Death of Massive Stars: Supernovae and Gamma-Ray Bursts
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Environments of massive stars and the upper mass limit

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Abstract. The locations of massive stars ($\geqslant 8M_{\odot}$) within their host galaxies is reviewed. These range from distributed OB associations to dense star clusters within giant H II regions. A comparison between massive stars and the environments of core-collapse supernovae and long duration Gamma Ray Bursts is made, both at low and high redshift. We also address the question of the upper stellar mass limit, since very massive stars (VMS, $M_{\rm init} \gg 100M_{\odot}$) may produce exceptionally bright core-collapse supernovae or pair instability supernovae.

Keywords. stars: early-type, stars: supernovae: general, stars: Wolf-Rayet, ISM: HII regions, galaxies: star clusters, galaxies: ISM

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1. Environments of Massive Stars

Massive star formation in the Milky Way spans a broad spectrum, from dispersed, low intensity OB associations to concentrated, high intensity starbursts. Within a few hundred parsec of the Sun, high mass stars ($M_{\rm init} \geqslant 8M_{\odot}$) are rather distributed, typically located in loose, spatially extended OB associations (de Zeeuw *et al.* 1999). A notable exception is Orion OB1, which hosts the Orion Nebula Cluster (ONC), responsible for our closest H II region. Further afield, large numbers of massive stars are associated with relatively intense bursts of star formation such as the high mass, compact clusters (Trumpler 14, 16) within the Carina Nebula giant H II region.

1.1. *Star clusters*

It is generally accepted that the majority of stars form within star clusters (Lada & Lada 2003), although recent evidence suggests star formation occurs in a continuum of stellar densities (e.g. Evans *et al.* 2009). Nevertheless, given their short-lifetimes (3–50 Myr) only a few percent of massive stars appear genuinely 'isolated' (de Wit *et al.* 2005) such that they either tend to be associated with their natal cluster or are plausible runaways from it†.

According to Weidner & Kroupa (2006), there is a tight relation between cluster mass, and the most massive star formed within the cluster, although this remains controversial (Calzetti *et al.* 2010, Eldridge 2012). Examples of well known star clusters spanning a range of masses are shown in Table 1, all of which are sufficiently young ($< 1 - 2$ Myr) that the most massive stars have yet to end their lives. We include the most massive star in each cluster, which increases towards the highest mass clusters.

If there is a relation between a cluster and its most massive star, the galaxy-wide stellar initial mass function (IMF) will also depend upon the cluster mass function and

† Runaways may be ejected from their cluster either dynamically during the formation process or at a later stage after receiving a kick following a supernova explosion in a close binary system.

Table 1. Selected young star clusters spanning a range of masses, $M_{\rm cl}$, for which (initial) masses of the highest mass stars, $M_{*,init}$, have been determined.

Cluster	$M_{\rm cl}/M_\odot$	Ref	Star	$M_{*,init}/M_\odot$	Ref
ρ Oph	$\sim 10^2$	a	ρ Oph Source 1	9	a
ONC	1.8×10^3	b	θ^1 Ori C	39±6	c
NGC 3603 (HD 97950)	$\sim 10^4$	d	NGC 3603-B	166±20	e
R136 (HD 38268)	5×10^4	e	R136a1	320^{+100}_{-40}	e

(a) Wilking *et al.* (1989); (b) Hillenbrand & Hartmann (1998); (c) Simón-Díaz *et al.* (2006)
(d) Harayama *et al.* (2008); (e) Crowther *et al.* (2010)

the range of cluster masses, as set out by Pflamm-Altenburg *et al.* (2007). In normal star-forming galaxies the cluster mass distribution follows a power law with index −2, albeit this is truncated at high mass depending upon the rate of star formation (Gieles 2009). Consequently, similar absolute numbers of stars are formed in low mass ($M_{\rm cl} \sim 10^2 M_\odot$), intermediate mass ($\sim 10^3 M_\odot$) and high mass ($\sim 10^4 M_\odot$) clusters, while high mass stars should be rare in the former. This is not always the case, since star formation in some nearby dwarf irregular starbursts is strongly biased towards a few very high mass clusters (e.g. NGC 1569, Hunter *et al.* 2000).

1.2. *H* II *regions and star formation rates*

Because of the (universal?) Salpeter IMF slope, the overall statistics of massive stars in galaxies will be heavily biased towards 8–20 $M_\odot$ (early B-type) stars. However, the most frequently used indicator of active star formation is nebular hydrogen emission (e.g. Hα) from gas associated with young, massive stars. The Lyman continuum ionizing output from hot, young stars is a very sensitive function of temperature (stellar mass), such that one O3 dwarf (∼75 $M_\odot$) will emit more ionizing photons than 25,000 B2 dwarfs (∼9 $M_\odot$, Conti *et al.* 2008). Therefore, H II regions are biased towards high mass (O-type) stars with >20 $M_\odot$ since B stars will produce extremely faint H II regions.

Beyond several Mpc, current sensitivies limit detections of H II regions to relatively bright examples, involving several ionizing early O-type stars (Pflamm-Altenburg *et al.* 2007). Still, the Hα luminosity of bright H II regions can be converted into the corresponding number of Lyman continuum ionizing photons, for which the number of equivalent O7 dwarf stars, N(O7V), serves as a useful reference (Vacca & Conti 1992), as indicated in Table 2. Kennicutt *et al.* (1989) have studied the behaviour of the H II region luminosity function in nearby spirals and irregular galaxies. Early-type (Sa-Sb) spirals possess a steep luminosity function, with the bulk of massive star formation occurring in small regions ionized by one of a few O stars, plus a low cut-off to the luminosity function. Late-type spirals and irregulars possess a shallower luminosity function, in which most of the massive stars form within large H II regions/OB complexes, for which 30 Doradus in the LMC serves as a useful template. For example, although the LMC contains considerably fewer H II regions than M31 (SAb), it contains ten H II regions more luminous than any counterpart in M31 (Kennicutt *et al.* 1989).

The integrated nebular Hα luminosity of a galaxy is widely used as a proxy for the rate of (near-instantaneous) star formation (Kennicutt 1998), although conversions into total star formation rates (SFR) rely upon the adopted stellar mass function and evolutionary models for single and binary stars (e.g. Leitherer 2008). In addition, since the youngest star forming regions are deeply embedded, the combination of gas (Hα) and dust (24μm continuum) provide a more complete SFR indicator (Calzetti *et al.* 2007), although the

Table 2. Examples of nearby H II regions, spanning a range of luminosities (adapted from Kennicutt 1984), for an assumed O7V Lyman continuum ionizing flux of 10^{49} ph/s).

Region	Type	galaxy	Distance (kpc)	Diameter (pc)	L(Hα) (erg s^{-1}	N(O7V)
Orion (M42)	Classical	Milky Way	0.5	5	1×10^{37}	<1
Rosette (NGC 2244)	Classical	Milky Way	1.5	50	9×10^{37}	7
N66	Giant	SMC	60	220:	6×10^{38}	50
Carina (NGC 3372)	Giant	Milky Way	2.3	300:	1.5×10^{39}	120
NGC 604	Giant	M33	800	400	4.5×10^{39}	320
30 Doradus	(Super)giant	LMC	50	370	1.5×10^{40}	1100
NGC 5461	(Super)giant	M101	6400	1000:	7×10^{40}	5000

situation is more complicated for galaxies with low SFR (e.g. Pflamm-Altenburg *et al.* 2007). In addition, Hα-derived star formation rates differ from FUV continuum diagnostics for dwarf galaxies (Lee *et al.* 2009b), while FUV indicators closely match the local ccSNe rate (Botticella *et al.* 2012).

1.3. *30 Doradus: Template extragalactic giant H* II *region*

30 Doradus, the brightest star forming complex within the Local Group, provides a useful template for extragalactic 'supergiant' H II regions (Kennicutt *et al.* 1995, Table 2). The 30 Dor nebula is shown in Fig. 1 and spans an angular size of $\sim 15' \times 15'$, corresponding to a linear scale of 220 $\times$ 220 pc at the distance of the LMC. Consequently, individual stars may be studied in detail (e.g. Evans *et al.* 2011). Walborn & Blades (1997) identified five distinct spatial structures within 30 Dor, (i) the central 1–2 Myr cluster R136; (ii) a surrounding triggered generation embedded in dense knots (< 1 Myr); (iii) OB supergiants spread throughout the region (4–6 Myr); (iv) an OB association to the southeast surrounding R143 ($\sim$5 Myr); (v) an older cluster containing red supergiants to the northwest (10–20 Myr). 30 Dor would only subtend $1.5''$ at a distance of 30 Mpc, so care should be taken for nebular-derived ages of stars within extra-galactic H II regions (e.g. Leloudas *et al.* 2011).

2. Environments of supernovae and gamma-ray bursts

2.1. *H* II *regions and core-collapse SNe*

Turning to studies of the environments of supernovae, locally neither type II nor type Ib/c supernovae are associated with ongoing star formation. Specifically, Smartt (2009) examined the host environment of a volume limited (cz < 2,000 km/s), statistically complete sample of ccSNe, of which 0 from 20 type II SN were located in bright H II regions. A number of type II SN were located in loose associations, with two in older clusters (e.g. SN2004am, II-P, in M82), while only 1 of 10 type Ib/c SN from Smartt (2009) was in a large star forming region (SN2007gr, Ic, in NGC 1058), albeit spatially offset from regions of H II emission.

Anderson & James (2008) took a different approach, studying the association between ccSNe and H II regions within (mostly) bright spirals, whose recession velocities extended up to cz = 10,000 km/s. In common with Smartt (2009), Anderson & James (2008) did not find type II SNe associated with H II regions, concluding that the *"type II progenitor population does not trace the underlying star formation"*. In contrast, Anderson & James (2008) found that type Ib, and especially Ic ccSNe were spatially coincident with (presumably bright) H II regions.

Figure 1. Three Local Group giant H II regions shown on the same physical scale: Carina Nebula (Milky Way, ESO/WFI, $60' \times 30'$), 30 Doradus (LMC, ESO/TRAPPIST, $20' \times 20'$). N66 (SMC, HST/ACS, $4.7' \times 4.7'$). 30 Doradus hosts multiple stellar generations (Walborn & Blades 1997) but would only subtend $1.5''$ at a distance of 30 Mpc, so care should be taken for characteristic ages of stars within extra-galactic H II regions.

Let us consider the typical duration of the H II phase in young, isolated clusters. Walborn (2010) compared the properties of young star clusters, revealing an association with a H II region only for the first ∼2–3 Myr, after which the gas has been dispersed (e.g. Westerlund 1, Clark *et al.* 2005). Therefore, one would *not* expect ccSNe to be spatially coincident with *isolated* H II regions unless the mass of the progenitor was sufficiently short for its lifetime to be comparable to the gas dispersion timescale. This is illustrated in Figure 2(a) where we compare the lifetime of the most massive stars in clusters (masses according to Eqn. 10 from Pflamm-Altenberg *et al.* 2007), adopting stellar lifetimes from Ekström *et al.* (2012), with an estimate of the duration of isolated H II regions (adapted from Walborn 2010). This naturally explains the lack of any association between type II ccSNe and H II regions for both Smartt (2009) and Anderson & James (2008).

How, then, can one explain the *empirical* association between type Ib/c SNe and H II regions in the Anderson & James (2008) study? These either arise from very massive stars, which would be inconsistent with Smartt (2009), or more likely we have to appreciate that not all massive star formation occurs within isolated, compact star clusters.

Late-type spirals and irregulars, which form the majority of Anderson & James' host galaxy sample, host large star forming complexes, up to several hundred parsec in size, involving (super)giant H II regions. These are ionized by successive generations of star clusters, separated by a few Myr (Table 2), with a total duty cycle of $\geqslant$10 Myr. Therefore, a massive star exploding within such an environment as a SN after 5–10+ Myr would still be associated with a bright H II region, as illustrated in Fig. 2(b), even if its natal star cluster had cleared the gas from its immediate vicinity. Resolving the location of the ccSNe within the region would be especially difficult at larger distances. Recall that the average distance of galaxies within the Anderson & James (2008) sample was ∼32 Mpc, and that their study was based upon moderate resolution ground-based Hα imaging. Typically higher spatial resolution datasets were employed by Smartt (2009), which together with a lower host distance (∼27 Mpc maximum for an adopted $H_0 = 75$ km/s/Mpc) enabled a higher spatial inspection of the SN environment (recall Fig. 1).

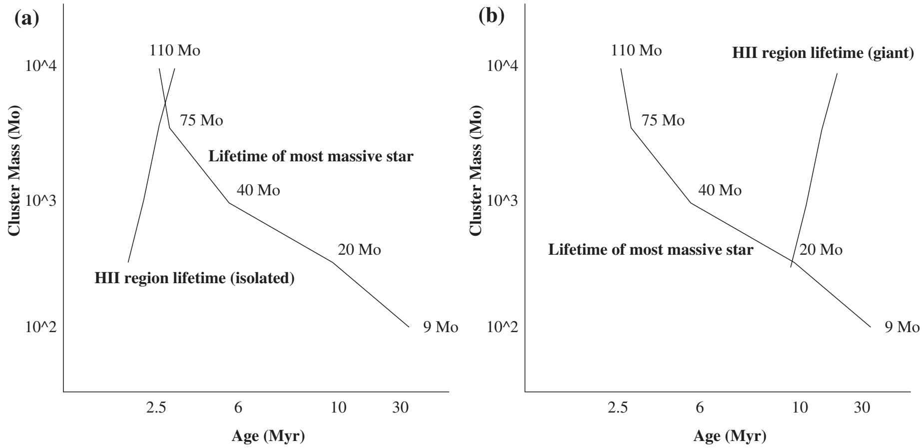

Figure 2. (a) Schematic comparing the lifetime of the most massive star in a cluster (according to Pflamm-Eltenberg *et al.* 2007) and isolated H II regions (adapted from Walborn 2010). Core-collapse SNe should only be associated with isolated H II regions for very massive progenitors; (b) as (a) except for (super)giant H II regions, whose 10–20 Myr lifetimes should imply an association with ccSNe except for only relatively low mass, long lived (type II-P) progenitors.

2.2. *Wolf-Rayet stars and ccSNe*

Main-sequence O stars may preceed ccSNe by up to 3–10 Myr, whereas Wolf-Rayet stars, their evolved descendents, should preceed (type Ib/c) SNe by a timescale that is an order of magnitude shorter (Crowther 2007). Therefore, comparisons between the environment of Wolf-Rayet stars and ccSNe provide information upon whether the former are plausibly the parent population of the latter (e.g. Leloudas *et al.* 2010), since lower mass close binaries might dominate type Ib/c SNe statistics (Smith *et al.* 2011). In addition, we can also compare the environment of Wolf-Rayet stars in their host galaxies (e.g. associated H II regions) with those of ccSNe.

Since the Wolf-Rayet content of the Milky Way is highly incomplete due to foreground interstellar dust, let us instead turn to local external galaxies. From the LMC Wolf-Rayet catalogue of Breysacher *et al.* (1999), 58% (78/134) lie within OB associations, while 83% (112/134) lie within catalogued H II regions. Of course, the LMC is not particularly representative of the local star forming galaxy population, since star formation is largely confined to several giant H II regions (Kennicutt *et al.* 1995) and faint H II regions would not necessarily be identified in distant galaxies. Neugent & Massey (2011) have re-assessed the Wolf-Rayet content of M33 (Scd), revealing a total of 206 stars which they argue is complete to $\sim$5%. As for the LMC, the majority of WR stars (80%) reside in OB associations. Further afield, a comparison between the recent Wolf-Rayet photometric survey of the Scd spiral NGC 5068 (Bibby & Crowther 2012) with Hα images reveals that 50% of the Wolf-Rayet candidates lie in bright or giant H II regions, while 25% are associated with faint H II regions and 25% lie away from any nebulosity.

Recalling Sect. 2.1, type Ib/c SN are rarely associated with H II regions. This suggests that most do *not* result from young, massive Wolf-Rayet stars, arising instead from lower mass close binaries in which the ccSNe arise from the H-deficient, mass-losing primary (Fryer *et al.* 2007). In contrast, the preference of type Ic SNe for H II regions suggest that massive Wolf-Rayet stars *are* realistic progenitors in such instances. Close binaries in such a scenario ought to mimic the masses, and in turn, the lifetimes of type II ccSNe progenitors, which positively shy away from H II regions.

Table 3. Summary of expected association between H II regions and ccSNe/long GRBs in different host galaxies (following Kennicutt *et al.* 1989, Gieles 2009).

Host	SFR	Cluster range ($M_\odot$)	Characteristic H II region	SN-H II association?	Example
Spiral (Sab)	Low	10^{2-4}	Isolated	No (all types)	M31
Spiral (Scd)	High	10^{2-6}	Giant	Yes (Ib/c), No (II-P)	M101
Irr	Low	10^{2-4}	Isolated	No (all types)	SMC
Irr	High	10^{2-6}	Giant	Yes (Ib/c, GRB), No (II-P)	NGC 1569

2.3. *ccSNe, long GRBs and host galaxy types*

Mindful of the spatial resolution issue, let us turn to the Kelly *et al.* (2008) study of SNe locations with respect to the continuum g'-band light from their low redshift ($z < 0.06$) host galaxies. Kelly *et al.* revealed that Ic SNe are much more likely to be found in the brightest regions of their hosts than Ib or II SNe. An earlier analysis of high redshift galaxies by Fruchter *et al.* (2006) revealed that long GRBs ($< z > = 1.25$) were also strongly biased towards the brightest pixel of their hosts, in contrast to core-collapse SNe ($< z > = 0.63$, presumably mostly type II-P) which merely traced the light from their hosts. Kelly *et al.* (2008) concluded that if the brightest locations correspond to the largest star-forming regions, type Ic SNe (and long GRBs) are restricted to the most massive stars, while type Ib and especially type II-P SNe are drawn from stars with more moderate masses, results in common with Anderson & James (2008).

However, one significant difference between the low-redshift SN Hα study of Anderson & James (2008) and the high-redshift GRB study of Fruchter *et al.* (2006) is that hosts of the former are relatively high mass, metal-rich spirals, while those of the latter are low mass, metal-poor dwarfs. In normal disk galaxies the number of stars forming across the mass distribution of star clusters is relatively flat, albeit with a cut-off linked to the star formation intensity (Gieles 2009). The star cluster mass function is repeated in nearby dwarf galaxies (Cook *et al.* 2012), but galaxy-wide triggers may induce intense, concentrated bursts of star formation, leading to disproportionately numerous massive star clusters (Billett *et al.* 2002)†. We have attempted to set out the potential association between H II regions, ccSNe and long GRBs in Table 3 for star forming spirals and irregulars, based upon the above arguments, although exceptions are anticipated (and subject to uncertainties regarding the main progenitors of type Ib/c SNe).

Relatively massive, metal-rich galaxies would represent the primary site of all star formation for the sample of Fruchter *et al.* (2006), resulting in (type II-P) ccSNe unassociated with the brightest regions in their hosts. Yet, when localised starburst activity does occur, it is very intense (Billett *et al.* 2002), leading to very massive clusters, and in turn large numbers of high mass, metal-poor stars, a subset of which would be progenitors of the long GRBs witnessed by Fruchter *et al.* (2006).

3. Upper Mass Limit

The lower limit to the mass of stars is relatively well known (e.g. Burrows *et al.* 1993), yet establishing whether there is a corresponding upper mass limit has proved elusive (Massey 2011). In part, this is because obtaining robust masses for VMS is extremely challenging, and in part because of the scarcity of star clusters that are sufficiently

† Of course, not all dwarf galaxies are starbursting. Within the local volume (<11 Mpc) only a quarter of the star formation from dwarf galaxies is formed during starbursts (Lee *et al.* 2009a)

nearby, young and massive for their most massive stars to be studied in detail. Up until recently, a mass limit of $\sim 150 M_\odot$ has been commonly adopted, based upon a near-IR photometric study of the Arches cluster (Figer 2005). However, it is well known that the temperature of hot, massive stars is rather insensitive to optical/IR photometry. Spectroscopic analysis is required for robust temperatures and in turn luminosities, from which stellar masses are derived.

3.1. *R136 stars*

The situation is especially difficult for the brightest main-sequence members of the most massive young clusters, which possess unusual (emission line) spectral morphologies, reminiscent of Wolf-Rayet stars (e.g. Drissen *et al.* 1995). The mass-luminosity relationship for main-sequence VMS is relatively flat, $L \propto M^{1.5}$ (e.g. Crowther *et al.* 2012), so inferred masses are particularly sensitive to temperature, $M \propto T_{\rm eff}^{8/3}$. Recent advances in atmospheric models for stars with dense stellar winds has led to an upward revision to the temperatures of such stars, by ~25%, corresponding to as much as an 80% increase in the resulting mass. Fortunately, several very massive, double-lined eclipsing binaries have been identified within the past few years, including the Wolf-Rayet binary NGC 3603 A1 (Schnurr *et al.* 2008), permitting an independent check on spectroscopic results for similar systems.

R136, the central ionizing cluster of 30 Dor, has both a very high stellar mass (~55,000 $M_\odot$) and a sufficiently young age (1–2 Myr) for its most massive stars not to have undergone core-collapse. Previous estimates of their stellar masses, based on conventional O star calibrations, implied 120 − 155 $M_\odot$ (Massey & Hunter 1998). Schnurr *et al.* (2009) searched for close binaries among the visually brightest members, but none revealed radial velocities, with the possible exception of R136c. Still, their near-IR integral field datasets provided spatially resolved spectroscopy of individual stars within R136, which, together with archival UV/optical spectroscopy and AO-assisted photometry permitted a reassessment of their stellar masses. Spectroscopic analyses together with new evolutionary models for VMS enabled Crowther *et al.* (2010) to revise their (current) stellar masses upward to 135–265 $M_\odot$. Initial masses of 165–320 $M_\odot$ were inferred, adopting standard main-sequence mass-loss rates for VMS (Vink *et al.* 2001) which closely matched spectroscopically-derived values, and were reinforced by the close agreement between spectroscopic and dynamical masses obtained for NGC 3603-A1. Overall, R136 supports the trend that higher (initial) mass stars reside within the most massive star clusters set out by Weidner & Kroupa (2006). However, statistics of high mass clusters for which accurate stellar masses have been determined remain very poor.

3.2. *Pair instability supernovae*

Based upon their re-assessment of the most massive stars in R136 and other young, high mass clusters (Arches, NGC 3603), Crowther *et al.* (2010) concluded that their stellar content was consistent with a revised upper mass limit of $\sim 300 M_\odot$. Regardless of the physical origin of this limit, such high initial masses raise the prospect of extremely luminous core-collapse SNe (Waldman 2008) or even pair-instability SNe (Heger & Woosley 2002). Models have recently been calculated for the post-main sequence evolution of VMS spanning a range of metallicities (N. Yusof, these proc.). From these, it would appear that the VMS in R136 will end their lives as core-collapse SNe, with lower metallicity (SMC-like) required to reduce mass-loss rates sufficiently for pair-instability SNe, as has been proposed for SN 2007bi (Gal-Yam *et al.* 2009). However, details remain very sensitive to mass-loss prescriptions for the post-main sequence evolution (e.g. Crowther *et al.* 2012).

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Discussion

MODJAZ: Could you comment on the agreement of spectroscopically derived mass loss rate with theoretically predicted ones for R136?

CROWTHER: Spectroscopically derived (clumped) mass-loss rates for the R136 very massive stars match the main-sequence Vink *et al.* (2001) predictions fairly well, but these rates are expected to increase for the post-main sequence phase as the star approaches the Eddington limit.

MODJAZ: If you were to use the light-weighted average of the spatially-resolved cluster, which ones are the dominating clusters?

CROWTHER: The integrated light from 30 Doradus is strongly biased towards the youngest high mass cluster R136a so an average characteristic age of ~ 3 Myr would be expected despite OB stars spanning 0 - 20 Myr within this region.

BROMBERG: Are most of the radio loud Ib/c SNe connected with HII regions or not?

CROWTHER: Natal gas is observed to be removed from clusters within only a few Myrs so I would not expect the SN environment to be affected by the ISM/HII region in general, although a high density ISM may exist in some circumstances such as the central region of starbursts such as M82.