Young Massive Clusters as probes of stellar evolution

Ben Davies

School of Physics & Astronomy, University of Leeds, Woodhouse Lane, Leeds LS2 9JT, UK;
Chester F. Carlson Center for Imaging Science, Rochester Institute of Technology, 54 Lomb Memorial Drive, Rochester NY, 14623, USA

Abstract. Young Massive Clusters (YMCs) represent ideal testbeds in which to study massive stellar evolution as they contain large, coeval, chemically homogeneous, samples of massive stars. By studying YMCs with a range of ages (and hence turn-off masses), we can investigate the post-main-sequence evolution of massive stars as a function of initial mass. Recent discoveries of YMCs over a range of ages within our own Galaxy - where we can successfully resolve individual stars - offers the unprecedented opportunity to test our ideas of massive stellar evolution. Here, I review some of the recent works in this field, and describe how we can use YMCs to investigate several topics, including (a) the evolutionary state of H-rich Wolf-Rayet stars; (b) the influence of binarity on stellar evolution in dense clusters; and (c) Red Supergiants and the post-supernova remnants they leave behind.

1. Introduction

It is increasingly apparent that all stars form in some form of cluster. In very massive star clusters, large numbers of massive stars can be found, and the strong winds of these stars can very quickly evacuate the leftover natal material, halting the star-forming process. What is left is a large collection of stars which have practically the same age, a freeze-frame in the evolution of stars with a range of initial masses. By assembling a large number of such clusters with a range of ages in which we can resolve the individual stars, we can build a movie of stellar evolution as we watch stars of progressively lower mass evolve off the main-sequence (MS). By measuring the point at which stars are just leaving the MS, we can make direct links between initial stellar mass, various post-MS evolutionary phases and even post-SN objects such as neutron stars.

The idea of using young clusters of stars to draw conclusions about stellar evolution is not new – there have been several pioneering works by, for example, Schild & Maeder (1984); Humphreys et al. (1985); Massey et al. (2000, 2001). However, these early works were typically confined to optically visible clusters, and hence objects which were within about 1kpc of the Sun. Unfortunately, the young star clusters within this volume of space are not the most dazzling; few have masses in excess of $10^3 M_\odot$. If a typical Salpeter Initial Mass Function (IMF) is assumed, one needs clusters which are more massive by a factor of $\sim 10$ in order to have a statistically-useful number of massive stars.
In the last 10-15 years, advances in infra-red astronomy – both from the point-of-view of instrumentation and of analysis techniques – have greatly increased the detectable volume of the Galaxy, it is now commonplace to observe objects at near-IR wavelengths which are obscured by \( \sim 30 \) mags of extinction in the optical. Consequently, the number of Galactic young star clusters with masses in excess of the magic figure of \( 10^4 M_\odot \) is growing at a rate of about 1 per year.

Using this sample of Young, Massive Clusters (YMCs) we can now begin to address several topics pertaining to the evolution of massive stars, such as the nature of Luminous Blue Variables, the progenitors of SNe, and the influence of binarity. They also offer the opportunity to critically test models of massive stellar evolution, which are an integral part of the study of unresolved starburst systems in external galaxies.

In the following sections, we will review how topics such as these have recently been addressed in a series of case studies of individual clusters.

2. Case study I. The Arches Cluster

This cluster, located only \( \sim 30 \) pc away from the Galactic Centre, has a mass of around \( 2 \times 10^4 M_\odot \) and is about 2-3Myr old (Cotera et al. 1996; Figer et al. 2002; Najarro et al. 2004; Figer 2005; Martins et al. 2008). Its age means that its most massive stars are still on – or at least are very close to – the MS. These stars appear as the so-called Hydrogen- and Nitrogen-rich Wolf-Rayet stars (WNLh). They are not what one typically means when talking about Wolf-Rayet stars (WRs); they still have H-rich envelopes and are core H-burning objects. However, they drive such massive, fast winds that their spectra are filled with the strong, broad emission lines synonymous with WRs.

The large, homogeneous sample of WNLh stars in the Arches Cluster offers the opportunity to re-assess the evolutionary state of these stars with respect to other massive post-MS objects, as we can be reasonably confident of the stars’ luminosities and initial masses. In Fig. 1, we show a plot of H mass-fraction versus luminosity for WNLh stars in comparison to Luminous Blue Variables (LBVs), taken from Smith & Conti (2008). The evolutionary path of stars on this diagram begins at the top (i.e. H-rich), and falls downwards as the H-fraction drops gradually to \( \sim 0 \) whereupon the star becomes a ‘typical’ WN star. By comparing the H mass fractions of LBVs to a sample of Galactic WNLh stars from Hamann et al. (2006), Smith & Conti argued that the LBVs represented a phase immediately preceding the WNLh phase, due to the H content of LBVs being generally higher than that of WNLh stars.

However, the Hamann et al. (2006) WNLh sample was not homogeneous; it contained objects located throughout the Galaxy with presumably a large range of initial masses, as well as uncertain distances. The Arches Cluster sample of WNLh stars is arguably a much better tool with which to address this problem. In Fig. 1, we overplot the Arches WNLh stars, using the data from Martins et al. (2008). We can see that, rather than being more evolved than the LBVs, many have similar H mass-fractions. Indeed, some of the Arches WNLh stars still have all their H.
Figure 1. Hydrogen mass-fraction versus luminosity for LBVs, a Galactic sample of WNLh stars (from [Hamann et al. 2006] and the WNLh stars in the Arches Cluster. From the Galactic sample of WNLh stars, it appears that they are more evolved than the LBVs. However, the homogeneous sample of the Arches cluster (taken from [Martins et al. 2008]) suggests that they occupy the same evolutionary space, and may even be less evolved than the LBVs. Adapted from a plot in [Smith & Conti 2008].

Figure 1 would seem to cast doubt on an evolutionary connection between WNLh stars and LBVs. Indeed, if the most massive stars in the Arches Cluster, whose luminosities are consistent with those of LBVs, can lose 80% of their H without apparently going through an LBV phase, does this suggest that not all massive stars become LBVs? This might mean that LBVs result from stars with special initial conditions such as fast rotation or binarity. Alternatively, it might mean that the LBV phase is much shorter than previously thought ($\sim 10^4$ yrs), and that even in a cluster as well populated with massive stars as The Arches the chances of catching a star as an LBV are still small.

3. Case study II. Westerlund 1

At 4-5Myr old, Westerlund 1 (Wd 1) is slightly older than The Arches. It is the most massive known young cluster in the Galaxy, approaching $10^5 M_\odot$ ([Clark et al. 2005; Brandner et al. 2008]). The cluster is notable for its rich stellar inventory – to date, there have been 24 WRs confirmed (20% of all known WRs in the Galaxy), as well as two candidate LBVs, four P Cygni-type hypergiants, many more ‘regular’ OB supergiants, six Yellow Hypergiants (YHG) and four extreme mass-losing Red Supergiants (RSGs).
Figure 2. Westerlund 1 as seen in X-rays. Many of the large number of point sources can be associated with massive stars in interacting binary systems, which imply a lower-limit to the binary fraction of massive stars of \( \gtrsim 70\% \) (Clark et al. 2008).

As Wd 1 is the closest thing we have to the so-called Super Star Clusters observed in star-forming galaxies, the obvious challenge to the Simple Stellar Population (SSP) models used to analyze unresolved extra-galactic starburst systems is to reproduce the properties of Wd 1. Perhaps predictably, they are unable to do so. Specifically, it was shown by Crowther et al. (2006) that single star evolutionary models under-predicted the numbers of N-rich WRs with respect to H-rich and C-rich WRs. They argued that, by incorporating the effects of close binary evolution such as Roche-lobe overflow and common envelope evolution, the ratios of WNh/WN and WC/WN could be reduced, and that the observed WR population of Wd 1 was evidence for a high binary fraction in Wd 1.

Further – and arguably more direct – evidence for a high binary fraction in Wd 1 was presented in Clark et al. (2008). Using X-ray data (see Fig. 2) they showed that 17/24 WRs in Wd 1 were in massive binary systems, whereby the wind-wind collision region between the WR and a companion star produces a hard X-ray spectrum. That is, 70% of stars in Wd 1 with masses greater than \( \sim 40 M_\odot \) are in interacting binary systems. This is very much a lower limit, as X-rays will only be produced if the separation between the two stars is large enough to allow the winds to accelerate to \( \gtrsim 1000 \text{ km s}^{-1} \) before colliding.

So, the key lesson to be learned from Wd 1 is that binarity plays a key role in the evolution of massive stars, especially in dense massive clusters. This point is particularly important when interpreting the integrated properties of unresolved systems such as young massive clusters in starbursting galaxies.
4. Case study III. The Red Supergiant Clusters

In recent years, two more young massive clusters have been discovered in the inner Galaxy by virtue of the large numbers of RSGs they contain and the brightnesses of these stars in the near-IR. The so-called Red Supergiant Clusters (RSGCs) in the direction of Scutum both have masses in excess of $10^4 M_\odot$, with ages of 12Myr and 20Myr for clusters 1 and 2 respectively (Figer et al. 2006; Davies et al. 2007, 2008). Each cluster on its own represents a large homogeneous sample of RSGs, while the two clusters together – with their differing ages and similar chemical abundances (Davies et al. 2009) – offer the opportunity to study RSG evolution at uniform metallicity and as a function of initial mass.

Cluster #1 (hereafter RSGC1) in particular allows us to study the phenomenon of maser emission in RSGs. Maser emission is typically observed in the most ‘extreme’ RSGs such as VY CMa and $\mu$-Cep, objects with high mass-loss rates and large amounts of circumstellar material. It is also seen in the proto-typical post-RSG IRC +10420, an object which is too hot for molecules to survive in its wind and must therefore have evolved away from a cooler phase very quickly. So, is the maser active phase of RSGs an indication that the star is experiencing a very high mass-loss rate, and is perhaps on the verge of shedding its envelope and beginning its evolution toward the blue?
We investigate this question of ‘masers as an evolutionary signpost’ in Fig. 3, where we plot a HR-diagram for the stars in RSGC1. In the figure we identify those stars which have SiO maser emission, which originates close to the photosphere, with a small circle. Masers of H$_2$O and OH, which originate at progressively larger distances from the star, are indicated with larger circles.

We find that only the most luminous stars in RSGC1 have maser emission. Further, we see that only F13 – a very bright star which appears to be on the verge of returning toward the blue – has all three masers switched on. From these data, we suggest the following scenario: once leaving the MS, stars with $M_{\text{init}} \sim 10 - 20 M_\odot$ evolve very quickly across the HR-diagram to become ‘early-stage’ RSGs. As the He core grows in mass, the star becomes more luminous, and the increased radiation pressure on the surface layers drives up the mass-loss rate. Eventually, the mass-loss has been high enough for long enough such that the density above the photosphere is ripe to produce SiO maser emission. As the mass-loss continues at a gradually increasing rate, the critical densities for the the H$_2$O and OH masers are reached at larger distances from the star, and all three masers are switched on. At this point the star may have shed enough of the H-rich envelope for the opacity in the outer layers to drop, causing a rapid evolution back toward the blue.

Further empirical evidence for this evolutionary scenario is found in RSGC1, in the form of a luminous yellow star, apparently similar in nature to $\rho$ Cas (Davies et al. 2008). This star has a similar luminosity to the brightest RSGs in the cluster (see Fig. 3), consistent with the idea that the star has evolved away from the tip of the RSG zone at constant bolometric luminosity.

4.1. The link between initial mass / post-SN remnant

In RSGC1, there is the further possibility to make a direct link between initial stellar mass, post-MS evolution and the type of object left over after SN. This is due to the recent discovery of a TeV gamma-ray source in the field of the cluster, which has subsequently been confirmed from X-ray observations as a young pulsar (Gotthelf & Halpern 2008). The H column density towards the pulsar is consistent with the optical extinction of the cluster, strong evidence that the two are physically associated. From the pulsar timing parameters, Gotthelf & Halpern determine that the pulsar is $\sim 10^4$ yrs old, meaning that the initial mass of the pulsar’s progenitor must be similar to that of the next most-massive star in the cluster which has not yet gone SN. In RSGC1, the next most-massive stars are the RSGs themselves, with $M_{\text{init}} = 18 M_\odot$ (Davies et al. 2008). Hence, we can now construct the evolutionary path for an $18 M_\odot$ star:

MS - (BSG??) → RSG → YSG → (WN??) → SN → neutron star

The evidence from RSGC1 that $M_{\text{init}} = 18 M_\odot$ leave behind neutron stars after SN is especially intriguing when discussed in the context of the recent results from Smartt et al. (2008). These authors claim that there is a statistically significant absence of Type-IIP SNe progenitors with masses above $17 M_\odot$. As explanation for this result, Smartt et al. suggest that stars with $M_{\text{init}}$ slightly greater than $18 M_\odot$ may retain enough of their initial mass by the end of their lives to produce a black-hole, which then suppresses the brightness of the SN
explosion to below a detectable limit. The evidence from RSGC1 that stars with $M_{\text{init}}=18M_\odot$ produce neutron stars seems to contradict this hypothesis, at least at Galactic metallicities.

5. Summary and outlook

In this review, I have discussed how young massive clusters, with their large numbers of coeval massive stars, may be used to provide direct links between stars of a certain initial mass, phases of post-MS evolution, and even post-SN remnants. In doing so I discussed case studies of three clusters in particular:

- **The Arches Cluster** – this cluster contains many stars with initial masses $\sim 100M_\odot$, and so allows us to address the evolutionary status of the ‘WNLh’ stars – core H burning objects whose dense winds give them the appearance of WR stars. The H mass-fractions and luminosities of these stars appear to ‘trespass’ into the domain of the LBVs, yet they do not seem to display the trademark variability. This raises the question of whether all stars above a certain mass limit do indeed pass through the LBV phase, or only those stars with certain initial conditions.

- **Westerlund 1** – being the closest thing in our Galaxy to the Super Star Clusters seen in starburst galaxies such as M51 and M82, Wd 1 is a natural laboratory with which to test the simple stellar population models used to study unresolved clusters. The result that the binary fraction seems to be higher than 70%, and that the WR population cannot be explained without a large degree of close binary interaction among the massive stars, serves as a note of caution when interpreting the integrated properties of unresolved systems.

- **RSGC1** – using this cluster we can make a link between maser emission and stars which are approaching the end of the RSG phase, as well as make a direct link between various evolutionary phases and post-SN remnants for ‘mid-range’ massive stars with $M_{\text{init}}=18M_\odot$.

In addition to these objects, there are several more known young clusters which may provide further evidence for the evolution of massive stars through to SN. These include Cl 1806-20, which is known to host an LBV and a highly magnetized neutron star [Figer et al. 2005; Bibby et al. 2008]; Cl 1813-18, which again hosts a young neutron star as well as WRs and an RSG [Messineo et al. 2008]; and NGC3603, which hosts the most massive star known with a direct mass measurement, $116\pm31M_\odot$ [Schnurr et al. 2008].

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