HOT AND COOL: BRIDGING GAPS IN MASSIVE-STAR EVOLUTION
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Age Paradigms for Massive Young Clusters

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Abstract. The correlated stellar and nebular properties of coeval massive young clusters as a function of age are discussed. The recently investigated object Westerlund 1 is an essential addition to the standard sequence, which is so far unique in the solar vicinity. The masses of its most evolved population are just at or below the Humphreys-Davidson Limit, resulting in a fully populated supergiant sequence across the entire Hertzsprung-Russell Diagram. In contrast, the comparably rich (albeit more extended) Scorpius OB1 association has no supergiants later than type B1.5; its most massive evolved stars must be just above the HD Limit. These two groups define the location of the Limit, to within the uncertainties introduced by apparent ranges in the masses of their evolving stars, and by possible metallicity differences. In two-stage starbursts, two sequential cluster age phases with a difference of 1–2 Myr coexist. On the basis of detailed age calibrations in the Large Magellanic Cloud, the morphology of giant H II regions (or their absence) accurately estimates the ages of extended regions in starburst galaxies.

1. Introduction

A consequence of the short evolutionary timescales of massive stars is that the stellar contents and environments of young clusters undergo drastic qualitative changes within the first 10 Myr. This fact in turn provides powerful morphological diagnostics of cluster age and coevality (or otherwise) from spectral classification of the stars and inspection of direct images. While well known, these basic phenomena are sometimes ignored or obscured by the uncertainties in purely photometric studies of young regions, to which the degenerate colors of the O stars and reddening-law heterogeneity contribute. In other studies involving longer timescales, the first 10 or even 30 Myr are sometimes placed in a single bin, so that the age progression from infrared, through Hα, to ultraviolet star-formation indicators is lost. Here I shall emphasize these distinctions as an example of the power of morphology to organize complex phenomena for subsequent physical investigation.

In a prescient study, Schild (1970) pointed out differences in the stellar contents of several clusters as a function of age. However, the complete lack of red supergiants in some young clusters was a mystery, given the short evolutionary timescales involved. The solution was provided by the discovery of the Humphreys-Davidson Limit (HDL; Humphreys & Davidson 1979, 1984, 1994; Humphreys 1983). The lack of stars in the upper right of composite Hertzsprung-Russell Diagrams (HRD) for nearby galaxies showed that the brightest blue stars have no red counterparts. The explanation is that their evolutionary tracks run into an instability limit, near which the Luminous Blue Variables are found, that prevents further redward evolution above masses of about 40–50 $M_\odot$. Thus, red supergiants do not appear until stars of those masses evolve.

Schild's approach was pursued by Walborn (1990a,b), in which several *standard* massive young clusters of progressively increasing ages were defined, and their stellar as well as nebular characteristics were listed. This methodology is updated and elaborated here in Table 1, with the critical addition of the recently investigated cluster Westerlund 1, which provides a "missing link" just at or below the HDL, as further discussed below. Some details of the four older clusters in the table will be considered next, including several surprising complications that emerged in the present study. For reference in the discussion, a number of the most massive stars in each cluster are plotted in a composite HRD in Figure 1.

Table 1. Characteristics of massive young cluster age paradigms

Object	Visually	MS Turnoff		Age	H II,	Red
	Brightest Stars	Spectrum	Mass[$M_\odot$]	[yrs]	Dust	Sg
Orion Nebula	ZAMS O, (IR)	(PMS)		$< 10^6$	Yes	No
Carina Nebula	O2, WNL	O3	100	$1–2 \times 10^6$	Yes	No
Scorpius OB1	OB Sg	O6	50	$3–4 \times 10^6$	No	No
Westerlund 1	AF Sg	O7–O8	35	$4–5 \times 10^6$	No	Yes
Perseus OB1	AF Sg	B0–B1	20	$7–9 \times 10^6$	No	Yes

2. Paradigm Clusters

2.1. Carina OB1

The stellar content of the Carina Nebula has been reviewed by Walborn (1995, 2009a) and Smith (2006). The age of the ionizing cluster Trumpler 16 (Table 1) has been reduced from earlier values by the recognition that WNL stars are still burning H in the core (Langer et al. 1994; Crowther, Hillier & Smith 1995; Crowther et al. 1995; Smith & Conti 2008). The very compact cluster Trumpler 14 is likely younger still. The two Carina OB1 stars plotted in Fig. 1 are the most luminous O stars in these clusters: HD 93129A in Tr 14, the prototype O2 If* star; and HD 93250 in Tr 16, an overluminous O3.5 V((f+)) star (Walborn et al. 2002). Bolometric corrections have been taken from (Clark et al. 2005). These very massive stars, although incipiently evolved, still lie very near the main sequence. The more evolved members of this association are three WNL stars and η Carinae.

2.2. Scorpius OB1

NGC 6231 is the "nuclear" cluster of this rich association, which is often studied in isolation, but the latter is far more extended, covering 2^o or 70 pc in the north-south direction (Braes 1967). It contains one WN and one binary WC star, or two WN if HD 152408, O8: Iafpe (Walborn 1982, 2009b; Walborn

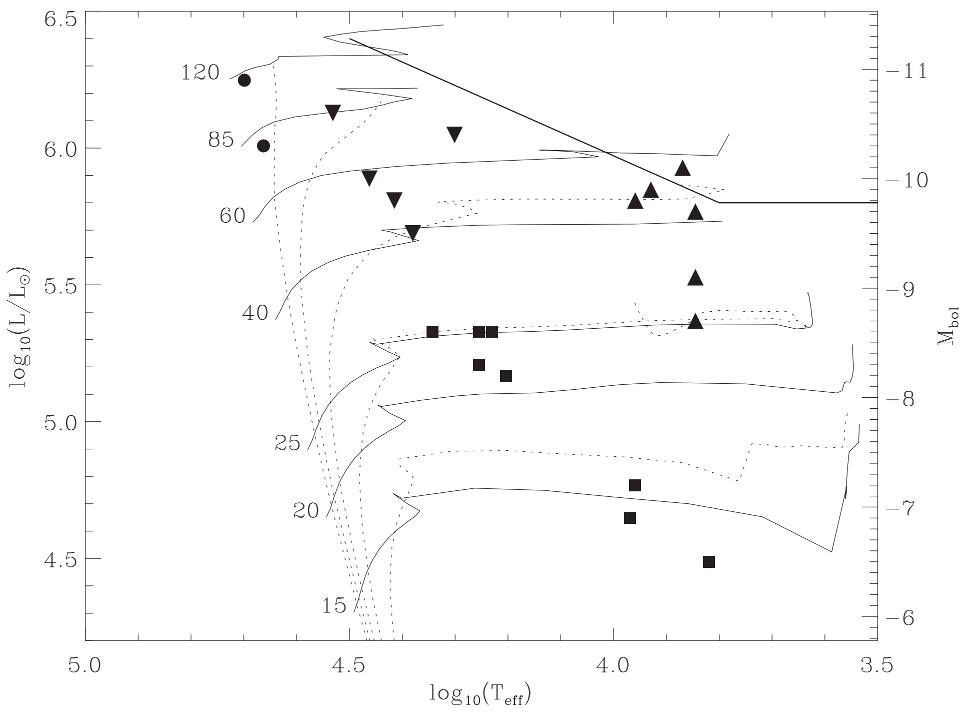

Figure 1. Composite HRD for 4 paradigm clusters. The Schaller et al. (1992) evolutionary tracks are labeled in $M_\odot$ and the isochrones correspond to 1.6, 2.5, 4.0, 6.3, and 10.0 Myr. The HDL is shown at upper right. *Circles*: Car OB1; *inverted triangles*: Sco OB1; *triangles*: Westerlund 1; *squares*: Per OB1.

& Fitzpatrick 2000), is reasonably classified as WN9 (Crowther & Bohannan 1997; Bohannan & Crowther 1999). The members plotted in Fig. 1 are the normal O8 Iaf standard HD 151804 (Walborn & Fitzpatrick 1990, WF); the three OBC supergiants HD 152234, 152235, and 152424 (Walborn 1976, WF); and ζ^1 Scorpii, B1.5 Ia+ (WF), which has the latest spectral type among the most luminous stars in the association. It is seen that the first and last of these have masses comparable to those in Carina OB1. All of these stars except for perhaps HD 152235 lie at or above the HDL. The implied range of evolved masses, more than a factor of two and much larger than the observational uncertainties, is somewhat surprising; the complete absence of later type supergiants would be incomprehensible without the HDL insight. The age of this association has also been reduced somewhat from previous listings by subsequent work (Fig. 1, Crowther et al. 2006). The binary fraction of NGC 6231 has been found to be remarkably high, at least 63% (Sana et al. 2008).

Scorpius OB1 is remarkably free of gas and dust despite its small age, demonstrating that rich OB clusters clear their surroundings on this timescale, contrary to what is often stated in the literature. Actually, there is a weak associated H II region, RCW 113 (Laval 1972), but it is only faintly visible on the red sky survey plates, on which the Orion and Carina Nebulae are black.

An even bigger surprise for the author emerged during the preparation of this report. Morgan, González, & González (1953) give a nearly complete list of blue HD stars in this region. When their spectral types are compiled from the Michigan Spectral Catalogue (Houk 1978, 1982), a significant population of B1–B3 II–Ib types results. To the author's knowledge, this fact has not been previously recognized or discussed. Is there an earlier stellar generation present here, such that the currently dominant population is the second? But then a population of red supergiants associated with the first generation would also be expected. A thorough investigation of this point is required; it is one of several unexpected complications encountered during this work. A complete census and mass estimate of this association would also be useful.

2.3. Westerlund 1

The significance of this remarkable cluster, with its rich array of evolved objects, has been recognized only relatively recently, primarily because of heavy interstellar extinction (Clark & Negueruela 2002; Clark et al. 2005). It is very compact (∼7 pc) despite a high mass ($\sim 5 \times 10^4\,M_\odot$; Brandner et al. 2008), so that it has been called a super star cluster and the most massive known in the Galaxy. Westerlund 1 contains 24 WR stars and counting (Crowther et al. 2006), which have a high binary fraction of at least 70% (Skinner et al. 2006; Bonanos 2007; Clark et al. 2008). It also contains a complete array of supergiant spectral types, from OB through AF to M. The large number of WR stars results not only from the cluster richness, but also from the optimum evolving mass range and possibly a higher than solar metallicity related to its proximity to the Galactic Center.

As discussed in the above references, it is not possible to construct a complete HRD for Westerlund 1, because the spectral types of the OB supergiants are insufficiently accurate to determine their bolometric corrections; also, the locations of the red supergiants are problematic (E. Levesque, these proceedings). Hence, the stars plotted in Fig. 1 are the yellow supergiants with spectroscopic absolute magnitudes determined from the O I criterion (Table 2 of Clark et al. 2005), which are thus insensitive to distance and reddening uncertainties; no bolometric corrections have been applied. As was the case for Sco OB1 above, a surprising range of masses over a factor of two results. While the numbers are small, there could be two groups: four stars clustered about the HDL at 40–$50\,M_\odot$, and two stars at 25–$30\,M_\odot$. I. Negueruela (private communication) has noted that most of the brighter members are located at the northern end of the cluster, while the southern end appears to have predominantly lower luminosities both visually and spectroscopically. Could there also be two spatially separated generations in Westerlund 1? If so, the progenitor masses of the red supergiants become ambiguous—another unwelcome complication.

2.4. Perseus OB1

h and χ Persei have been studied intensively for many decades and might be hoped to be well understood. They are known to also display a supergiant HRD ranging from B through M, albeit at lower luminosities and masses than in Westerlund 1. The stars plotted in Fig. 1 are the B1–B3 Iab–Ia supergiants HD 13854, 14134, 14143, 14818, 14956; and the AF supergiants HD 14433, 14489, 14662. Yet again, the now canonical factor of two in masses recurs, with the earlier types at or below 25 $M_\odot$, and the later ones at or below 15 $M_\odot$. Several complexities of the region have been discussed previously in the literature; e.g., Walborn (2002a) showed that the so-called "halo" of O stars around the double cluster is a substantially more distant association. Schild (1967) concluded that the two clusters have significantly different distances and ages, which has been largely discounted in subsequent work. Perhaps those points require reconsideration. Certainly, a detailed investigation of the distributions of all the B through M supergiants on the sky is an essential first step toward clarifying their likely associations or otherwise with the two clusters.

3. Discussion

This study was begun with the optimistic expectation that it would entail a straightforward compilation of well established results. As detailed above, such has not been the case, with unexpected complications emerging for all of the paradigm clusters, which emphasizes anew the complexity of massive young regions. The good news is that several promising avenues for further research have been identified! Nevertheless, the salient characteristics of these regions as a function of advancing age, as summarized in Table 1, remain useful paradigms for further applications.

One interesting application is the morphological calibration of massive young clusters for age determinations. Typically, they involve two-stage starbursts, in which a central cluster has triggered a second generation around its periphery (Walborn & Parker 1992; Walborn 2002b). 30 Doradus and N11, the two largest H II regions in the Large Magellanic Cloud, are essential composite paradigms, in which extensive spectral classification of the stellar contents establishes the ages. The central cluster of 30 Dor is in the Carina phase and has triggered an Orion phase at its periphery (Walborn & Blades 1997; Walborn et al. 1999a; Walborn, Maíz-Apellániz, & Barbá 2002), while the giant shell H II region N11 is more evolved, with a central Sco OB1 association and surrounding Carina clusters (Parker et al. 1992; Walborn et al. 1999b; Heydari-Malayeri et al. 2000). The age *differences* between the cores and peripheries are the same in both cases. Then, entire regions of nearby starburst galaxies such as NGC 4214 (MacKenty et al. 2000) and even as far as the Antennae (Whitmore et al. 1999, 2002; Whitmore 2007) can be classified into 30 Dor, N11, and earlier or later epochs than those, in *HST* images.

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