Super star clusters as probes of massive star evolution and the IMF at extreme metallicities

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Abstract. Young super star clusters and young compact massive star forming regions can provide useful information on their burst properties (age, burst duration, SFR), the upper end of the IMF and yield new constraints on the evolution of massive stars. Through the study of their stellar populations we can in particular extend our knowledge on massive stars to extreme metallicities unavailable for such stars in the Local Group.

Here we summarise the main results from recent studies on two metallicity extremes: Wolf-Rayet and O star populations in very metal-poor BCD, and metal-rich compact nuclear SF regions.

1. Introduction

Two “modes” of star formation are observed in (optically or UV selected) starburst galaxies (e.g. Meurer et al. 1995): a young unresolved population responsible for emission of diffuse UV light (Meurer et al. 1995, also Calzetti these proceedings), and compact stellar clusters, loosely termed super star clusters (SSCs) hereafter. SSCs have been the focus of numerous recent studies related in particular to the possibility that these clusters may represent the progenitors of globular clusters (cf. Fritze von Alvensleben, Miller, these proceedings). A different aspect is emphasized in the present work. We use spectroscopic observations of young star forming (SF) regions to determine their massive star content with the aim of providing constraints on stellar evolution models and the upper end of the IMF.

SSCs and similar compact young SF regions have the following properties: 

a) Numerous such objects are known. 
b) They represent clusters rich enough ($\sim 10^2-4$ O stars) such that the IMF can be well populated and stochastical effects (cf. Lançon these proceedings) are negligible. 
c) A priori the clusters cover a wide range of metallicities, and 
d) consist likely of a fairly coeval population. 

Given these properties, SSCs resemble “normal” Galactic of Local Group clusters which represent fundamental test-cases for stellar evolution. 

The only disadvantage
is that their stellar content can only be studied through observations of their integrated light. On the other hand b) and c) represent important advantages for studies focussed on massive stars over using “local” clusters. This shows that young SSCs provide ideal samples for studies of massive star evolution in different environments, such as e.g. extreme metallicities largely inaccessible in Local Group objects.

After a brief introduction on the type of objects used here (Wolf-Rayet rich SF region) we will summarise recent work along these lines.

2. Wolf-Rayet galaxies and clusters

We will concentrate on the so-called Wolf-Rayet (WR) galaxies (cf. Schaerer et al. 1999b for the latest catalogue), which are objects where broad stellar emission lines (called “WR bumps”, mostly at He II λ4686 and C IV λ5808) in the integrated spectrum testify to the presence of WR stars. For the study of massive star populations these objects are ideal since WR stars are the descendents of the most massive stars in a short-lived phase ($M_{\text{ini}} \gtrsim 25 M_\odot$, $t_{\text{WR}} \sim 10^5$–$10^6$ yr). Their detection is also a good age indicator for young systems ($t \lesssim 10$ Myr), and allows good measure of the burst duration and the best direct probe of the upper end of the IMF. An overview of studies on WR populations in starburst regions can be found in the reviews of Schaerer (1998, 1999).

In the context of the present workshop it is important to note that the objects broadly referred to as WR “galaxies” are found among a large variety of objects including BCD, massive spirals, IRAS galaxies, Seyfert 2, and LINERs (see Schaerer et al. 1999b). The “WR rich” regions contained in the spectroscopic observations will thus in general cover quite a large scale of sizes, different morphologies etc. In the case of blue compact dwarfs (BCD), one is however mostly dealing with one or few individual compact regions or SSC dominating the observed light. Although this statement cannot, with few exceptions, be quantified so far for the objects studied below (but see e.g. Conti & Vacca 1994) we will mostly assume that the spectroscopic observations correspond closely to light from one young compact SF region or SSC.

3. Studies of Wolf-Rayet populations in metal-poor environments

The spectroscopic sample of dwarf galaxies from Izotov, Thuan and collaborators, obtained for the main purpose of determining the primordial He abundance and other abundance studies, has proven to be very useful for analysis of massive star populations especially at very low metallicities. Indeed, ~20 WR rich regions are found in this sample at metallicities below the SMC ($12 + \log O/H \ll 8.1$) extending to I Zw 18 with ~1/50 solar metallicity. No bona fide massive star of such low a metallicity is known in the Local Group!

The analysis of the WR and O star content in these objects has been presented by Guseva et al. (1999, hereafter GIT99). Some of their main results are summarised in Fig. 1, which shows (left panel) the derived WR/(WR+O) number ratio as a function of metallicity from their objects and observations of Kunth & Joubert (1985), Vacca & Conti (1992), and Schaerer et al. (1999a, hereafter SCK99). The left Fig. considerably extends the previous samples (cf.
The trend of increasing WR/O with metallicity is well understood (Arnault et al. 1989). The comparison with appropriate evolutionary synthesis models (Schaerer & Vacca 1998, SV98; shown as solid lines) calculated for a “standard” Salpeter IMF with $M_{\text{up}} = 120 M_\odot$ and using the high mass loss Geneva tracks shows a good agreement. This and more direct comparisons of the observed WR features (see Schaerer 1996, de Mello et al. 1998, SCK99, GIT99) indicate that the bulk of the observations are compatible with short (“instantaneous”) bursts with a Salpeter IMF extending to large masses. The short burst durations\(^1\) derived by SCK99 for the metal-poor objects are also in agreement with the study of Mas-Hesse & Kunth (1999).

Of particular interest for evolutionary models is the relative number of WR stars of the WN (exhibiting H-burning products on their surface) and WC subtypes (He-burning products). The relative lifetimes vary strongly with initial mass and metallicity and are sensitive to various mass loss prescriptions and mixing scenarios currently not well known (see Maeder & Meynet 1994, Meynet these proceedings). The recent high S/N spectra of SCK99 and GIT99 have now allowed to establish number ratios of WC/WN stars in a fair number of WR rich regions. The determinations of GIT99 are shown in Fig. 1 (right panel); similar values are derived by SCK99. The comparison with synthesis models shows a

\(^1\)See Meurer (these proceedings) for a discussion of SF durations.
reasonable agreement. To reproduce sufficiently large WC/WN ratios the use of the stellar tracks based on the high mass loss prescription are, however, required as shown by de Mello et al. (1998) and SCK99.

It is understood that part of the “requirement” for the high mass loss (cf. Schaerer 1998) may be compensated by additional mixing processes leading to a similar prolongation of the WR phase (cf. Meynet, these proceedings). In any case in addition to the well known stellar census in the Local Group (cf. Maeder & Meynet 1994 and references therein) the present new data from integrated populations place important constraints on the evolutionary models which have to be matched by successful stellar models. Especially the new studies extend the range of available metallicities to very low $Z$, well beyond the SMC.

4. Massive stars and the IMF in metal-rich starbursts

A small sample of metal-rich (O/H $\gtrsim$ solar) starbursts (4 objects from GIT99 and Mrk 309) have recently been analysed in detail by Schaerer et al. (2000). In this case the observations (high S/N, intermediate resolution optical spectroscopy) correspond to compact nuclear SF regions. Despite this complication we use these objects as a first step to probe the upper end of the IMF at high-metallicity. Subsequent studies of more isolated and simple, cluster-like objects will be undertaken in the future.

Figure 2. Observed and predicted EW of WR features (left: blue bump, right: C IV $\lambda 5808$). Model predictions are shown for instantaneous bursts at $Z=0.02$ (solid line) and $Z=0.04$ (dashed), and extended bursts at $Z=0.02$ (dotted; burst durations $\Delta t = 2, 4, 6, 8, 10, 12$ Myr). All models assume a Salpeter IMF with $M_{up}=120$ $M_\odot$.

For our comparison with evolutionary synthesis models (cf. below) we use following main observational constraints: H$\beta$ and H$\alpha$ equivalent widths serving as age indicator, H$\alpha$/H$\beta$ determining the gaseous extinction, intensities and equivalent widths of the main WR features (4650 bump, C IV $\lambda 5808$), TiO bands at $\sim 6250$ and 7200 Å indicating the presence of red supergiants from a popula-
Figure 3. Observed and predicted EW of the blue WR bump. The predictions show the dependence of the WR bump on the upper mass cut-off. A conservative approach yields a lower limit of $M_{\text{up}} \gtrsim 30 M_\odot$.

...tion with ages $\gtrsim 7-10$ Myr, and the overall SED provide an important constraint on the population responsible for the continuum.

Model calculations have been done using the SV98 synthesis code. The basic model parameters we consider are: stellar metallicity, IMF slope and upper mass cut-off, star formation history (instantaneous or extended bursts, constant SF), fraction of Lyc photons absorbed by the gas, stellar extinction (which may differ from gaseous).

4.1. Results

The comparison of the observed and predicted WR features is shown in Fig. 2. The observations are well reproduced by $Z=0.02$ models with a “standard IMF” (Salpeter, $M_{\text{up}}=120 M_\odot$) assuming extended burst durations of $\Delta t \sim 4-10$ Myr. The longer burst durations found here are physically plausible and likely explained by the different nature of the metal-rich objects analysed here (larger nuclear regions vs. compact clusters in BCD, cf. SCK99). The corresponding ages of our objects, as indicated by $W(H\beta)$, are between $\sim 7$ and 15 Myr, also in agreement with the presence of the TiO bands. A very good fit is also obtained to the overall SED. This requires, however, an extinction of the stellar continuum which is less than that derived from the gas. The differences are of similar amount that found by other methods in other studies (e.g. Calzetti 1997, Mas-Hesse & Kunth 1999).

In short, we conclude that all the given observational constraints can be well reproduced by models with a Salpeter IMF extending to high masses for a burst scenario with star formation extending over $\sim 4-10$ Myr. This solution is not unique. Therefore a variety of alternate models have been considered (cf.
Schaerer et al. 2000). Regarding the IMF we find that steeper (with slope $\sim$ Miller-Scalo) IMFs are very unlikely.

In view of several studies indicating a possible lack of massive stars in metal-rich environments (e.g. Bresolin et al. 1999, Goldader et al. 1997) we have used the present set of metal-rich WR galaxies to put a lower limit on the value of $M_{\text{up}}$ from the strength of the WR features. As mentioned above our data is compatible with a large upper mass cut-off. The real range of values our data is sensitive to is, however, limited; intrinsically younger regions need to be sampled to probe the most massive stars. Adopting a conservative approach (cf. Fig. 3) we obtain $M_{\text{up}} \geq 30 M_\odot$ (for a Salpeter slope). We also find similar values ($M_{\text{up}} \sim 35–50 M_\odot$) from comparisons of H$\beta$ equivalent width measurements in metal-rich HII regions (see Schaerer et al. 2000).

In contrast with previous studies of metal-rich starbursts and related objects based on properties of the ionized gas our work provides first constraints on the upper end of the IMF measured directly from stellar signatures. Future work on larger samples and using detailed coupled stellar population and photoionisation models should be of great interest.

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Q. (Manfred Pakull): Some years ago it was thought that WRs do not form in very low Z environments because the massive stellar winds were too weak. Is that still the state of the art in stellar evolution models? Or are the broad emission features due to a population of H-rich, very young objects like in 30 Dor and NGC 3603?

A. (Daniel Schaerer): Indeed the metallicity dependence of mass loss causes an important decrease of the WR population toward low Z. Despite this evolutionary models applying recent mass-loss prescriptions predict some WR stars at the lowest metallicities (1/50 solar) corresponding to I Zw 18 (see de Mello et al. 1998), quite in agreement with the observations. The role of other formation channels (massive close binaries, rotation) at these low Z remains unexplored.

In Schaerer et al. (1999, SCK99) we have explored the effect of such R136-like WR stars during H-burning in addition to other WR and Of stars with broad emission lines. Given their high initial mass their integrated contribution to the WR bump should in most cases not be very important compared to “normal” WR stars. An exception could be very young ($\lesssim 2–3$ Myr) and strongly coeval populations. Few such observational cases seem, however, known to date (see SCK99).