficient internal mixing and hence chemically homogeneous evolution. This halts the expansion of the primary and, as a consequence, it remains within its Roche lobe, preventing binary-driven mass loss.

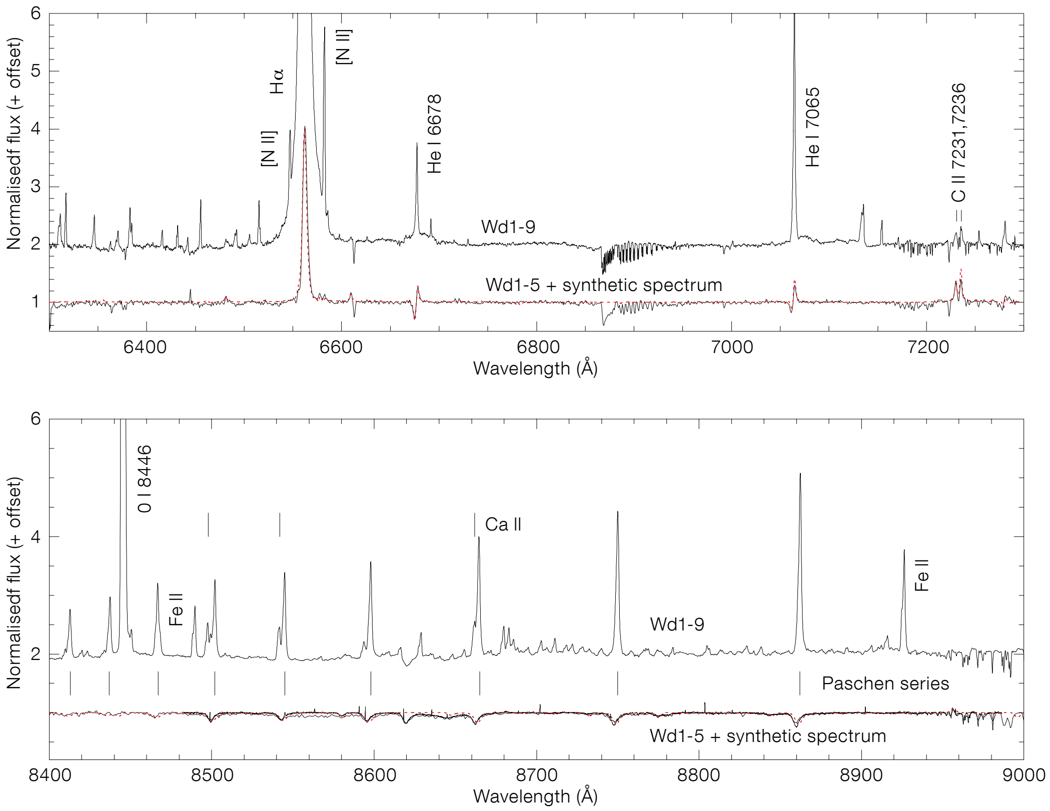

Figure 3. Optical spectra of the supergiant B[e] binary Wd1-9 and the blue hypergiant Wd1-5, a post binary interaction product. A best-fit synthetic spectrum derived from a non-local thermal equilibrium model atmosphere for Wd1-5 is overplotted in red. Major transitions are indicated; weaker emission features in the spectrum of Wd1-9 are from low excitation metals such as Fe II.

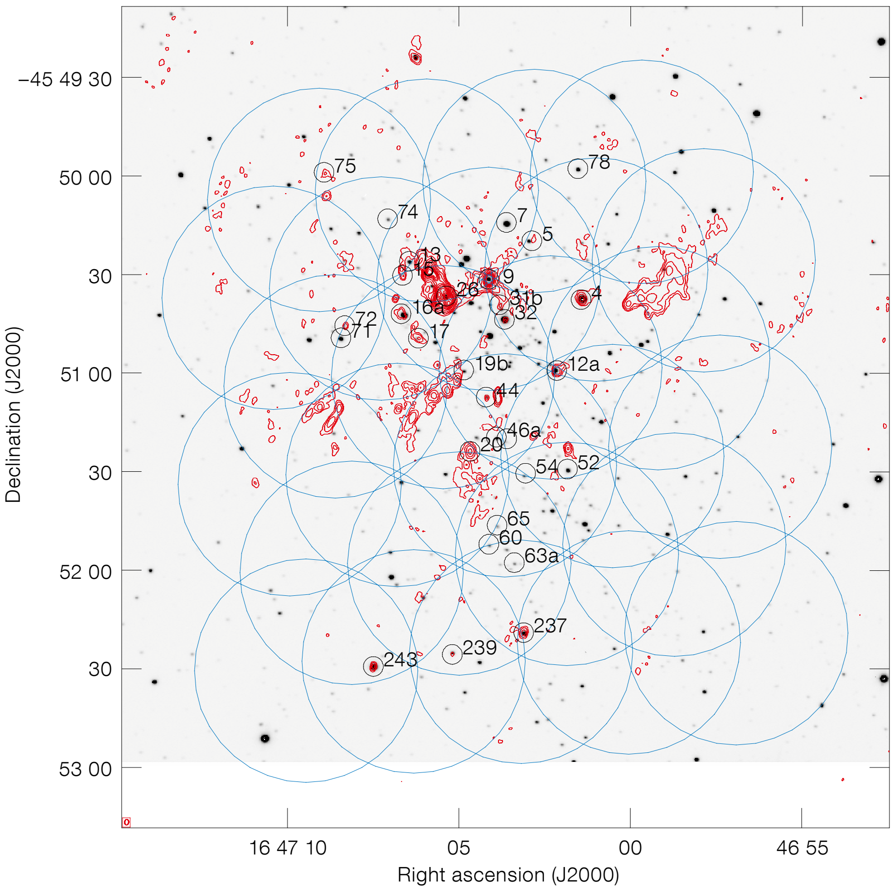

Figure 4. Optical image of Westerlund 1 (greyscale) with both the 3 cm radio map (red contours; Dougherty et al., 2010) and ALMA pointings (blue circles) overplotted.

In contrast to the former scheme this in turn leads to a high pre-SN core mass and resultant black hole (BH) formation.

Clearly then, the evolutionary history of a given star — e.g., single versus binary and chemically homogeneous versus inhomogeneous — plays a critical role in the "choice" of post-SN relativistic remnant. With an initial mass > 35 $M_\odot$ (c.f., Ritchie et al., 2010), one would expect that any single star undergoing a SN within Wd1 at this epoch would result in the formation of a BH. Hence, following the arguments above, the discovery of a young, highly magnetised neutron star within Wd1 — a magnetar (Muno et al., 2006) — provides a powerful motivation for validating these scenarios, more so since the birth of such magnetars has been implicated in some of the most energetic explosions in the Universe (gamma-ray bursts and super-luminous SNe).

It is therefore reassuring that observational support for this paradigm has been provided by the discovery of a candidate for the pre-SN binary companion of the magnetar — the runaway BHG Wd1-5 (Figures 1 and 3; Clark et al., 2014). Tailored spectral analysis reveals a carbon-rich chemistry that can only have arisen via binary evolution, a conclusion buttressed by its over-luminosity for its spectroscopic mass. We employed the current properties of Wd1-5 to infer a pre-SN history for the putative Wd1 magnetar progenitor system whereby the primary in a compact (P_{orb} < 8 days) 41 + 35 $M_\odot$ binary transfers its outer layers to the secondary. As a result it rapidly spins up and becomes so massive that it evolves more rapidly than the primary, initiating a second interactive phase in which its outer layers are also ejected, revealing the chemically processed core. A final phase of reverse mass transfer from this newborn WR star pollutes the primary, yielding carbon-enhanced chemistry, before the secondary is lost to the type Ibc SN in which the magnetar forms and the primary is unbound, which we observe today as Wd1-5. Encouragingly, such a binary pathway naturally leads to rapid rotation in the magnetar progenitor, as well as physical conditions in which a significant magnetic field may be born, which are both pre-requisites of current theories of magnetar formation.

Future prospects

In the preceding text we have highlighted some recent results from our ongoing efforts to fully exploit the opportunity presented by Wd1, but where do we go from here? In the near future our immediate goals are to fully characterise the binary population in terms of frequency, separation and period. Tailored quantitative analyses of individual systems will run in parallel to this; the first aim of this strand being the determination of the evolutionary status of the cool BHG population — i.e., are they the progenitors or descendants of the RSGs?

Our current and archival data will also permit us to identify massive blue stragglers and other binary products within Wd1 that have been predicted on theoretical grounds (de Mink et al., 2014). This is of importance for both the verification of our putative magnetar formation scenario and also because Schneider et al. (2014) suggest that such a route may produce some of the most massive stars known — essentially suggesting that massive star formation may be a two-stage process, and in the process modifying the primordial cluster initial mass function.

The advent of the *K*-band Multi Object Spectrograph (KMOS) enables the efficient accumulation of spectra sampling the chemical and rotational diagnostics essential for the model-atmosphere analysis of the lower luminosity, less-evolved stars; hitherto inaccessible due to interstellar extinction. Novel approaches

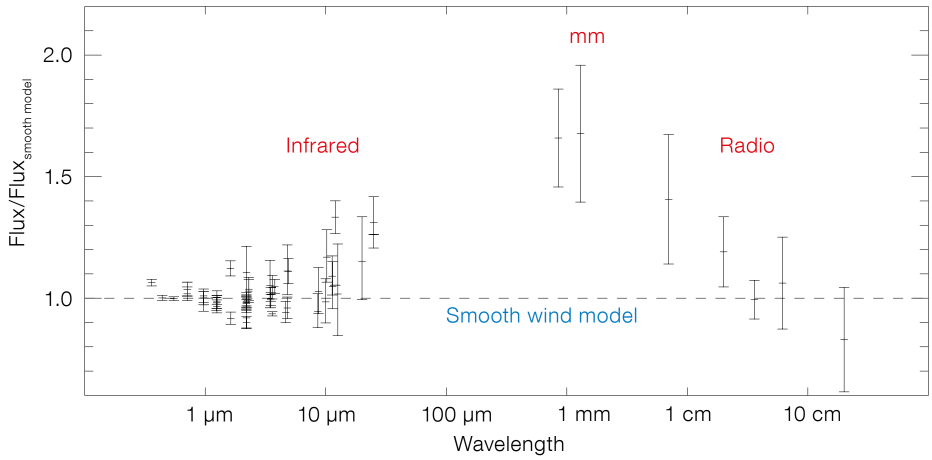

Figure 5. Representative spectral energy distribution for the B0 Ia star ε Ori showing the submillimetre excess introduced by wind clumping (from Blomme et al., 2002).

to understand the nature of these stars may also be employed. For instance current observations indicate that pulsational variability is ubiquitous across all stellar populations within Wd1 (Clark et al., 2010); theoretical modelling by Saio et al. (2013) suggests that the periodicities of such pulsations provide important information on the evolutionary state of the pulsators. A synthesis of such data would allow the accurate construction of an enhanced Hertzsprung–Russell diagram for the cluster, potentially allowing us to break temperature/luminosity degeneracies and determine whether, for example, a given BSG or B-/YHG is in a pre- or post-RSG phase.

Moving beyond multi-object spectroscopy, the proximity of Wd1 permits the resolution and detection of individual stars at submillimetre and radio wavelengths, a feat not yet replicable for 30 Dor. Figure 4 shows the coverage of extant radio observations (Dougherty et al., 2010) and approved Atacama Large Millimeter/submillimeter Array (ALMA) observations (PI: Fenech). At long wavelengths, the submillimetre and radio observations will allow the degree of substructure (clumping) present in the winds of the OB star cohort to be quantified, and refinement of the mass-loss estimates, which are currently uncertain by a factor of ~ 5 or more due to their dependence on this parameter. Figure 5 shows as an example the effect of wind clumping compared to the smooth wind model for a nearby B0 supergiant. Similarly, the ALMA observations will permit estimates of mass loss for the YHGs and RSGs to be made via the dust content of their winds. In combination these approaches will better constrain the rate at which mass is lost throughout the full evolutionary cycle of massive stars — critical input physics for theoretical modelling.

Very Large Telescope (VLTI) observations of the hypergiant population permit the direct resolution of their photospheres and circumstellar environments. This is essential in order to quantify the effects of the harsh ultraviolet environment of Wd1 on such distended stars — do they experience surface ablation and/or dust destruction, and are the extended CO and water layers (called MOL-spheres; Arroyo-Torres et al., 2015) that characterise isolated RSGs precluded? Similar observations will also allow constraints to be placed on the geometry and properties of the circumstellar torus of Wd1-9 and hence on the physics of the common-envelope binary evolution.

Binary interactions may also be probed with the ~ 350 ks of archival Chandra and XMM-Newton observations that have accumulated via studies of the magnetar (Bartlett et al., in prep.), a six-fold increase in integration time compared to previous studies (Clark et al., 2008). Determining the origin of the high-energy emission of Wd1 is a particularly exciting prospect, given that it has recently been recognised to be both a GeV and TeV source (Ohm et al., 2013).

To summarise, Wd1 is an enticing target across the whole electromagnetic spectrum, with its youth, mass and proximity conspiring to create a unique environment for the study of massive star and star cluster formation and evolution. Complementing ongoing studies in the low-metallicity environment of 30 Dor, it naturally falls along a sequence of Galactic clusters with ages ranging from 1–3 Myr (e.g., the Arches and NGC 3603) through to 15–20 Myr (the RSG-dominated clusters at either end of the Galactic bar) allowing us to address the evolution of stars from ~ 10 to > 100 $M_{\odot}$, while providing fresh insights into the recent star formation history of the Milky Way. Moreover its integrated mass and stellar density allow us to probe the physics of the unresolved super star clusters that characterise external starburst galaxies through cosmological time and, given its apparent sub-virial nature, the birth throes of a future globular cluster.

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