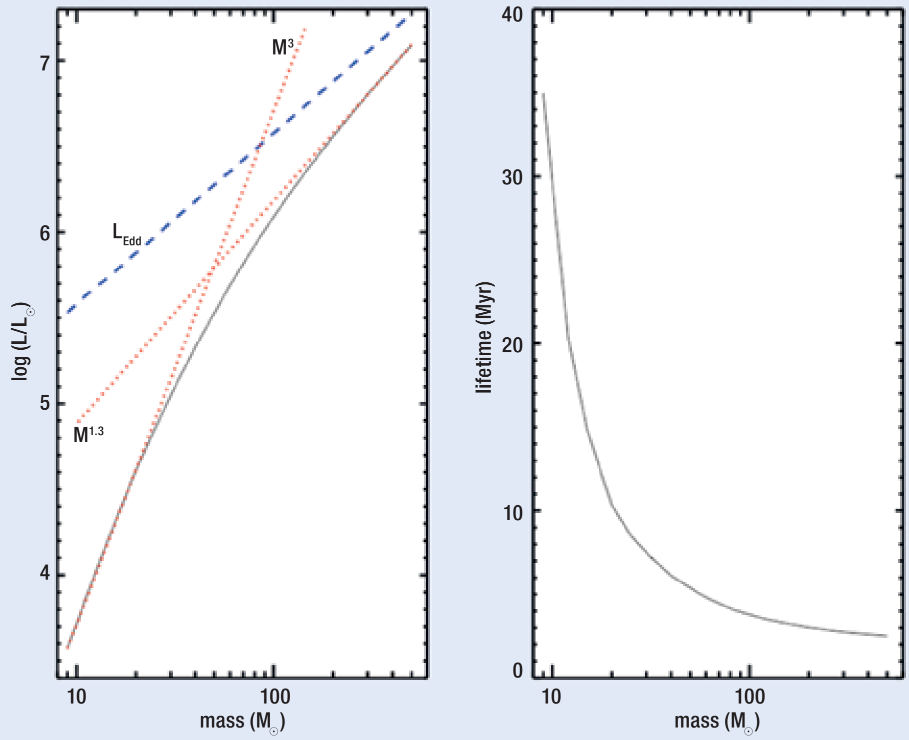
Birth, life and deat

Paul Crowther gives an overview of the lifecycles of massive stars, the 1% of stars that live fast and die young, producing some of the most remarkable transient objects in the sky in the process.



1 (Left): Mass–luminosity relation for solar composition, rotating, zero age main-sequence stars (solid black line), plus the corresponding Eddington luminosity (dashed blue line, L_{Edd}). We also indicate $L \propto M^{\alpha}$ for $\alpha \sim 3$ at low masses and $\alpha \sim 1.3$ for high masses (red dotted lines). If the former extended to higher masses, the Eddington limit $\Gamma_e = 1$ would be reached at ~100 M⊙. However, because $\alpha \rightarrow 1$ for very massive stars, the Eddington limit is never achieved for zero age main-sequence stars. (Right): Lifetimes (in Myr) for solar composition, rotating stars. Since $\tau \propto M/L \propto M^{1-\alpha}$, lifetimes scale with the inverse square of masses close to ~10 M⊙ but are almost mass-independent for very massive stars ($\alpha \rightarrow 1$). (Adapted from N Yusof *et al.* 2012 *MNRAS* sub.)

Massive stars distinguish themselves from their lower mass cousins by their eventual fate. The overwhelming majority of stars will simply fade away as white dwarfs, while all stars with initial masses between ~8 M⊙ and ~150 M⊙ form a degenerate iron core that collapses to a proto-neutron star. Their subsequent evolution may lead to an explosion in the form of a (core-collapse) supernova, a long duration gamma-ray burst (GRB) or direct collapse to a black hole. Transient astronomy is very much on the ascendancy, with the advent of wide-field optical facilities (Pan-STARRS1, LSST) plus non-photonic means of detection (gravitational wave and neutrino experiments). But our physical understanding of transients remains rather patchy, and is reliant upon the far less glamorous field of stellar astrophysics. In this review, I shall set out some of the current issues relating to massive stars, involving their formation, evolution and ultimate demise. Extensive review articles on these topics include Zinnecker and Yorke (2007), Maeder and Meynet (2000), Smartt (2009) and Woosley and Bloom (2006).

Massive stars comprise less than 1% of the stellar content of a new-born population in galaxies, as a result of the (Salpeter) slope of the initial mass function (IMF), and are spectroscopically either early B stars (8–20 M⊙) or O stars (≥20 M⊙). Their high bolometric luminosities (more than 10^4–10^6 L⊙) mean that they dominate the appearance of star-forming galaxies. The lifetimes of massive stars are short (up to a few tens of million years, see figure 1) because of their high luminosities, so their death rate closely mimics the stellar birth rate. For example, the Milky Way is forming stars at a rate of a few M⊙ per year, such that massive stars die at a rate of approximately one per century. The most recent core-collapse supernova (ccSN) in the Milky Way is thought to be Cas A (Krause *et al.* 2008) some 330 years ago, so the next one is long overdue. Other nearby star-forming galaxies have hosted several SNe in the past century. For example, nine historical SNe have been observed in NGC 6946, while M51 alone has hosted two ccSNe in the past decade.

How big?

The Orion A giant molecular cloud represents our nearest massive star-forming region, for which the Orion Nebula Cluster (ONC) beautifully illustrates some of the characteristics of high-mass stars. Massive stars form predominantly in clusters, although details about their formation process remains scarce since they are rare, form quickly, and are often highly obscured by dust (Zinnecker and Yorke 2007). In normal star-forming galaxies the cluster mass distribution follows a power law with index –2, albeit truncated at high mass depending upon the star-formation rate. Consequently, similar absolute numbers of stars are formed in low, intermediate and high-mass clusters, although massive stars are restricted to the latter since there is an empirical relationship between the maximum stellar mass and cluster mass. Low mass (~100 M⊙) clusters barely form any massive stars (e.g. ρ Oph), the most massive star formed in the ONC (~2000 M⊙) has ~40 M⊙ (θ^1 Ori C), while the NGC 3603 cluster (~10 000 M⊙) hosts several stars in excess of 100 M⊙ (Schnurr *et al.* 2008, Crowther *et al.* 2010).

It is likely that the formation of high-mass stars up to ~20 M⊙ mimics lower mass stars, except for elevated accretion rates and shortened formation timescales for massive protostars, known as massive young stellar objects. A 30 M⊙ star (mid O-type) forms in only ~10^5 yr, implying a time-averaged accretion rate of 3×10^{-4} M⊙/yr (Mottram *et al.* 2011), the late stages of which are observationally hyper-compact H II regions once the massive star is hot enough to ionize gas left over from the star-formation process. Historically, it has not been clear how accretion can overcome the outward radiation pressure from hot, luminous protostars, although recent studies have demonstrated radiation pressure does not necessarily limit the build-up of stellar mass (e.g. Krumholz *et al.* 2009). Alternatively, high-mass stars may

h of massive stars

2: HST/WFC3 image (5×5pc) of the young massive cluster NGC3603, which hosts NGC3603-A1, the highest massive binary that has been reliably measured (Schnurr *et al.* 2008). (NASA, ESA, R O'Connell *et al.*)

be produced via multiple mergers of lower mass stars (Bonnell *et al.* 1998), although this scenario is only realistic at the highest stellar densities (~$10^8\,M_\odot\,pc^{-3}$), such as the protocluster(s) that produced R136, the central cluster of the Tarantula Nebula (30 Doradus) in the Large Magellanic Cloud (LMC).

The formation of massive stars inevitably raises the question of the upper stellar mass limit. The lower stellar limit is relatively well established, since there is a clean distinction between the lowest mass stars capable of hydrogen fusion from brown dwarfs. However, establishing whether there is a firm upper limit has proven to be elusive (Massey 2011). In part this is because establishing robust masses is challenging, and in part because of the scarcity of star clusters that are sufficiently nearby, young and massive for their individual stars to be studied in detail.

Until recently, an upper limit of $150\,M_\odot$ has been commonly adopted. This was largely on the basis of a near-infrared photometric study of the Arches cluster located closer to the galactic centre (Figer 2005). This empirical "limit" coincides with the intersection between the standard mass–luminosity relation $L \propto M^\alpha$ ($\alpha \sim 3$) for high-mass stars and the (Eddington) luminosity at which the outward acceleration from radiation pressure balances gravity. In reality, this limit is never reached for main-sequence stars, since the slope in the mass–luminosity relation, α, flattens out, approaching unity for very massive stars (figure 1). As a byproduct, the lifetime of very massive stars is more-or-less mass independent (~2.5–3 Myr).

It is well known from photometric studies that early-type stars, far from the peak of their energy output, are largely degenerate. Therefore, spectroscopic techniques are required for the reliable determination of physical properties. Sophisticated tools have been developed

3: Hubble Space Telescope WFC3/ACS composite image of the Tarantula Nebula (30 Doradus) in the LMC, obtained as part of a multi-epoch proper-motion study to identify massive runaway stars. The field of view corresponds to ~200 × 175 pc. The R136 star cluster, containing exceptionally massive stars, is offset to the left of centre. (NASA/ESA/D Lennon *et al.*)

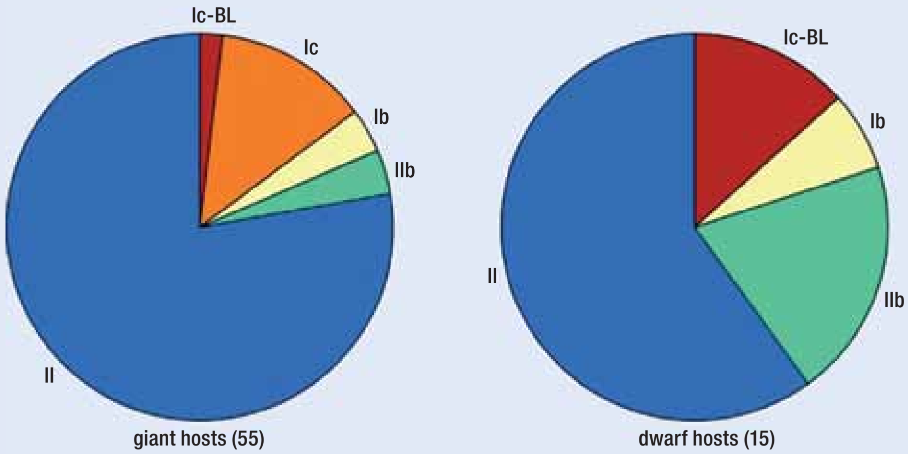
that take into account stellar winds and metal line blanketing. We have used such tools, together with the SINFONI instrument at the European Southern Observatory's Very Large Telescope, to interpret the spectra of the brightest members of the R136 and NGC 3603 star clusters (figure 2), revealing exceptional stellar luminosities ($10^{6.5-7} L_\odot$). These clusters are sufficiently young that no stars have evolved off the main sequence, so these high luminosities directly imply high stellar masses (up to $300 M_\odot$). Spectroscopic masses are supported by an independent dynamical mass determination for NGC 3603–A1 (Crowther *et al.* 2010, Schnurr *et al.* 2008). Refined parameters for these stars should result from two Cycle 19 HST/STIS spectroscopic programmes that I and Olivier Schnurr (AIP) are leading.

The high stellar densities of young massive clusters enables dynamical interactions between single stars and binaries, and between pairs of binaries, while the cluster is still in the process of forming. Therefore, some massive stars are located in relative isolation, having been dynamically ejected from clusters. An example of such a "runaway" is the $90 M_\odot$ early O-type star VFTS 016, located in the periphery of the Tarantula Nebula in the LMC, that was presumably ejected from R136 following interactions with yet more massive stars ~2 Myr ago. The runaway nature of this star was established from an ESO Large Programme, the VLT-FLAMES Tarantula Survey (VFTS), involving multiple epoch spectroscopy of 800 massive stars in the Tarantula Nebula (Evans *et al.* 2011). Additional runaways are anticipated from a follow-up proper motion study with HST/WFC3+ACS, led by Danny Lennon (STScI), the first epoch of which is presented in figure 3. An alternative mechanism for high-mass runaways involves the recoil following the supernova explosion of a close companion.

Until recently, the magnetic properties of high-mass stars were largely unknown. Fortunately, a large survey entitled Magnetism in Massive Stars (MiMeS), exploiting the high throughput spectropolarimeters ESPaDOnS (CFHT) and Narval (Bernard Lyon Telescope), is investigating the incidence of magnetic fields in several hundred early-type stars. To date, results reveal only about 6–10% of O and B stars have strong (~kG), magnetic fields, with the majority of magnetic O stars also spectroscopically peculiar, including Of?p stars (e.g. HD 191612) and θ^1 Ori C, the ionizing star of the Orion Nebula. The rarity of strong magnetic fields, comparable to intermediate-mass stars, suggests that they are the fossil remnants of the star-formation process, rather than being produced via dynamos in their convective cores.

Evolution: how important are luminous blue variable giant eruptions?

Historically, theoretical isochrones for high-mass stars involved a single parameter: metallicity. However, over the past decade, rotation has been recognized as another key parameter for massive stars, while the presence of a close companion dramatically influences the evolution



4: Distribution of ccSNe types from the Palomar Transit Factory (PTF), in which giant (80%, left) and dwarf (20%, right) galaxies have been separated (Arcavi *et al.* 2010), revealing that "normal" Ic SNe dominate in giant ($M_r < -18$ mag), metal-rich galaxies whereas broad-lined (BL) Ic SNe dominate in dwarf ($M_r > -18$ mag), metal-poor galaxies.

of both components (e.g. de Mink *et al.* 2009). It is well known that the binary frequency among massive stars is high, with the VFTS survey establishing that approximately two out of every three massive stars in the Tarantula Nebula are born in a binary system that will interact during their evolution. In many cases the primary dominates the optical spectrum, so extremely high angular resolution is required to identify secondary components. Examples include HD 93129A in the Carina Nebula, whose binary nature required observations with the Fine Guidance Sensor aboard HST (Nelan *et al.* 2010), and θ^1 Ori C from the near-infrared IOTA long-baseline interferometer at Mt Hopkins (Kraus *et al.* 2007).

Examples of the late stages of evolution of massive binaries include high-mass X-ray binaries (HMXB). The most massive cases typically involve an OB supergiant with a neutron star or black hole companion, while more modest examples are Be/X-ray binaries, involving neutron stars. Black hole masses in HMXB typically cluster around 10 $M_\odot$, although a few examples in external galaxies have been discovered in recent years that exceed 15 $M_\odot$ (e.g. M33 X–7, IC10 X–1).

Typical rotational rates of main-sequence massive stars are 100–200 km s^{-1}, a relatively modest fraction of the break-up velocity, although some extremely fast rotators have been identified, such as VFTS 102, a late O star with a rotation velocity of >500 km s^{-1} (Dufton *et al.* 2011). Stars of a particular age and metallicity may occupy a very different position in the Hertzsprung–Russell diagram, depending upon rotational mixing. For example, massive rapid rotators at low metallicity are predicted to evolve chemically homogeneously, moving blueward after their main-sequence phase, rather than the usual redward path.

Metallicity influences the evolution of high-mass stars in two respects. The first involves the reduced opacity for metal-poor stars, while the second relates to mass-loss. In contrast to low and intermediate-mass stars, mass-loss plays an important role in the evolution of massive stars at all phases. Fast, dense winds are driven from hot, luminous stars by a combination of their proximity to the Eddington limit (figure 1), and the absorption of ultraviolet radiation by metal lines. Consequently, the rates of mass loss in massive stars in metal-poor regions are predicted to be lower than in metal-rich hosts. Indeed, winds from O stars in the Small Magellanic Cloud are weaker than in the Large Magellanic Cloud, which, in turn, are weaker than those in the Milky Way (Mokiem *et al.* 2007).

The fate of massive stars also depends upon their post-main-sequence mass-loss. The majority of massive stars are predicted to advance towards a hydrogen-rich red supergiant phase after the main sequence. Radiatively driven wind theory applies to the former category, while the mechanism(s) by which, and rate at which, cool supergiants lose mass is more uncertain, although pulsations and dust are likely to play a leading role in driving stellar winds. Red supergiants, such as Betelgeuse, are physically the largest stars known, with radii comparable to the orbits of the gas giants in our solar system. Binaries with separations below the size of red supergiants are therefore expected to interact during their evolution.

The highest mass stars are thought to initially move to lower temperatures, as blue supergiants or luminous blue variables (LBVs), and later advance to higher temperatures as a hydrogen-deficient Wolf–Rayet phase. LBVs are blue supergiants that vary photometrically and spectroscopically, fairly irregularly, on timescales of years. They also undergo occasional giant eruptions, in which tens of solar masses are ejected on timescales of decades, as witnessed by η Carinae during the mid-19th century, producing the famous Homunculus nebula. This star became the second brightest in the night sky during its giant eruption, despite being located 2.3 kpc away, so such events would easily be seen in external galaxies. Indeed, some bright transients witnessed in nearby galaxies have been coined η Car-like "supernova imposters". The physical nature of such eruptions is unclear, although binary interactions may have been responsible for η Carinae since it is known to be a highly eccentric (0.9), long-period binary (5.5 yr). Recently, light echo techniques have been used to reveal a cool, G-type spectrum for η Car during the giant eruption (Rest *et al.* 2012).

In order to shed the hydrogen-rich envelope, either strong mass-loss or binary interaction is required. Over the past decade, it has been recognized that the winds of hot, massive stars are clumped, which has led to a downward revision in their continuous mass-loss rates, and in turn an increased role for eruptive mass-loss during the LBV phase has been proposed (Smith and Owocki 2006). The duty cycle for giant eruptions from LBVs remains poorly known, although establishing the frequency of ejecta nebulae from blue supergiants in nearby galaxies (e.g. Zooniverse Milky Way Project) should help pin down this quantity.

Supergiant H II regions

There are several tracers of the rate of star formation in galaxies, each involving massive stars either directly (far-ultraviolet continuum luminosities, ccSNe rates) or indirectly (gas ionized from hot, luminous stars or dust heated by their UV radiation). Of these, Hα luminosities measured from H II regions are most widely used (Kennicutt 1998). The ionizing output from massive stars is a very sensitive function of temperature, such that a single early O star with $T_{eff} \sim 45\,000$ K emits more Lyman continuum photons than ten thousand B2 dwarfs with $T_{eff} \sim 21\,000$ K. Therefore, although the statistics of massive stars are dominated by 8–20 $M_\odot$ (B-type) stars, H II regions are very strongly biased towards higher mass O-type stars. Nebular-derived star-formation rates will therefore be more susceptible to stochastic effects than direct, far-UV continuum indicators, to which a broader range of stellar masses contribute.

Of course there are two prerequisites for a H II region, namely the extreme UV radiation field from O stars (e.g. θ^1 Ori C is responsible for the Orion Nebula) plus the gas left over from the star formation process. However, radiation fields, together with mechanical (stellar winds, supernovae) feedback, remove the gas on timescales comparable with the lifetime of massive stars. Westerlund 1 is a high-mass star cluster in the Milky Way whose age is only 4–5 Myr, yet its H II region phase has already ceased. H II regions may be longer lived in large star-forming regions, involving multiple clusters extending over several hundred parsec (e.g.

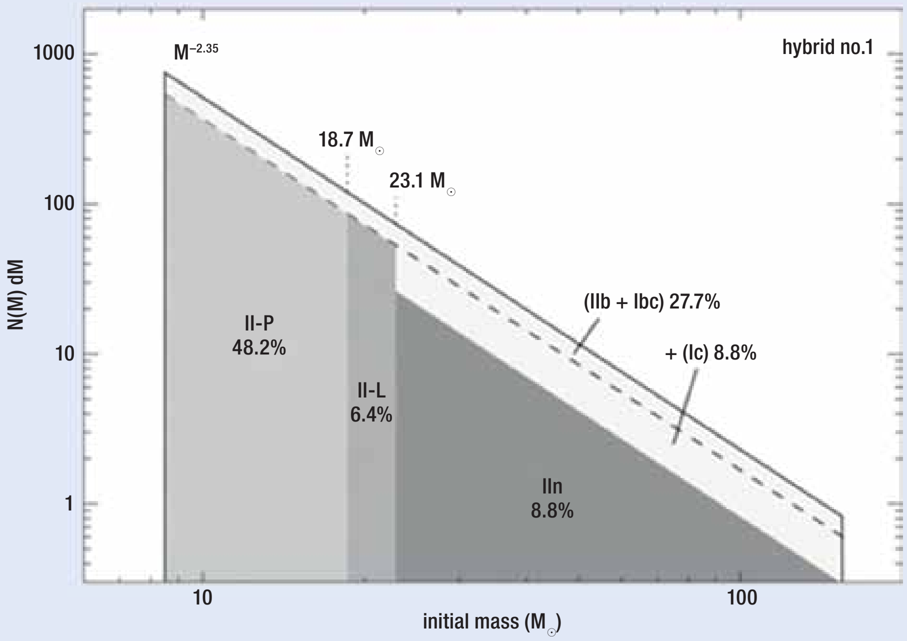
Carina Nebula). Stellar and supernova feedback in such "supergiant" H II regions succeeds only in shifting the gas away from their immediate vicinity, so the duty cycle of such regions may extend to 10–20 Myr.

Early-type spiral galaxies possess a steep H II region luminosity function, with the bulk of massive-star formation occurring in small regions ionized by one or a few O stars. In contrast, late-type spirals and irregular galaxies possess a shallower luminosity function, in which massive stars form predominantly within large OB complexes. By way of example, although the LMC contains fewer H II regions than M31, ten H II regions are more luminous than any M31 counterparts (Kennicutt *et al.* 1989). In the extreme environment of dwarf irregular galaxies undergoing starbursts, star formation is strongly biased towards a few very high mass, compact star clusters (e.g. NGC 3125).

30 Doradus (recall figure 3) is the most luminous H II region within the LMC, and indeed the entire Local Group, and provides a useful template for extragalactic "supergiant" H II regions. Indeed, the star-formation intensity of high-redshift star-forming galaxies closely matches 30 Doradus (Swinbank *et al.* 2010). The Hα luminosity of 30 Doradus is about a thousand times higher than the Orion Nebula Cluster, while its spatial extent is 100 times greater. Still, its proximity enables individual massive stars to be studied in detail (e.g. VFTS). Five distinct massive-star populations have been identified within 30 Doradus, ranging from ages of <1 Myr to between 10 and 20 Myr, which should be borne in mind when considering unresolved extragalactic H II regions (30 Dor would subtend only one arcsec at a distance of 50 Mpc).

Explosive transients: superluminous supernovae

As set out in the introduction, massive stars or their progeny are responsible for the majority of extragalactic transient explosions, the most common examples of which are core-collapse supernovae (ccSNe). Among other things, ccSNe are responsible for the majority of alpha elements in galaxies. Hydrogen-rich, or type II, ccSNe are subdivided into two main photometric types, involving a plateau in their light curves (II-P), or a linear decline in brightness (II-L). Spectroscopically, there are cases of type II SNe that show narrow emission superimposed upon their broad lines (IIn) and hydrogen-rich SNe which rapidly become hydrogen-poor (IIb). Hydrogen-deficient, or type I, SNe are subdivided into thermonuclear explosions of white dwarfs (Ia), helium-rich ccSNe (Ib) and helium-poor ccSNe (Ic). A subset of the latter group display unusually broad lines (SNIc-BL), and are often accompanied by either long GRBs or X-ray flashes (XRFs). Hydrogen-rich supernovae are by far the most common types (figure 4), with the ratio of Ib/c to II ccSNe approximately 30% (Smith *et al.* 2011).



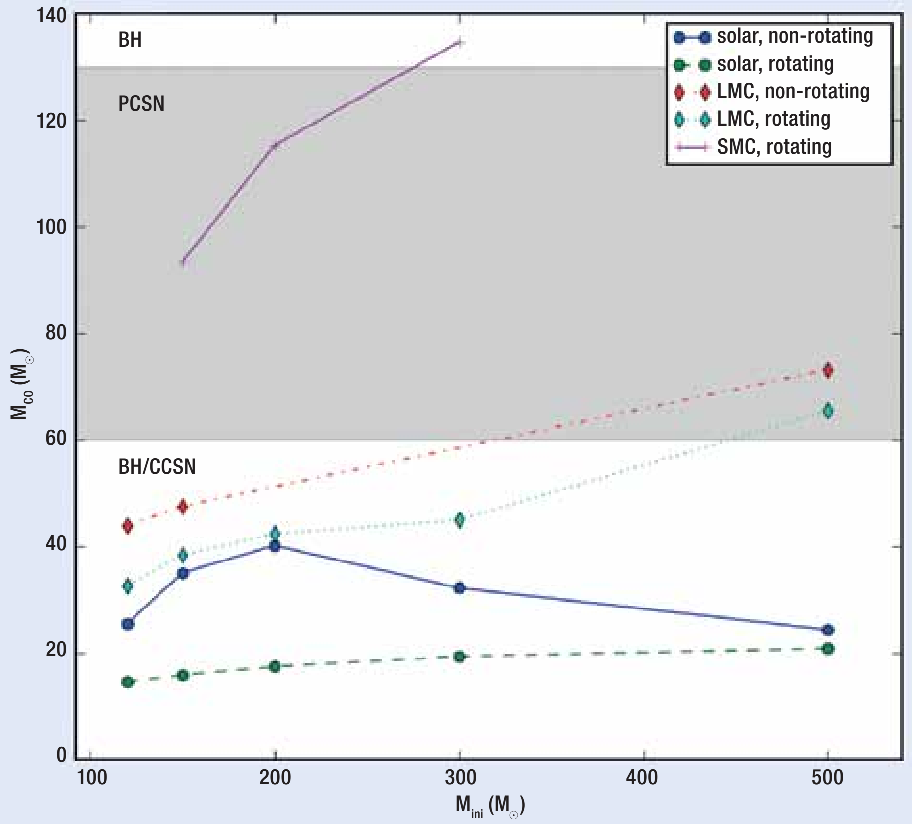
5: A possible scenario for the distribution of the various flavours of ccSNe and massive stars from Smith *et al.* (2011), combining binaries (above dotted line) and single stars (below dotted line). In this scenario, 50% of single stars above ~23 M$_\odot$ are capable of shedding their hydrogen-rich envelope (via winds or LBV eruptions), leading to Ic SNe, while 50% retain their hydrogen-rich envelope until just before core-collapse, due to differences in rotation, metallicity.

In the conventional picture, hydrogen-rich SNe arise from red supergiants (RSG) that have retained their extended hydrogen envelopes, and whose initial masses span 8–20 M$_\odot$. In contrast, hydrogen-deficient ccSNe have been thought to arise from higher mass Wolf–Rayet stars which have shed their hydrogen envelopes via powerful stellar winds. The former are expected to produce neutron-star remnants, with black holes predicted for the latter. However, there are simply too many type Ib/c with respect to type II supernovae for the high-mass Wolf–Rayet scenario to hold (Smith *et al.* 2011). Indeed, high-mass cores are predicted to either directly implode to a black hole without any visible SN, or produce a weak SN explosion, followed by fallback to a black hole. A second channel for stripped core-collapse SN involves mass exchange in close binary systems, with primary masses of >12 M$_\odot$ (e.g. Yoon *et al.* 2010). Overall, it is likely that both channels contribute to type Ib/c SNe. The binary channel is likely to dominate overall statistics, while massive single stars are plausibly responsible for the bright, broad-lined ccSNe that are favoured in dwarf galaxies (figure 4).

Considerable effort is underway trying to link these different ccSNe types to progenitor massive stars. Inspection of pre-supernova images of nearby SN hosts have revealed that RSG are indeed responsible for type II-P supernovae (e.g. Maund and Smartt 2009), albeit deficient in progenitors close to the expected ~20 M$_\odot$ upper limit (Smartt *et al.* 2009). However, no progenitors to type Ib/c ccSNe have been detected to date, largely because they are rarer events and both flavours involve primaries that are optically faint, and so are much harder to detect than RSG at optical or infared wavelengths. One possible scenario linking the various types of ccSNe to progenitor stars is shown in figure 5 (Smith *et al.* 2011),

Anderson and James (2008) have compared the location of ccSNe in their host galaxies and find type Ib/c SNe to be more likely to be co-located with H II regions than type II SNe. Owing to the relatively short lifetimes of H II regions, they attribute this result to higher masses for their progenitors, favouring the Wolf–Rayet channel. Indeed, hydrogen-poor core-collapse SNe, especially type Ic-BL, are also more likely to be located in the brightest regions of their hosts (Kelly *et al.* 2008). However, this question will not be resolved until several type Ib/c progenitors have been detected. Towards this goal, our group has obtained narrow-band imaging of several nearby star-forming galaxies using VLT and Gemini which are sensitive to Wolf–Rayet populations, and so providing a census with which to compare to future H-poor ccSNe.

Of course the only ccSNe whose progenitor has been observed spectroscopically was the peculiar type II supernova 1987A in the periphery of 30 Doradus in the LMC. Unusually, the immediate progenitor was the blue supergiant Sk–69 202, and has been explained by a binary merger. Of course, SN 1987A remains the only



6: Predicted CO core for very massive (120–500 $M_\odot$) rotating and non-rotating models at solar, LMC and SMC metallicities. The grey region shows the domain of PCSNe, indicating that they are preferred in low-metallicity galaxies, with mass-loss rates too high in metal-rich environments. (Adapted from N Yusof *et al.* 2012 *MNRAS* submitted)

core-collapse event that was independently confirmed from the detection of neutrinos. If another massive star were to undergo core-collapse in the Milky Way or its satellite galaxies, large numbers of neutrinos would be detected by the largest current neutrino experiments (e.g. Super-Kamiokande), although only ~1 neutrino would be detected from an event in M31 or M33. Much larger neutrino detectors would be required to probe a volume corresponding to the rate at which core-collapse events exceed one per year (Kistler *et al.* 2011).

Historically, supernova searches have involved nearby bright (massive) star-forming galaxies, thereby limiting statistics to relatively metal-rich hosts. Recently, unbiased wide-field optical surveys have been initiated, which include the Palomar Transient Factory (PTF) and Pan-STARRS1 in the northern hemisphere. These will be followed shortly by the SkyMapper survey of the southern sky, plus LSST at the end of the decade. These surveys provide statistics of the different flavours of ccSNe across all galaxy types (figure 4, Arcavi *et al.* 2010). One outcome from such surveys has been the discovery of extremely bright supernovae, typically an order of magnitude brighter than type Ia SNe (Quimby *et al.* 2011). Those that reach peak absolute magnitudes in excess of –21 mag have been termed superluminous supernovae (SLSNe, Gal-Yam 2012) and include H-rich (typically IIn) and H-poor (I) varieties.

Superluminous IIn are believed to result from massive stars exploding within a dense hydrogen-rich circumstellar environment (e.g. SN 2006gy), reminiscent of η Carinae shortly after its giant eruption. The nature of some type I SLSNe remains to be established (Quimby *et al.* 2011), while others are candidate pair creation supernovae (PCSNe). These involve explosive burning within the high temperature, low density, oxygen-rich cores of very massive stars, leading to its complete disruption. Historically, it was thought that solely the first generation of stars, known as Population III stars, were realistic candidates for PCSNe. Owing to the absence of metal coolants in primordial gas clouds, many Population III stars were thought to be sufficiently massive (>140 $M_\odot$) for them to retain sufficiently massive (60–130 $M_\odot$) CO cores at late evolutionary stages, as a result of negligible mass-loss during the evolution of the star. However, the chemical signature of Population III PCSNe has not been seen in extremely metal-poor halo stars, and indeed a recent theoretical study suggests that primordial stars may have been somewhat lower mass binaries (Stacy *et al.* 2012).

It is notable that the host for the best PCSN candidate identified to date, SN 2007bi, is a very faint metal-poor dwarf (Neill *et al.* 2011), with SLSNe hosts typically low-mass, high specific star-formation galaxies (SN 2006gy is a notable exception). Inevitably if SN 2007bi is a PCSN, it adds to the evidence in support of very massive stars (>150 $M_\odot$). Recent evolutionary model calculations for very massive, rotating stars at SMC-like metallicities suggest that SN 2007bi is consistent with an initial 150–200 $M_\odot$ star ending its life as a PCSN with a 95–125 $M_\odot$ CO core mass (N Yusof, priv. comm.). The enhanced mass-loss rates for 150–500 $M_\odot$ stars at higher metallicity would result in conventional ccSNe, as illustrated in figure 6.

Long GRBs from metal-rich hosts

Long duration GRBs are intimately related to the death of (certain) massive stars. They have long been recognized as being restricted to star-forming galaxies, but the association was proven by the discovery that nearby, low-redshift long GRBs are accompanied by a (type Ic-BL) core-collapse supernova. The first example observed was GRB 980425/SN 1998bw. The ccSNe was unusually bright – albeit not as bright as SLSNe – yet the gamma-ray burst itself was extremely faint, such that this is now recognized as a prototype for a class of low-luminosity, long GRBs. A subsequent event, GRB 030329/SN 2003dh, exhibited similar SN properties to SN 1998bw, but this burst was comparable in gamma-rays to cosmological GRBs. Less than 1% of hydrogen-deficient ccSNe are associated with a cosmological GRB.

To date, a number of low-redshift GRB-SN have been detected, to which XRF 060218/SN 2006aj is usually added. Statistically, the rate of these sub-energetic GRB/XRFs is ~10 times higher than cosmological long bursts, but is comparable to the local rate of broad-lined Ic SN, which represent ~2% of the entire core-collapse population (Soderberg *et al.* 2006, Smith *et al.* 2011).

Until recently, all long GRB-SN have been associated with metal-poor star-forming galaxies. This has been attributed to be in support of the standard "collapsar" model for GRBs, which involves the core-collapse of a rotating massive star to a black hole. In this scenario material accretes onto the compact remnant in the equatorial plane via a dense Keplerian disc, permitting a relativistic jet to propagate through the lower density polar axis of the progenitor. The central engine producing the jet needs to be sufficiently long for it to break out of the star, favouring a relatively compact progenitor, for which a Wolf–Rayet star is a leading candidate.

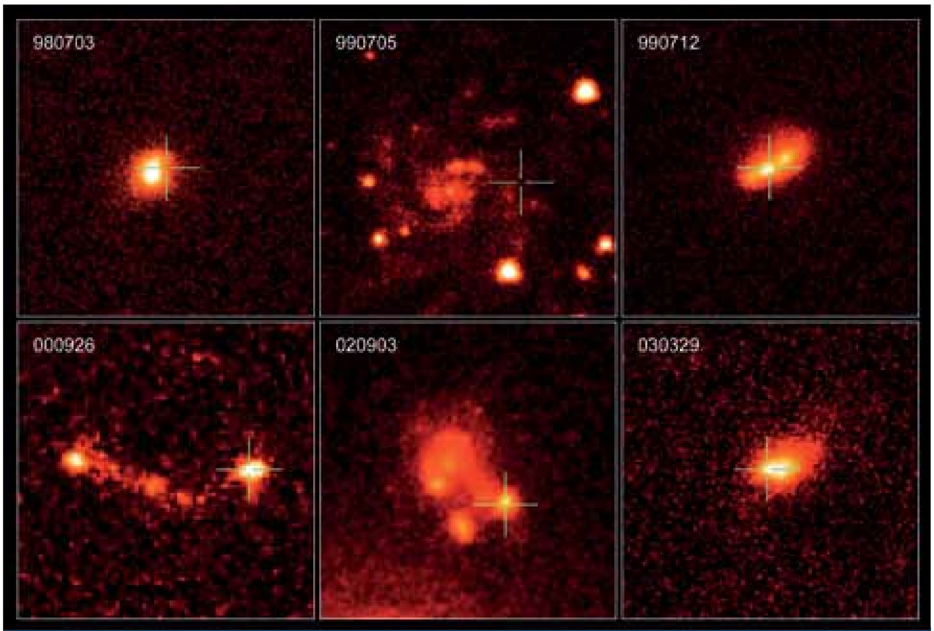
An alternative to the collapsar (black hole) model involves the formation of a proto-magnetar, a highly magnetized (~10^{14-15} Gauss) neutron star. Magnetars have the advantage of explaining the late activity that has been observed in some GRB afterflows, extending several hours after the prompt emission. A persistent injection of energy is difficult to reconcile with a black hole remnant, as are flares, which are also seen in some afterglows at late times. Flares would correspond to a magnetic readjustment of the proto-magnetar, reminiscent of giant bursts from soft gamma repeaters (SGRs), which are a class of young magnetars seen in nearby galaxies. The exceptional December 2004 burst from SGR 1806–20, located at a distance of ~9 kpc, is a prototype of such events (Hurley *et al.* 2005).

Rotating cores seem to be a prerequisite for long GRBs, which have been associated with metal-poor single stars that avoid core spin down (due to weak mass-loss). However, metal-rich GRBs have recently been identified (Levesque *et al.* 2010), suggesting alternative scenarios (e.g. Podsiadlowski *et al.* 2010), although metal-poor host environments do appear to be favoured. Regardless of the role played by metallicity, long GRBs are linked to the most massive stars, since they are preferentially located in the brightest regions of their host galaxies (figure 7, Fruchter *et al.* 2006).

There is also an intimate connection between massive stars and short GRBs. Merging double neutron stars are the leading candidates for short GRBs. Such systems lose orbital angular momentum extremely slowly via release of gravitational radiation, first demonstrated using the Hulse and Taylor binary pulsar PSR 1913+16. This system, with an eccentric, short period (7.75 hr), is expected to merge on a timescale of 300 Myr. The lag between the formation of NS–NS binaries and their eventual merger naturally explains the association between short GRBs and both star-forming galaxies and those that are "red and dead". Neutron star binary mergers should be detected by the advanced LIGO and VIRGO gravitational wave experiments in the next few years, once they become sensitive to mergers at distances of several hundred Mpc.

To date, LIGO has been able to rule out the neutron star binary merger scenario for two recent short GRBs, GRB 070201 and GRB 051103, whose error boxes overlapped with M31 and M81, respectively. It is conceivable that these were giant flares from magnetars in these galaxies, since the initial spike from SGR flares are reminiscent of short GRBs. Giant flares from extragalactic magnetars will contaminate the cosmological short GRBs. Up to ~10% of short GRBs detected by the BATSE instrument aboard the Compton Gamma-Ray Observatory were SGR giant flares, for an assumed rate of one giant flare per Milky Way galaxy per 30 year interval. Since the process of merging neutron stars is exceptionally short-lived, the presence of extended emission in the afterglow of some short GRBs suggests the presence of a proto-magnetar, created either from the merger of either a NS–NS or WD–WD binary.

Several young massive clusters in the Milky Way host magnetars, allowing their progenitor



7: HST ACS/WFPC2/STIS images of selected gamma-ray burst host galaxies (3.75×3.75 arcsec). Green crosshairs mark the location of the GRB, illustrating that, with the exception of GRB 990705, they are preferentially located in the brightest regions of their (typically) irregular host galaxies (Fruchter *et al.* 2006). (NASA, ESA, A Fruchter and GRB Optical Studies with HST collaboration)

masses to be estimated. These span a wide range from ~17 $M_\odot$ (Cl 1900+14) to ~50 $M_\odot$ (Westerlund 1, Cl 1806–20). The latter pair demonstrate that neutron star remnants can arise from high-mass stars, at least at solar metallicity, although the physical origin of such magnetars remains to be established.

Concluding remarks

Massive stars are cosmic engines, responsible for much of the ionized gas and alpha elements in normal galaxies, stellar explosions including core-collapse supernovae and long gamma-ray bursts, and exotica, such as neutron stars and stellar-mass black holes. Advances over the past decade include establishing:

- the progenitors of Type II-P ccSNe;
- the binary characteristics of massive stars;
- the frequency of massive stars with strong magnetic fields;
- the identification of superluminous supernovae including candidate PISNe;
- the rate of low luminosity and cosmological long GRBs.

Much remains to be done, especially relating to the formation of very massive stars, the role played by LBV giant eruptions, and establishing the progenitors of non-Type II-P ccSNe. Large photonic surveys such as VFTS, MiMeS, PTF, together with non-photonic experiments (advanced LIGO, Super-Kamiokande) will hopefully contribute to resolving these questions over the next decade. ●

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