Progenitors of core-collapse supernovae

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Abstract

Knowledge of the progenitors of core-collapse supernovae is a fundamental component in understanding the explosions. The recent progress in finding such stars is reviewed. The minimum initial mass that can produce a supernova has converged to $8 \pm 1M_\odot$, from direct detections of red supergiant progenitors of II-P SNe and the most massive white dwarf progenitors, although this value is model dependent. It appears that most type Ibc supernovae arise from moderate mass interacting binaries. The highly energetic, broad-lined Ic supernovae are likely produced by massive, Wolf-Rayet progenitors. There is some evidence to suggest that the majority of massive stars above $\sim 20M_\odot$ may collapse quietly to black-holes and that the explosions remain undetected. The recent discovery of a class of ultra-bright type II supernovae and the direct detection of some progenitor stars bearing luminous blue variable characteristics suggests some very massive stars do produce highly energetic explosions. The physical mechanism is open to debate and these SNe pose a challenge to stellar evolutionary theory.

CONTENTS

Introduction ................................................................. 4
## Supernova Progenitors

Supernovae and resolved stellar populations in nearby galaxies ........................................ 7
- **Supernova types and classification** ................................................................. 7
- **Supernova surveys and explosion rates** ......................................................... 8
- **Extragalactic stellar astrophysics from space and the ground** ......................... 10
- **A decade of intensive searching for progenitors** ........................................... 12
- **SN impostors and their progenitors** ............................................................. 14

Two fortuitous and surprising events: 1987A and 1993J ............................................. 16
- **The binary progenitor system of SN1993J** .................................................. 16
- **The nearest progenitor: SN1987A** .................................................................. 21

The progenitors of type II-P supernovae: the most common explosion ................. 25
- **II-P progenitors: the “gold” set** ................................................................. 25
- **II-P progenitors: the “silver” set** ............................................................... 31
- **II-P progenitors: the “bronze” set** ............................................................... 32
- **The masses of the progenitor population and the initial mass function** ........... 34
- **Transients of uncertain nature: core-collapse or not?** ................................... 36

The progenitors of Ibc supernovae ........................................................................ 39
- **Searches for Ibc progenitors** ......................................................................... 39
- **SN2008ax: a WNL progenitor of a IIb or a binary in a cluster?** .................... 41
- **SN2007gr: possible mass estimate from host cluster properties** ..................... 42
- **The rate of Ibc SNe and interacting binary stars** ........................................... 43
- **The environments of type Ibc SNe** .............................................................. 45
- **Ejecta masses from SNe Ibc and GRB related SNe** ....................................... 46

The fate of very massive stars ............................................................................... 50
- **SN2005gl: a very massive star** .................................................................... 51
- **SN2006jc: a giant outburst followed by core-collapse** .................................... 52
- **Constraints on II-L SNe progenitors** ......................................................... 53
- **Are LBVs direct SNe progenitors?** .............................................................. 54
| Section                                                                 | Page |
|------------------------------------------------------------------------|------|
| Explosion parameters and compact remnants                              | 58   |
| $^{56}$Ni production and explosion energies                            | 58   |
| NS and magnetar progenitors : turn-off masses                           | 62   |
| An overview and comparison with massive stellar populations            | 64   |
| The lower mass limit for core-collapse                                 | 64   |
| Comparison with Local Group massive stellar populations               | 65   |
| The red supergiant problem                                             | 66   |
| Mass ranges for progenitors                                            | 68   |
| Summary points                                                         | 70   |
| Future issues and prospects                                            | 71   |
1 Introduction

Stellar explosions have shaped the nature of the visible Universe. The chemical elements heavier than boron were created in stars and propelled through the galactic interstellar medium by virtue of the enormous kinetic energies liberated during stellar deaths. The most massive stars are the primary drivers of galactic chemical evolution with for example $\sim 0.4\, M_\odot$ of oxygen ejected by every $15M_\odot$ star (Thielemann, Nomoto, and Hashimoto 1996). Such stars (with masses more than about 7-10$M_\odot$) have long been thought to produce supernovae (SNe) when their evolutionary path ends with a core of iron and further nuclear burning no longer provides thermal pressure to support the star. Given the astrophysical knowledge at the time, Baade and Zwicky (1934) made a great leap of faith in predicting their newly named super-novae in external galaxies were the deaths of massive stars that produced neutron stars and high energy cosmic rays. This paradigm has stood for more than seventy years with great efforts invested to understand supernovae and their remnants. A major goal has been theoretically predicting what type of stars can produce iron or oxygen-magnesium-neon cores and collapse to give these explosions (for example, a non-exhaustive list of recent work is: Woosley, Heger, and Weaver 2002, Heger et al. 2003, Eldridge and Tout 2004, Hirschi, Mevnet, and Maeder 2004). Observationally testing these models with measurements of the physical characteristics of the progenitor stars alongside the explosion parameters can constrain the theory.

The mechanism of conversion of gravitational potential energy from the collapsing $1.4M_\odot$ Fe core (with a radius similar to that of the earth) into a shock induced explosion has been the subject of intense theoretical activity in the modern computational era. The bounce from the imploding mantle rebounding off
the nuclear density proto-neutron star does not inject enough energy to produce a shock with enough momentum to reach the surface (Woosley and Weaver 1986, Janka et al. 2007). At the extreme temperatures and densities in the collapsing core, neutrinos of all three flavours are created with a total luminosity of around $3 \times 10^{53}$ ergs. Deposition of a small fraction of their energy has been proposed as the energy source to drive the explosion (Janka et al. 2007) and recent work has advocated the idea of acoustic vibrations of the proto-neutron star (Burrows et al. 2006). The discovery of neutrinos from SN1987A confirmed the collapsing core idea in spectacular fashion (Hirata et al. 1987).

The community is patiently waiting for a Galactic core-collapse event to test this physics with, presumably, a strong neutrino and gravitational wave signal. The youngest SN remnant in the galaxy G1.9+0.3 is of order 150 yrs old (Green et al. 2008) and we may have a long wait for the next. Constraints on the models of stellar evolution, chemical element synthesis and explosion mechanisms thus rely on the studies of SNe and their progenitor stars in other galaxies in the Local Universe. Supernovae from massive stars (CCSNe) have observed kinetic energies of typically $\sim 10^{51}$ ergs and their integrated luminosities are usually 1-10% of this value. However they display a huge range in their physical characteristics, including chemical composition of the ejected envelope, kinetic energy, radiated energy and the explosively created radioactive composition ($^{56}$Ni, $^{57}$Ni, $^{44}$Ti). Their properties are much more diverse than the thermonuclear type Ia SNe, which originate in white dwarf binary systems (Hillebrandt and Niemeyer 2000). The energetically most extreme CCSNe are those associated with GRBs with kinetic energies of $2-5 \times 10^{52}$ ergs (Woosley and Bloom 2006). A new class of ultra-bright SNe have total radiated energies $\sim 10^{51}$ ergs. (see Section 6.4).
This diversity reflects the large range of stellar types seen in the upper region of the Hertzsprung Russel Diagram (HRD) above $\sim 10M_\odot$ (Humphreys and Davidson 1994, Massey 2003, Crowther 2007). Mass, binarity, metallicity, rotation rate, mass-loss rate and probably magnetic fields play critical roles in forming evolved objects of various radii, density profiles and surrounding circumstellar medium (Podsiadlowski, Joss, and Hsu 1992, Heger and Langer 2000, Eldridge and Tout 2004, Hirschi, Meynet, and Maeder 2004, Yoon and Langer 2005).

The last decade has seen direct discoveries of many SN progenitors and an explosion in the numbers and diversity of SNe discovered. This review will discuss the remarkable and rapid progress there has been in the last decade in identifying massive stars which have subsequently exploded. For every nearby CCSNe which is discovered the global astronomical archives can be carefully searched to identify deep, high resolution images of the CCSN position before explosion. Precise positioning of the CCSN location on these pre-explosion images, with space and ground-based large telescopes, offers the possibility of massive progenitor stars to be identified. Extraordinary theoretical progress has been made since Zwicky & Baade by comparing stellar evolution models to lightcurve models of SN observations. Multi-wavelength surveys have discovered a huge diversity of explosions and outbursts. The possibility of glimpsing stars before they explode is a new and powerful way to test theory. This review focuses on linking the knowledge we have gained from these observational discoveries to our knowledge of stellar evolution and the explosion parameters of SNe. It is a summary of the observational advances in the field, although some of the most interesting results come from interpretation of the observations using theoretical stellar evolution models. Where quantitative results depend on models, this is specifically mentioned.
2 Supernovae and resolved stellar populations in nearby galaxies

2.1 Supernova types and classification

Supernovae are primarily classified by the appearance of their optical spectra, usually around the time of peak brightness. A thorough review of the types and the criteria used to classify them is provided by Filippenko (1997). The article points out that the approach of is largely taxonomical and that there is value in grouping similar SNe as variations of broad themes, rather than the introduction of new types. This has largely held true in the last ten years and with many new observational discoveries the same SN types are by and large used. The type I SNe are defined by the lack of hydrogen features (either in emission or absorption). Type Ia SNe also show no helium features but have a characteristic Si absorption feature. Type Ib have unambiguous signatures of helium and type Ic SNe show no hydrogen or helium. Both Ib and Ic SNe show strong features of the intermediate mass elements O, Mg and Ca. The type II SNe are all defined by the presence of strong hydrogen lines and a further sub-classification is made based on the lightcurves. Most type II SNe can be further subdivided into the II-P SNe (which show a plateau phase) and the type II-L which exhibit a linear decay after peak brightness. The type IIn SNe show hydrogen emission lines which usually have multiple components of velocity and always have a strong “narrow” profile. There are often variations on these major sub-categories, for example SN1987A is usually referred to as a plateau-type event but was clearly peculiar. The type Ic SNe which are associated with long gamma-ray bursts (Woosley and Bloom 2006) all show much broader lines than typical Ic SNe. They have been referred to as “hypernova” or broad-lined Ic SNe, due to them having large inferred kinetic
energies. It can often be hard to distinguish between the Ib and Ic SNe and it is useful often to term the group Ib c SNe and such terminology will be used in this review (Filippenko 1997). Finally the IIb SNe are those which begin with spectra like type II but evolve rapidly to exhibit He lines, and at the same time the H lines weaken and disappear.

2.2 Supernova surveys and explosion rates

The SNe for which one can directly attempt to identify progenitor stars must be fairly nearby (\(\lesssim 30\) Mpc) or the obvious problems of resolution and limiting magnitude render searches meaningless. SN discoveries in catalogued galaxies in the local Universe (within about 140 Mpc) have been dominated by the Lick Observatory Supernova Search over the past 10 years (LOSS; Filippenko et al. 2001), although a large number of well equipped and experienced (but unsalaried) astronomers with 0.3-0.7 m telescopes play a major role in discovering the closest explosions (e.g. K. Itagaki, T. Boles, T. Puckett and R. Evans are amongst the most prodigious SN hunters working outside professional astronomical institutions). How many nearby SNe are missed due to dust extinction in their hosts, or intrinsically faint luminosities, or neglected faint host galaxies, is still an open question. And how those issues could affect the relative rates of different physical types of explosion is also not well understood. This may be addressed in future all-sky imaging surveys with larger apertures such as Pan-STARRS and LSST (Young et al. 2008).

The existence of an initial mass function (IMF) with a slope that strongly favours the formation of lower mass stars is now well established to exist for massive stars in the Local Universe (Elmegreen 2008, Massey 2003). If CCSNe
arise from stars with masses greater than about 8\(M_\odot\) then the IMF necessitates that stars in the 8-15\(M_\odot\) mass range should dominate the rate of explosions (60\% of all, assuming a Salpeter slope of \(\Gamma=-1.35\)). Of course this is moderated by the effects of stellar evolution, binarity, initial rotation and metallicity. The frequency of occurrence of the different SN types and their true rate can give principal constraints in establishing their nature. This section will distinguish the measurement of \textit{SN rates} (the true rate of explosion per unit time and per unit of galaxy luminosity) and the relative frequency of SN types (the relative occurrence of each different subtype). Table I lists the relative frequency of each sub-type from five different studies.

The most reliable measurement of the local SN rate is still that of \textit{Cappellaro, Evans, and Turatto} (1999). They split the CCSN types into two broad categories of type II and type Ibc and applied simple empirical bias corrections to mitigate the effects of galaxy inclination and extinction in their visual and photographic methods. Both \textit{Li et al.} (2007) and \textit{van den Bergh, Li, and Filippenko} (2005) have used the discoveries of the LOSS only to estimate relative frequencies within distance limits of about 30 Mpc and 140 Mpc (the limit for the LOSS) respectively. They go further than \textit{Cappellaro, Evans, and Turatto} (1999) in separating the IIn and IIb SNe from the overall type II class. \textit{Smartt et al.} (2009) have compiled all SNe discoveries in the literature in a fixed 10.5 year period within galaxies with recessional velocities \(V_{\text{vir}} < 2000\text{km s}^{-1}\) (corrected for Virgo infall, this implies a distance of 28 Mpc, assuming \(H_0 = 72\text{ km s}^{-1}\)) and reassessed all available data on the 92 CCNe to estimate the relative frequency of all the subtypes. The agreement between these four studies, which have different distance and volume limits and sample a wide range of SN surveys, is reasonably good and within
the Poisson statistical uncertainties there is no clear discrepancy between them. Prieto, Stanek, and Beacom (2008) caution that their sample of SNe in SDSS star-forming galaxies would suggest that the ratio of the frequency of Ibc to II ($N_{\text{Ibc}}/N_{\text{II}}$) goes down from $0.4 \pm 0.1$ at solar metallicity ($Z_{\odot}$) to $0.1 \pm 0.1$ at a metallicity of $0.3Z_{\odot}$. The results in Table 1 effectively average over metallicities between about $0.3-2Z_{\odot}$ (see Smartt et al. 2009 for a discussion). The agreement between the studies suggests that the relative frequencies (averaged over near solar metallicities) of the subtypes are now reliably determined. In the future the challenge will be to determine metallicity dependent rates with better measurement resolution, more statistics and more accurate nebular oxygen abundances of the SNe environments.

An important question is how complete the local samples of SNe are. At the distance limits of 28-30 Mpc ($\mu \simeq 32.3$) one might naively think that the samples of Smartt et al. (2009) and Li et al. (2007) do not suffer serious bias from missing known classes of SNe, as the limiting magnitude of LOSS and other well equipped amateur searches is around $m_{\text{CCD}} \sim 19$. However this is far from clear and there are arguments put forward recently that we may even be missing events within 10 Mpc (Thompson et al. 2009, Smartt et al. 2009). The physical interpretation of the relative frequencies and the possibility of missing events will be further discussed in Sections 4.5 and 8.

2.3 Extragalactic stellar astrophysics from space and the ground

The study of individual massive stars in resolved galaxies out to $\sim 20$ Mpc has become fairly routine with 15 years of post-refurbishment Hubble Space Telescope (HST) operations. The HST Key Project on the Extragalactic Distance Scale
Smartt is a pioneering example of the feasibility of carrying out quantitative photometry on individual stars in other galaxies (Freedman et al. 2001). The Cepheid variables have typical masses of 5-10$M_\odot$, absolute magnitudes of $M_V \simeq -6$ and $(V-I) \simeq 1$ (Silbermann et al. 1999). The Key Project surveyed galaxies out to around 21 Mpc identifying variable stars at $V \simeq 25 - 26.5^m$ and providing photometric precision to around 0.1-0.3$^m$ (in HST WFPC2 exposures of around 2500 s). The limit for HST images for this type of quantitative photometry is probably around 30-40 Mpc (Newman et al. 1999). Certainly within 20 Mpc it is possible to resolve the brightest and most massive stars in star forming galaxies. At 20 Mpc, the 2-pixel diffraction limited resolution (at $\sim 8000$ Å) of HST’s Wide-Field-Channel (WFC) of the Advanced Camera for Surveys (ACS) of 0.1 arcsec corresponds to 5 pc. Thus single stars can be confused with the most compact stellar clusters which can have diameters of between 0.5-10 pc (Larsen 2004, Scheepmaker et al. 2007). It is often possible to distinguish clusters from single stars with a combination of spectral-energy-distribution (SED), shape analysis and absolute luminosity (Bastian et al. 2005). Although the analysis methodology must be meticulous, resolving and quantifying the flux of individual stars at these distances is quite possible in HST images. If a SN is located spatially coincident with a compact and presumably coeval stellar cluster then it can provide a further reliable constraint on the progenitors age and mass.

The largest ground-based 8-10 m telescopes have also played a vital role in probing the stellar content of galaxies. Natural seeing at the best sites on earth provides 0.6 arcsec image quality routinely in the optical and near infra-red. The distance limit within which massive stars have been quantitatively studied is reduced by a factor of approximately 6 compared to HST campaigns. The Araucaria
Project has studied Cepheids and massive blue supergiants in spirals between 2-4.4 Mpc (Kudritzki et al. 2008, Garcia-Varela et al. 2008). High signal-to-noise quantitative photometric and spectroscopic data allow application of model atmosphere and stellar wind models to determine fundamental parameters of massive stars, even out to distances of 6-7 Mpc (e.g. NGC3621 Bresolin et al. 2001). While the targets for spectroscopic study are the brightest, most massive and hence rarest of all massive stars, these studies show that extragalactic stellar analysis is practicable. Stars may be predominately formed in clusters, but dissolution of moderate mass, unbound clusters on timescales of a few tens of Myrs is probably common place in starforming galaxies. (Chandar, Fall, and Whitmore 2006, Pellerin et al. 2007). Hence the possibility of massive stars being resolvable in either field populations or resolved OB associations is relatively good. Davidge (2006) has studied the resolved red supergiant population of M81 in the NIR showing that the most massive 10-20M⊙ stars peak at magnitudes M_K = −11.5.

Using accurate stellar photometry from a 4m ground based telescope (the Canadian France Hawaiian Telescope in this case), individual stars were easily resolved and used to measure the recent star formation history of the disk.

2.4 A decade of intensive searching for progenitors

The superbly maintained and publicly accessible archive of HST precipitated the search for the progenitors of CCSNe discovered in nearby galaxies. The HST archive has become a model for other space and ground-based observatories world-wide. As described above, galaxies within about 20-30 Mpc, have resolved massive stellar populations in HST images and these galaxies are all on the SN search list of LOSS and the global amateur astronomy efforts.
Studies of the unresolved environments and host galaxies of SNe started in earnest in the 1990s with Van Dyk (1992) and Van Dyk, Hamuy, and Filippenko (1996) suggesting that there was no obvious trend for Ibc SNe to be more closely associated with giant H II regions than type II SNe. Archive and targeted observation work with HST began after the first servicing mission with groups looking at the resolved stellar populations around SNe (Van Dyk et al. 1999b). By the late 1990’s the HST archive, along with the highest resolution ground based image archives, were rich enough that it was only a matter of time before SNe exploded in galaxies with resolved massive star populations. The cases of SN1987A and SN1993J had shown the feasibility of progenitor classification albeit in very nearby systems (see Section 3). Two groups in particular began actively searching for archive pre-explosion images for all nearby SNe. Perhaps surprisingly the identification of progenitor stars at the positions of these SNe was more difficult than first thought, with good images of the II-P SNe 1999em, 1999gi and 2001du showing no progenitor (Smartt et al. 2001, 2002, 2003, Van Dyk, Li, and Filippenko 2003b). Extensive searches of the HST archive were carried out by both groups (Van Dyk, Li, and Filippenko 2003c, Maund and Smartt 2005) again with little success. Although progenitors were not discovered, the large numbers of events and the restrictive luminosity limits were to play an important role in investigating progenitor populations (Section 4 and 5). The first unambiguous discovery of a stellar progenitor in these painstaking searches of the HST archive which allowed the stellar progenitor to be quantified was for SN2003gd (Van Dyk, Li, and Filippenko 2003a, Smartt et al. 2004), showing the expected red supergiant progenitor of a type II-P SN (see Section 4.1.1)

As these studies showed, conclusive evidence of association of a SN with a
progenitor in high resolution HST images requires differential alignment to within 10-30 milli-arcsec, hence observation of the SN with either HST or adaptive optics ground-based systems is essential. There is a long list of misidentifications of progenitors which have used either low resolution images or astrometry with unacceptably large errors (e.g. see Smartt et al. 2009).

The discovery of the progenitor of SN 2003gd was followed by the hunt for progenitors for all nearby SNe in HST or ground-based images and these are discussed in Section 3, 4 and 5. Smartt et al. (2009) reviewed all SNe discovered within 28 Mpc in a 10.5 yr period (see Section 2.2) and found a 26% chance that a CCSN within this volume would have an image in the HST archive taken before explosion, with the SN site on the field of view of WFPC2 or ACS. The community have been extending this search for the precursor objects and systems to both the Spitzer and Chandra archives (see Section 4.5 and Nelemans et al. 2008, Prieto et al. 2008).

2.5 SN impostors and their progenitors

The most massive stars very likely pass through a luminous blue variable (LBV) phase during their lifetime and the progenitors are thought to be core-H or core-He burning stars, ejecting their outer H (and He) envelope as they experience high mass-loss rates and on the way to becoming WR stars (see Section 6, Figure 9 and Massey 2003, Crowther 2007). During this phase Galactic and Local Group LBVs are known to show sporadic and unpredictable variability. Many show modulated mass-loss and variability of a few magnitudes (commonly known as S-Doradus type variability). However occasionally they can undergo giant outbursts, such as the great eruption of η-Carina in 1843,
which reached an amazingly bright $M_V \simeq -14.5$. Such energetic outbursts have been recently discovered in nearby galaxies as optical transients initially identified as SN candidates. Spectroscopy usually provides fairly unequivocal classification of these transients as LBV eruptions and outbursts rather than SNe and they have been termed “supernova impostors” (Van Dyk et al. 2000). The identification and characterisation of these precursor stars will not be discussed in detail here, although we will discuss the possibility that LBVs die in a complete destructive explosion in Section 6. The likely LBV giant eruptions which were originally given supernova designations and have progenitors identified are SN 1961V (Goodrich et al. 1989, Van Dyk, Filippenko, and Li 2002a); SN 1954J (Van Dyk et al. 2005, Smith et al. 2001); SN 1978K Ryder et al. (1993); SN 1997bs (Van Dyk et al. 2000); SN 2002kg and SN 2003gm (Maund et al. 2006). A complete list of nearby events is in Smartt et al. (2009) which suggests that the rate of these transients make up about 5% of all SN candidates in nearby galaxies.
3 Two fortuitous and surprising events: 1987A and 1993J

Up until the establishment of voluminous space and ground-based archives that now allow regular searches, the hunt for progenitor objects was confined to the closest events. Two SNe with clear detections of a stellar source at the SN position are the well documented SN 1987A and SN 1993J. Both of these events were peculiar in their own way and surprised the SN and massive star communities by not matching the canonical pre-collapse stellar evolution ideas of the time. SN1993J is most usefully discussed first as the interacting binary model has implications for understanding SN1987A retrospectively.

3.1 The binary progenitor system of SN1993J

The explosion and very early discovery of SN 1993J in M81 \( (d = 3.6 \text{ Mpc}, \) \cite{Freedman+al2001}) provided an unprecedented opportunity to follow the evolution of a core-collapse SN in the northern hemisphere with modern observational techniques. The wealth of images of this nearby spiral made a progenitor identification almost inevitable. The photometric and spectroscopic evolution were both peculiar, although it matched SN1987K and many similar examples have been found since 1993 \cite{Matheson+al2000}. The lightcurve rose to a sharp peak only 4 days after explosion, faded to a minimum 6 days later and rose to a secondary peak at 25 days. The optical spectra of SN 1993J underwent a transformation from a type II to a Ib. After 2-3 weeks the spectra showed unusually prominent He I absorption features and the Hα P-Cygni emission component weakened substantially \cite{Matheson+al2000}. The lightcurve was well matched with models of an explosion of a He core of mass 4-5M\(_{\odot}\) which had a residual low mass H-envelope (of around 0.2M\(_{\odot}\)). Three independent models of the lightcurve
came to essentially similar conclusions for the exploding star (Nomoto et al. 1993, Podsiaklowski et al. 1993, Woosley et al. 1994). The low-mass, but radially extended (≈500R⊙) H-envelope is required to produce the initial sharp peak in the lightcurve and this qualitatively accounts for the transformation of the spectral evolution from a II to a Ib. The three physical models all suggested an interacting binary scenario to produce the 4-5M⊙ He core; a primary star of initial mass around 15M⊙ becomes a He core-burning red supergiant which fills its Roche lobe and loses around 10M⊙ during mass transfer.

A progenitor object coincident with the position of SN1993J was rapidly identified and a detailed study of its $UBVRC_{IC}$ spectral energy distribution from a homogeneous set of deep images emerged. Aldering, Humphreys, and Richmond (1994) found that the SED could only be fit with two components. A red supergiant of spectral type G8-K5I matched the $VR_{IC}$ colours and a blue component from either an OB association or single supergiant was required to account for the apparent excess in the $UB$ bands. The binary scenario of the progenitor being a stripped K-type supergiant and the secondary star being an OB-supergiant was attractive as it could neatly account for the lightcurve model results, the spectral evolution and the progenitor colours and luminosity. The ground based resolution of the best seeing images (1.5 arcsec at best in the blue and 1.1 arcsec in $I_{IC}$) corresponds to about 20 pc hence the possibility of the progenitor being embedded in an OB association was plausible. SN1993J remained bright in the optical for many years due to strong nebular lines produced by interaction of the ejecta with circumstellar material (Matheson et al. 2000, Weiler et al. 2007) and this dense CSM was presumably created during the mass-transfer phase. Hence it required a wait of almost 10 years to search for the putative companion.
Van Dyk et al. (2002a) analysed HST *UBVRI* images of the site of SN1993J taken between 1994-2001 and suggested that 4 stars lying within a radius of 2.5 arcsec of the progenitor position could have had enough flux in the *U* and *B* bands to account for the excess seen in the pre-explosion images. However this depends on how the fluxes are modelled and combined and it also depends on how the flux of the pre-explosion source is determined. Van Dyk et al. (2002a) presented a sum of the fluxes of the neighbouring bright stars (stars A, B, C and D in Figure 1) employing both a simple sum and Gaussian weighted estimate. As Aldering, Humphreys, and Richmond (1994) used a careful PSF fitting method the latter is probably most accurate. They found that the combined fluxes of the neighbouring blue stars are nearly 1.4 magnitudes fainter than the pre-explosion *B* flux and 0.8 magnitudes fainter than the *U* band flux. The large uncertainties (∆0.5 magnitudes), led Van Dyk et al. (2002a) to suggest that within the errors one could not yet claim definite evidence of further blue flux from a binary companion at the SN position.

Maund et al. (2004) went somewhat further and imaged SN1993J ten years after explosion with the ACS High-Resolution-Camera (HRC) on HST and took deep *UB*-band spectra of the SN at a moderate resolution (2.4 Å) with the Keck I telescope. The ACS image is shown in Figure 1 with SN1993J still quite bright at this epoch (*M*<sub>B</sub> ≃ −8). They estimated the total flux contributions of the neighbouring sources (stars A-G in Figure 1) and found similar results to Van Dyk et al. (2002a). Maund et al. (2004) were somewhat bolder in their conclusions and stated that the sum of the Gaussian weighted fluxes in the high resolution images was unlikely to be able to account for the excess *UB* light in the pre-explosion images. The numerical results of Van Dyk et al. (2002a) and
Maund et al. (2004) are not discrepant and the conclusions drawn differ in the interpretation of the sum of the fluxes of stars A-G. In measuring the $B$-band pre-explosion flux, Aldering, Humphreys, and Richmond (1994) note that their PSF fit to the $B$-band leaves residuals to the north and south and comparing their Fig. 1 with the HST image in Figure 1 here, it looks likely that stars A+C are the northern residual and B+D make up the southern residual flux. Hence the excess $UB$-band flux detected at the progenitor position is not due to surrounding OB-stars and this now appears quite clear in the ACS images. The high signal-to-noise ratio of the Keck spectrum taken by Maund et al. (2004) shows distinct sharp absorption features at the position of the $\text{H}_\text{I}$ Balmer lines which were attributed to a B-type supergiant binary companion lying coincident with the SN1993J remnant flux. They found consistency between the pre-explosion magnitudes and the flux required to produce the absorption lines for a binary system with a B-type and K-type supergiant shown in Fig. 2.

This represents a rather satisfying picture for SN1993J in which the unusual SN evolution is accounted for by explosion of a stripped K-type supergiant and the detailed studies of the progenitor before and after explosion now strongly support a binary system. The original mass-transfer binary model of Podsiadlowski, Joss, and Hsu (1992) was adjusted, but only slightly, to better match the observations in Maund et al. (2004). Figure 2 illustrates the pair of $15+14\,M_\odot$ stars with an initial orbital period of 5.8 yr. The mass transfer rate is initially high (reaching a peak of $4 \times 10^{-2}\,M_\odot\,\text{yr}^{-1}$) and around $2\,M_\odot$ is lost to the surrounding CSM. In this model, mass transfer begins at the end of core He burning when the star has about 20,000 yrs to go before collapse. The extensive radio monitoring campaign of Weiler et al. (2007) suggests a sudden increase in the progenitors mass-loss rate.
Supernova Progenitors

∼8000 yr before the SN and this is also supported by the X-ray lightcurves. This would, approximately, match the timescale for mass lost during the mass transfer model.

Although this is a fairly consistent scenario, perhaps there are other surprises in store, as the radio and x-ray fluxes are now dropping indicating that the luminous interaction phase is coming to an end. This may allow a clearer detection of the progenitors companion, as the Maund et al. (2004) ground-based spectrum and HST magnitudes were contaminated with the still bright remnant interaction. Ryder, Murrowood, and Stathakis (2006) have suggested a similar interacting binary system as the progenitor for the IIb SN2001ig. This event bears many similarities with SN1993J and a point source visible ∼1000 days after explosion could be blue supergiant (B to late F-type) companion.

The SN that produced the Cassiopeia A remnant occurred about 1681 AD at a distance of around 3 kpc. The detection of the scattered light echoes from Galactic SNe (Rest et al. 2008) now allows spectra of the scattered SN light (from around peak) to be collected (Krause et al. 2008). This stunning look back at the SN showed Cassiopeia A to be of type IIb, very similar to the time averaged optical spectrum of SN1993J. Krause et al. (2008) point out the lack of a detection of any viable binary companion for the Cas A progenitor and suggest an alternative merger scenario (e.g. Nomoto, Iwamoto, and Suzuki 1995). However as will be discussed in Section 5.2 it is possible that some IIb come from massive single WN-type stars.
3.2 The nearest progenitor: SN1987A

The most famous stellar progenitor of a supernova is Sk$-69^{\circ}202$ which collapsed to give SN1987A in the Large Magellanic Cloud (LMC). White and Malin (1987) showed this star to be coincident with the SN very soon after discovery and a trawl through the photographic plate material for the LMC provided Walborn et al. (1989) with several spectra of the star and $UBV$ magnitudes. These convincingly suggest a spectral type of B3I, a $T_{\text{eff}} \simeq 15750$ (from the calibration of LMC B-supergiants Trundle et al. 2007) and hence $\log L/L_\odot = 5.1 \pm 0.1$. This star has certainly disappeared and we can now probe deep into its core as the ejecta expands (Graves et al. 2005, Kjær et al. 2007). Extensive analysis and discussion of the event already exists (e.g. Arnett 1987, Arnett et al. 1989) and this section will focus on putting SN1987A and its blue progenitor star into context with the knowledge we now have of other progenitors.

The detection of a neutrino burst preceding the optical explosion epoch and the disappearance of a massive star confirms the basic theory of core-collapse. The main surprise in the SN1987A event was that its progenitor star was a blue supergiant. As discussed in Arnett et al. (1989) and Smartt et al. (2009) the luminosity of $\log L/L_\odot = 5.1 \pm 0.1$ should be compared with the evolved He core mass, not simply the luminosity of an evolutionary track that passes through the HRD position of Sk$-69^{\circ}202$. This implies a He core mass in the region $5^{+2}_{-1}M_\odot$, which can be produced from a star of initial mass in the region 14-20$M_\odot$. Most published tracks of 8-25$M_\odot$ stars still do not predict that single stars of this mass should end their nuclear burning lives in the blue and in fact do not predict large numbers of He-burning (or later stage burning) OB-type supergiants. Arnett et al. (1989) and Podsiadlowski (1992) show numerous examples of models
which can certainly end as blue supergiants with appropriately chosen (and not implausible) parameters of mass-loss and convective overshooting. But a consistent explanation also requires one to explain the triple ring structure ejected by the progenitor 20,000 yrs before explosion, the chemical abundances in the ring and also account for the properties of the supergiant population in the LMC. Both binarity and rapid rotation have been proposed as explanations.

The binary model discussed for SN1993J (Figure 2) actually ends with a second explosion of the blue supergiant, remarkably similar in its predicted parameters to Sk−69°202. A similar idea was proposed by de Loore and Vanbeveren (1992) and in this case there should be a double NS-NS system embedded in the remnant of SN1987A. This model however doesn’t have a quantitative explanation for the triple ring morphology, although the timescales for mass ejection during the mass transfer phase are not inconsistent with the 20,000 yr dynamical age of the rings. Morris and Podsiadlowski (2007) invoke a wide binary model of a 15-16M⊙ primary and a lower mass 3-6M⊙ star with an orbital period of more than 10 yrs. Unstable mass-transfer results in a common envelope phase and their 3-dimensional hydrodynamic model of the ejection produces a triple ring structure similar to that observed.

A rapidly rotating single star progenitor has alternatively been suggested as a possible cause of the almost axi-symmetric shape of the surrounding nebular rings. Chita et al. (2008) employ hydrodynamic calculations of the stellar wind properties of a 12M⊙ star which had an initial rotational velocity of 300km s⁻¹. However the model star ends its life as a red supergiant which doesn’t match Sk−69°202. The pre-supernova rotating model of a 20M⊙ star derived by Hirschi, Meynet, and Maeder (2004) can end its life in the blue, but the model
star has a low hydrogen content and would probably result in a IIb or Ib SN rather than a type II. There are four Galactic blue supergiants with similar circumstellar nebulae to Sk−69°202 (Smith, Bally, and Walawender 2007). An investigation into their possible binary nature, rotation rates and photospheric abundances would be an important way to discriminate between the scenarios.

The nitrogen abundance in the circumstellar ring found by Lundqvist & Fransson (1996) is significantly higher than the baseline LMC nitrogen content. The ratios of nitrogen to carbon and oxygen (N/C ≃ 5 and N/O ≃ 1 ; by number) are extremely high and are indicative of CNO-processed material from the H-burning phase having been dredged to the stellar surface and then ejected in the mass-loss episode that formed the ring. The CNO abundances in twenty-four B-type supergiants in the LMC were recently presented by Hunter et al. (2008). The CNO ratios ranged from 0.2 < N/C < 8 and 0.03 < N/O < 1. Hence the CNO abundances in Sk−69°202 are similar to the most highly processed B-supergiants known in the LMC. Hunter et al. (2008) showed these high abundances could be produced by a rotationally induced mixing with a rotation rate of ∼300 km s$^{-1}$ or post-red supergiant dredge-up. At least 25% of the highly processed LMC B-supergiants are binaries, although their orbital parameters remain undetermined. While rapid rotation seems attractive, there isn’t yet a single model that quantitatively explains the ring structure, collapse in the blue and the photospheric abundances consistently, while also matching the properties of the OB-population of the LMC. The merger, interacting binary and rapid rotation models are all still viable and future study of the LMC B-supergiant binary population as well as the Milky Way B-supergiants with ring nebulae seem promising avenues to constrain models further.
The small radius of Sk−69°202 of \( \sim 40R_\odot \), compared to typical red supergiant radii of 500-1000\( R_\odot \) resulted in the distinctive bolometric and visual lightcurve of SN1987A. At the time it was thought that due to it being relatively faint for a type II, \( M_V \approx -15.5 \) at peak) such events could have been missed within the \( \sim 20 – 30 \) Mpc local volume. However it now appears that such SN1987A-like events are indeed intrinsically rare, with Smartt et al. (2009) suggesting they are less than about 3% of all CCSNe. SN1987A and SN1993J are the two most extensively studied SNe of modern times and neither had the expected red supergiant progenitor expected. It appears that we have been rather fortunate, or unfortunate to have these explode on our door step. The next closest events since SN1993J were 2004am (M82 ; 3.3Mpc), 2004dj (NGC2403 ; 3.3 Mpc), 2002hh and 2004et (NGC6946 ; 5.9 Mpc) and 2008bk (NGC7793 ; 3.9 Mpc). All of these were fairly normal II-P SNe hence giving some semblance of balance to the relative rates of the SN types discussed in Section 2.2. Another nearby event was SN1996cr which was missed at the time (in the Circinus Galaxy ; 3.8 Mpc) and was likely a IIn Bauer et al. (2008), a less common SN type. Additionally a number of faint, nearby transients have been discovered which have been suggested to be SNe, but their nature is currently under debate (See Section 4.5).
4 The progenitors of type II-P supernovae: the most common explosion

It has been suspected for many years that the type II-P SNe are the most common explosions, by volume, in the Universe. The rates compiled in Section 2.2 now quantifiably endorse this perception. Perhaps surprising is how rare the brighter type II-L are. The lightcurves of II-P have generally been accepted to result from the near instantaneous ejection of energy into an extended hydrogen dominated envelope. Numerical hydrodynamic models (Chevalier 1976) and analytic solutions of the diffusion equation (Arnett 1980) both showed that large initial radii of order $10^{13} - 10^{14}$ cm were required. In these calculations the energy released (in the collapse of an iron white dwarf core) led to an expanding photosphere with velocities compatible with those observed. For over half a century stellar evolution models have predicted that stars between about $8-30M_\odot$ should begin helium core burning when they have expanded and cooled to become red supergiants and that further nuclear burning phases should occur while they are red supergiants. The latter depends somewhat on the mass-loss assigned, but standard estimates result in the end of the nuclear burning stages being reached during the RSG stage when the stars have radii of between $500-1500R_\odot$. Even the addition of rapid rotation ($V_{\text{rot}} \sim 300\text{km s}^{-1}$) in the stellar models still results in $8-22M_\odot$ stars becoming red supergiants during core He burning and beyond (Hirschi, Meynet, and Maeder 2004) as long as they avoid chemically homogeneous evolution (Yoon and Langer 2005). The recently detected UV-flash from young II-P SNe has been interpreted as the shock breakout signature in a RSG progenitor (Schawinski et al. 2008, Gezari et al. 2008). This further strengthens the case for RSGs being the direct progenitors of II-P SNe and may allow their
density profiles to be probed in the future.

As the type II-P SNe dominate the rate of explosions in the nearby Universe it is not surprising that their progenitor population is observationally now the best constrained from direct detections of progenitors or limits thereon. Images of SNe sites taken before explosion will naturally be of variable quality in terms of depth, resolution and wavelength coverage. Additionally, nearby SNe have had observing campaigns of rather variable quality and time coverage. Thus the total information package that is available for a SN plus its progenitor varies widely and the combination of high quality pre-explosion images with detailed observation and analysis of the SN is the optimum dataset to physically constrain the explosion.

The analyses of data samples of such variable quality have often adopted subjective quality bins to describe the caliber of information available, such as using gold and silver categories (e.g. in designating the quality of high-z SNe Ia data sets, see Riess et al. [2007]). We shall group the II-P progenitor detections into three classes to illustrate the confidence in the progenitor detection and the quality of the data available for characterisation of the progenitor and the SN explosion. A “gold” event should have enough information to estimate a colour or spectral type of the progenitor and an initial mass. A “gold” event should also have enough monitoring data to allow the SN to be characterised. SN2003gd, SN2005cs and SN2008bk all have unambiguous and reliable detections ($>10\sigma$) in one or more bands. All three are almost certainly red supergiants. Two events fall on unresolved, compact coeval star clusters (SN2004dj and SN2004am) and we consider these to be gold for reasons discussed below. The “silver” events are those with a detection in one band which is around $3 - 5\sigma$ or have no detailed
study of the SN evolution (SNe 1999ev, 2004A and 2004et). The “bronze” are those events with no detection of the progenitor, but with magnitude limits that set a useful luminosity and mass constraint. The latter turn out to be very useful as there are now a substantial number. The results that are reviewed fall into two categories. The first are those results that are model independent, the most important of which is that the detected progenitor stars are red supergiants of moderate luminosity. However many authors have then gone one to derive quantitative luminosities and initial stellar masses. These are dependent on the stellar atmosphere models and stellar evolutionary models employed. Hence one should be careful to distinguish between results that are purely observational discoveries and those which require a theoretical model for interpretation.

4.1 II-P progenitors: the “gold” set

4.1.1 SN2003gd  
SN2003gd exploded in the nearby face-on spiral M74 (NGC628). Hendry et al. (2005) showed that it had a fairly normal plateau luminosity and kinetic energy although it ejected a low amount of $^{56}$Ni (around $0.02 \pm 0.01 M_\odot$). M74 had been imaged by WFPC2 on HST (3100s in F606W) and GMOS on Gemini North (480-960s in $g^\prime r^\prime i^\prime$) six to nine months before the SN explosion. A rapid attempt to identify a progenitor using ground based astrometry isolated two candidates within the 0.6 arcsec error box and the authors favoured the brighter star (Van Dyk, Li, and Filippenko 2003a). Images of the SN with HST showed that this single point source was coincident with the SN to within $13 \pm 33$ milli-arcsec, which corresponds to 0.6 – 1.5 parsecs at the distance of M74. (Smartt et al. 2004). The images are shown in Fig. 10 with the progenitor identified at $V = 25.8 \pm 0.15$. It is almost certain the progenitor has been iden-
tified, if not then the progenitor must have been fainter than $V \simeq 27.1$, which both Van Dyk, Li, and Filippenko (2003a) and Smartt et al. (2004) note would put the progenitor mass uncomfortably below the core-collapse limit and probably around $5M_\odot$. The $I$-band magnitude of the progenitor has been estimated by both Smartt et al. (2004) and Van Dyk, Li, and Filippenko (2003a). The value from Smartt et al. (2004) uses deeper, higher resolution images and employed a deconvolution technique to estimate the flux of the progenitor in the Gemini $i'$-band image. This resulted in $M_V = -4.5 \pm 0.6$ $(V-I)_0 = 2.3 \pm 0.2$ which would imply the object is a red supergiant within the range K5-M3Ib and the position on an HR diagram is shown in Fig.4. The distance to this galaxy is still, perhaps surprisingly, not reliably determined with estimates ranging from 7.5-10.2 Mpc (reviewed by Hendry et al. 2005), it would be desirable to establish this more reliably as the mass and luminosity estimate of the progenitor is critically reliant on this estimate. Comparison with the stellar evolutionary models show the progenitor is likely to have had an initial mass in the range $8^{+4}_{-2} M_\odot$. The progenitor’s estimated location on an HRD is similar to RSGs in Milky Way clusters, with the Galactic stars shown for comparison in Figure4. The metallicity at the site of the explosion was probably around solar.

4.1.2 SN2005cs The progenitor of SN 2005cs has been reliably identified in the Whirlpool galaxy M51 (NGC5194). In January 2005 the Hubble Heritage team mapped M51 and its interacting companion galaxy with HST’s ACS, producing a stunning colour mosaic image of the galaxy made from four filters (F435W, F555W, F658N, F814W). Rather fortuitously, SN 2005cs was discovered close to explosion on 2005 June 28.9. Additionally the galaxy had also been imaged by HST’s NICMOS instrument in five near infra-red bands and by the
Gemini-north telescope in $JHK$ with image quality of 0.5-0.6 arcsec. Both the NIR image sets covered the pre-explosion site of SN 2005cs providing extensive wavelength coverage for a progenitor search. Two groups used HST to observe SN 2005cs in July 2005 to identify a progenitor (Maund, Smartt, and Danziger 2005, Li et al. 2006). The two studies identified the same object in the ACS F814W images as the likely progenitor (see Fig. 3). Although only detected in one band, the limits from the other wavelengths constrain the progenitor to be a red supergiant, later than approximately K3-type. Similarly to SN 2003gd the star was quite low luminosity and low mass, with the two $I$-band measurements of $23.3\pm0.2$ and $23.5\pm0.2$ in reasonable agreement. The likely position of the progenitor on an HRD is shown in Fig. 4 suggesting a mass of approximately $8\pm2M_\odot$ (like SN2003gd, the nearest HII regions in M51 display near solar metallicity). SN 2005cs has been followed in detail since its explosion and is a clear example of a low-luminosity II-P. (see Figure 10 and Section 7.1).

The low mass of the progenitor suggests these types of explosion come from stars at the lower mass range that can produce CCSNe. Eldridge, Mattila, and Smartt (2007) investigated the possibility that SN 2005cs was the explosion of a massive asymptotic giant branch star (or Super-AGB star) which underwent electron-capture induced core-collapse. They suggested this to be unlikely, from the restrictions on the photospheric temperature implied from the NIR colours.

4.1.3 SN2008bk The II-P SN 2008bk exploded in the nearby Scd spiral NGC7793 at approximately 3.9 Mpc. This southern spiral had been extensively imaged with ESO telescopes and deep optical and NIR images from the VLT provide a high quality data set for progenitor identification. Mattila et al. (2008) used the VLT NACO adaptive optics system with the SN itself ($m_V \sim 13$) as
a natural guide star to provide near diffraction limited images in the $K_S$-band. Their alignment with pre-explosion $BVIJHK$ VLT images found a progenitor star within 40 milli-arcsec of the SN position, corresponding to 0.8 parsecs (Figure 4). The progenitor source is a strong detection in the $IJHK$ bands and a very red object, with $I = 21.2 \pm 0.2$ and $(I - K) = 2.86 \pm 0.2$. Mattila et al. (2008) show the stellar SED can be fit by a late type M4I with $A_V = 1$, and this corresponds to a red supergiant of initial mass $8.5 \pm 1.0M_\odot$. The metallicity of the host galaxy at the position of the explosion appears to be low, intermediate between the SMC and LMC hence the RSGs of the LMC and $Z = 0.08$ tracks are shown in Figure 4.

4.1.4 SN2004dj and SN2004am The vast majority of CCSNe in the local Universe occur in starforming regions of their host galaxies but perhaps somewhat surprisingly are rarely coincident with bright star clusters (Van Dyk, Li, and Filippenko 2003c, Maund and Smartt 2005). Quantitatively it is probably 10% or less. Smartt et al. (2009) show that in their volume limited sample of twenty II-P SNe, only two SNe fall on compact coeval star clusters. If these clusters are indeed coeval then a measurement of their age gives a reasonable estimate for the evolutionary turn-off mass and hence initial mass of the progenitor. SN2004dj was coincident with the well studied compact star cluster Sandage 96 (Maíz-Apellániz et al. 2004) in the nearby galaxy NGC2403. The proximity of SN meant that it was well studied and its exploding core was found to suggest an asymmetric explosion (Leonard et al. 2006). A composite stellar population was calculated by Maíz-Apellániz et al. (2004) and compared with the cluster $UBVIJHK_S$ observed SED. They estimated a cluster age of approximately 14 Myrs and hence an initial mass for the progenitor of around $15M_\odot$. Using different photometry and population synthesis models, Wang et al. (2005) suggested an age of 20 Myrs and
a main-sequence mass of 12M\(_\odot\). A detailed multi-wavelength study of Sandage 96 has now been carried out by Vinkó et al. (2009) after the SN faded. They determine a young age for the cluster which suggests a probable main-sequence mass for the progenitor of between 12-20M\(_\odot\).

The other example of a II-P SN originating in a star cluster is SN2004am which is coincident with the super star cluster L in M82. Smartt et al. (2009) infer that the progenitor star had a mass of 12\(^{+7}_{-3}\)M\(_\odot\), from the age of the star cluster of 18\(^{+17}_{-8}\) Myrs recently estimated by Lançon et al. (2008). In both these clusters there is a clear sign of a red supergiant population either from their JHK colours or the absorption lines in the 0.8 – 2.4\(\mu\)m spectra. Although coincidences between SNe and compact star clusters are rare, they provide a valid method to estimate progenitor masses.

4.2 II-P progenitors: the “silver” set

There are three SNe for which progenitor objects have been detected but the significance of the detections is either low or more ambiguous than the gold events, and in one case the study of the SN itself is poor. The progenitor of SN1999ev is a 4.8\(\sigma\) detection in a prediscovery HST image of NGC4274 \((d = 15.1 \pm 2.6\) Mpc). It is detected at \(m_{F555W} = 24.64 \pm 0.17\) or \(M_V \approx -6.5 \pm 0.3\) (Maund and Smartt 2005). The sparse and mostly amateur measurements of its photometric evolution and one spectrum suggest it is most likely to have been a type II-P but it is not certain. If it was a red supergiant then Maund and Smartt (2005) suggest a likely progenitor mass of 15-18M\(_\odot\).

There is also a probable detection (4.7\(\sigma\) significance) of the progenitor of SN 2004A (Hendry et al. 2006). The SN optical evolution was well studied and it
is a fairly normal type II-P. The putative progenitor is detected in a single filter (F814W) in an HST pre-explosion image at $M_I \simeq -7.2$. The non-detection in a fairly deep F606W suggests the progenitor was a red star, likely a supergiant later than mid G-type which led Hendry et al. (2006) to suggest a red supergiant progenitor of mass $9^{+3}_{-2} M_\odot$.

Li et al. (2005) have claimed that the progenitor of the II-P SNe2004et is a fairly massive yellow supergiant of initial mass around $15 M_\odot$. They identified the object in pre-explosion CFHT archive images of the nearby spiral NGC6946 in $BVR$ filters. This posed a challenge to well established ideas that II-P SNe came from larger radii progenitors. However, it is now clear that the object identified is not the progenitor star and is not a single yellow supergiant. Smartt et al. (2009) and Crockett (2009) show that the object is still visible at the same luminosity (in $BVR$) four years after the SN exploded. Crucially, with near-diffraction-limited Gemini NIR images, they showed that the object is a stellar cluster or association of several massive stars (see Figure 5). There is a significant difference between the pre-explosion and late post-explosion images of SN2004et in the $I$-band filter images presented by Smartt et al. (2009) which suggests that the progenitor was indeed detected, but only in the reddest optical band. The detection magnitude ($I = 22.06 \pm 0.12$) and colour restriction ($R-I > 1.8 \pm 0.22$) led Smartt et al. (2009) to suggest it was a supergiant of spectral type M4 or later and an initial mass of $9^{+5}_{-1} M_\odot$.

4.3 II-P progenitors: the “bronze” set

It is routine now that the community searches high quality image archives for deep prediscovery images for every nearby CCSN discovered. But the vast majority of
SNe which have images of the pre-explosion site show no detection of a progenitor star. In spite of the low rate of discovery, the sensitivity of the images can still set interesting restrictions on the exploding progenitor stars and now the large number of non-detections can be used to statistically constrain the parent population.

The detection of two further progenitors in Virgo cluster galaxies was asserted by Li et al. (2007), in which they suggested the identification of a red supergiant progenitor of SN 2006my and a yellow supergiant of SN 2006ov. However two independent studies of the same data have rejected these two detections. Using the same data Leonard et al. (2008) and Smartt et al. (2009) show that SN 2006my is not coincident with the Li et al. (2007) source. Leonard et al. (2008) estimate that the possible progenitor and SN2006my positions are not coincident with a confidence level of 96%. Smartt et al. (2009) also find that the star suggested to be the progenitor of SN2006ov by Li et al. (2007) is not coincident with the SN and cannot be confirmed as a significant detection at the correct spatial position. These two II-P events are relegated to bronze, but the upper limits derived by Li et al. (2007), Leonard et al. (2008) and Smartt et al. (2009) are still useful.

The volume limited search of Smartt et al. (2009) provides a succinct summary of the data and information available for the progenitors of type II-P SNe. Of the 20 nearby events, eight are the “gold” and “silver” SNe discussed above and twelve have no progenitor detected. Of these twelve, two are SN 2006my and SN 2006ov now considered as null detections and categorized “bronze”. Detection limits can be converted into luminosity limits by employing distance to the galaxy, extinction to the SN line of sight and a temperature dependent bolometric correction (Thompson 1982, Smartt et al. 2001). This defines an exclusion region
in the HRD within which the progenitor was unlikely to lie. This exclusion region is defined by the luminosity of a star that, if one converts its flux to a broad-band filter magnitude, would render the star detectable in the pre-explosion images. If one assumes that the progenitors of II-P SNe are red supergiants (which seems well justified by the “gold” detections and the theory of the recombination powered plateau; see Section 4) comparison to stellar evolutionary models then allows an upper mass to be determined. Any particular mass estimate could be uncertain because of extinction, distance and measurement uncertainties but the sheer number of non-detections now appears to be significant.

Van Dyk, Li, and Filippenko (2003c) studied the HST prediscovery sites of 16 CCSNe and suggested possible progenitor candidates for a few events. However none of these have been confirmed with follow-up HST imaging. The sensitivities of the prediscovery imaging and limiting luminosities and masses tend to be meaningful for galaxies within about 20–30 Mpc (see Section 2.3); hence, the volume and time-limited sample of Smartt et al. (2009) is the most useful statistical analysis of the the masses of II-P progenitors.

4.4 The masses of the progenitor population and the initial mass function

The twelve upper mass limits presented in Smartt et al. (2009) (see their Table 2) together with the eight estimates of progenitor masses are summarised in Fig.6a. The mass distribution can be adequately fit with a Salpeter IMF of slope \( \alpha = -2.35 \), assuming a minimum mass of \( 8.5 \pm 1.0 \). But this fit requires a fixed maximum mass of \( 16-17M_\odot \). As a comparison, a Salpeter IMF running from 8.5 to 30\( M_\odot \) is shown and is not supported by the data. The lack of high mass
progenitor stars of II-P SNe is surprising. Smartt et al. (2009) have further used a maximum likelihood analysis to estimate the best fitting minimum and maximum masses for the II-P progenitors. They find that the the minimum stellar mass for a type II-P to form is $m_{\text{min}} = 8.5^{+1.5}_{-1.5} M_\odot$ and the maximum mass for II-P progenitors is $m_{\text{max}} = 16.5 \pm 1.5 M_\odot$ (Fig. 6b). This assumes that a Salpeter IMF is appropriate for the underlying stellar population, although the upper mass limit appears robust even if the IMF slope is increased to $\alpha = -3.00$. In OB associations and young clusters in the Milky Way disk and Magellanic Clouds there is no evidence for significant deviations from a Salpeter type slope (Massey 2003, Elmegreen 2008). The $m_{\text{min}}$ value derived appears to be a robust estimate of the minimum mass required to undergo core-collapse. The apparent maximum mass that can produce a type II-P has interesting implications, which will be discussed further in Section 8.

The stellar masses and mass limits that have been derived in the studies discussed above are critically dependent on theoretical stellar models. These physical models provide the estimate of mass from a luminosity measurement. The estimate of minimum and maximum masses for II-P SNe was made using the Cambridge STARS code (see Eldridge and Tout 2004). The internal stellar physics in modern codes are fairly similar in that they employ the same nuclear reaction rates and opacity tables. The differences are in the treatment of mixing (convective or rotationally induced) and mass-loss. Both the mass-loss and rotation rates of massive stars have been critically linked to initial metallicity. As shown in Smartt et al. (2009) the STARS code produces model red supergiants with luminosities very similar to the those from the rotating models of Hirschi, Meynet, and Maeder (2004) and Heger and Langer (2000). Thus the
masses derived are likely to be similar whether rotation is employed or not. If mass-loss recipes beyond those adopted as standard (or within a factor 2) are used, this could indeed affect the masses. Mass-loss in the red supergiant stage is particularly uncertain. A major uncertainty in the stellar models is the treatment of convective core overshooting. Increasing the overshooting will increase the core mass and hence its luminosity. As the surface luminosity is set by the core, the masses derived for RSG progenitors will depend on the amount of overshooting employed. This fact highlights the explicit dependence of the masses on the input physics and the stellar models. Another factor is the assumption that binaries do not play an important role in the production of II-P SNe. It is possible that the minimum initial mass could be reduced to below \(8\,M_\odot\) if a lower mass star (for example around \(5\,M_\odot\)) evolves to a higher mass through accretion. There is no clear observational evidence for binarity in II-P SNe but theoretically the possibility remains open.

4.5 Transients of uncertain nature: core-collapse or not?

An intriguing new twist in the story of optical transients occurred in 2007 and 2008. The discovery of two objects with similar luminosities, colour temperatures and line velocities within a few months led to suggestions that they are physically related and that other peculiar transients could be of the same class. Kulkarni et al. (2007) reported the discovery of an optical transient in M85 (M85-OT2006) and suggested the origin was a stellar merger, naming the event a “luminous red nova”. An optical transient was discovered in NGC300 in April 2008 (NGC300-OT2008 Monard 2008) which has also not yet been given a supernova designation due to its uncertain nature. Bond et al. (2009) proposed
it could be outburst of a relatively massive OH/IR star rather than a true supernova explosion. Just 3 months earlier, a stellar eruption in NGC6946 showed similar photometric properties and narrow emission lines and this time was given a supernova designation, it is known as SN 2008S. It has been given the label of a supernova of type IIn based on the narrow, Balmer dominated, emission line spectrum.

Prieto et al. (2008) and Thompson et al. (2009) have studied the pre-explosion sites of SN2008S and NGC300-OT2008 and found a bright mid-IR point source visible in Spitzer Space Telescope images (between 3.5-8.0µm) coincident with both the eruptions. Neither progenitor was visible in deep optical images which led the authors to suggest that these were the result of core-collapse of massive stars which were enshrouded in an optically thick, dense dust shell. The MIR SED is suggestive of black body emission from the dust shell at a temperature of $T_{\text{dust}} \sim 440 - 300$ K, luminosities of between $\log L / L_\odot \sim 4.5 - 5.0$, and black body radii of $R_{\text{BB}} \sim 150 - 520$ AU (for SN2008S and NGC300-OT2008 respectively). Stellar luminosities in this range require either evolved massive stars (with a He core) of mass around 8-15M$_\odot$, or possibly lower mass stars (5-8M$_\odot$) which have gone through 2nd dredge up (see Figure4 and Eldridge, Mattila, and Smartt 2007).

The latter can reach luminosities of around $\log L / L_\odot \sim 4.5 - 5.0$ dex and if the stellar flux is totally absorbed and re-emitted in the MIR they are plausible heating sources for the detected dust shells. Thompson et al. (2009) searched multi-wavelength images of the Local Group spiral M33 for possible counterparts and found this type of object extremely rare. It appears that there are fewer than 10 similar objects in this galaxy and they are likely extreme AGB
stars. Thus a plausible scenario for these transients (at least SN2008S and NGC300-OT2008) is that they are electron-capture SNe (ECSNe; Nomoto 1987, Kitaura, Janka, and Hillebrandt 2006).

The progenitors would be super-AGB stars, having undergone 2nd dredge up and carbon ignition, and collapse of their O-Mg-Ne cores is triggered by electron capture before Ne ignites (Nomoto 1984, Poelarends et al. 2008). Various groups are monitoring SN2008S and NGC300-OT2008 transients intensely and conclusions as to the explosive nature of the two transients will be forthcoming soon. Three ways to provide evidence for the ECSNe scenario are the detection of a $^{56}$Ni decay phase, possible broad-lines from intermediate mass element ejecta in the very late time spectra and the disappearance of the progenitors in future observations.

There is no Spitzer source at the position of M85-OT2006 in an image from 2004 but Thompson et al. (2009) note that the post-explosion MIR evolution may be comparable to SN2008S and NGC300-OT2008, hence suggesting a common origin. Whether or not all three transients are really of the same nature and whether or not they are ECSN from dust obscured super-AGB stars still remains to be confirmed. The alternative scenario put forward by Kulkarni et al. (2007) is that M85-OT2006 is the result of a violent merger of a low or intermediate mass star with a more massive primary or a compact remnant. This is still a viable possibility for M85-OT2006 and also for the other two. A full comparison of the energetics and kinematics of all three events (and also possibly SN 1999bw; see Thompson et al. 2008) will guide future discussion.
5 The progenitors of Ibc supernovae

The simple fact that Ibc SNe do not, on the whole, show evidence for hydrogen ejected at velocities similar to the intermediate mass elements is convincing evidence that the exploding star did not have a hydrogen atmosphere. It is likely that some Ib SNe do show evidence of hydrogen absorption features in their early photospheric spectra (Branch et al. 2002) and there is almost certainly a continuum of hydrogen line strengths between the classic Ib SNe (with no sign of H) and the IIb (Elmhamdi et al. 2006). The progenitors of Ib and Ic SNe have been proposed to be massive Wolf-Rayet stars (Gaskell et al. 1986) as these are massive evolved stars that have shed most, if not all, of their hydrogen envelope. An alternative scenario is that the Ibc SNe progenitors are stars of much lower initial mass in close binaries which have had their envelopes stripped through interaction (Roche lobe overflow, or common envelope evolution; Podsiadlowski, Joss, and Hsu 1992, Nomoto, Iwamoto, and Suzuki 1995). This section will review the evidence from direct searches for progenitors of Ibc SNe within about 30 Mpc and we will include the IIb SNe in this discussion as they have also been stripped of much of their hydrogen atmosphere.

5.1 Searches for Ibc progenitors

There are 10 SNe classified as Ibc which have deep pre-explosion images available and none of them have a progenitor detected. Maund and Smartt (2005) and Maund, Smartt, and Schweizer (2005) attempted to use a combination of evolutionary models of single WR stars and model spectra to constrain the physical parameters of the progenitors. Crockett et al. (2007) also discussed this approach for SN 2002ap but the uncertain and variable bolometric correction of WR stars
makes it difficult to determine restrictions on mass. WR stars in the LMC and Milky Way show highly variable broad-band magnitudes with little direct correlation with current (or initial) mass. Gal-Yam et al. (2005) have preferred a simpler comparison of their magnitude limit for the progenitor of SN 2004gt with known WR populations. Van Dyk, Li, and Filippenko (2003c) carried out a similar comparison for several Ibc SNe. Figure 7 shows the broad-band magnitudes of WR stars in the LMC with a comparison of the limits for all the Ibc progenitors with HST pre-explosion images (or deep CFHT images in the case of SN2002ap). The deepest limit is for the Ic SN2002ap in which there is no detection of a progenitor star to a limit of $M_B \geq -4.2 \pm 0.5$ and $M_R \geq -5.1 \pm 0.5$. For this event and any other individual SN in Fig 7 the magnitude limits cannot rule out a massive WR star progenitor. However lets make a hypothesis that the progenitor population of all Ibc SNe are massive WR stars as we see in the Local Group (and that the LMC luminosity distribution is a fair reflection). Then we can ask, what is the probability that we have not detected any of the 10 progenitors simply by chance. A simple probability calculation would suggest the probability is 11% if one assume that the likely Ib progenitors are WN stars and Ic progenitors are WC/WO stars. Thus we conclude, at 90% confidence level that the hypothesis is false and the massive WR population we see in the Local Group cannot be the only progenitor channel for Ibc SNe. The implication is then that some of the population come from lower mass stars within interacting binaries and how this compares with the rate of Ibc SNe will be discussed below. The following two sections discuss interesting events in which a possible WN progenitor has been detected and a possible host cluster has been identified. They represent two of the best opportunities for characterising the local IIb-Ib-Ic populations.
5.2 SN2008ax: a WNL progenitor of a IIb or a binary in a cluster?

A detection of a point source coincident with a IIb SN has been reported for SN2008ax in NGC4990. This event had a bolometric lightcurve almost identical to SN1993J apart from no detected shock breakout and the early explosion phase was well enough observed for this to be a robust conclusion (Pastorello et al. 2008). The strong H\(\alpha\) absorption feature in the spectrum faded rapidly and by 56 days nearly all traces of hydrogen had disappeared from the spectrum which became He dominated. Crockett et al. (2008) showed that the SN was coincident to within 22 milli-arcsecs of a bright point-like source detected in three HST bands (F435W, F606W and F814W) in pre-explosion WFPC2 images. Using a distance of 9.8 Mpc and extinction of \(E(B-V) = 0.3\), Crockett et al. (2008) estimated absolute magnitudes of \(M_B = -7.4 \pm 0.3\), \(M_V = -7.3 \pm 0.3\), \(M_I = -7.8 \pm 0.3\). A single supergiant SED cannot be fit to these colours and Crockett et al. (2008) show that it is difficult to come up with a binary system which has a combined colour matching the observed and consistent luminosities to explain the evolutionary path to explosion for the more evolved star. The progenitor could have been a binary, similar to that proposed for SN1993J, but with additional flux within the PSF from other neighbouring stars. The object is consistent with a single PSF, but at a distance of nearly 10Mpc, the PSF width corresponds to about 6pc. Crockett et al. (2008) propose that the magnitudes are similar to WN and WNL stars in the LMC and M31. The progenitor of SN2008ax would be one of the brightest of this population but its colours are quite consistent with it being such a stripped massive star and possibly of initial mass between 25-30M\(_\odot\). Hence this remains the only possible direct detection of a WR star.
as a SN progenitor and the comparison models shown in [Crockett et al. (2008)] show reasonable agreement with the final position of the progenitor in colour magnitude diagrams. When the SN fades we shall see if this object disappears, which it should if a massive WR star origin is correct, or if the “binary within a cluster” scenario is true. The SN was not a Ibc, but a IIb in which clear evidence of hydrogen was seen although the transformation to a Ib was more rapid than that seen in SN1993J. The lack of a strong shock breakout is suggestive that the stellar radius was much smaller than the extended (but H-deficient) K-type supergiant proposed for SN1993J, hence suggesting a compact WN star could be viable. The [Nomoto et al. (1993)] model of SN1993J required an extended, but low mass H-shell to reproduce the shock breakout and naked He-cores produced the secondary rise well without the initial luminosity peak.

5.3 SN2007gr: possible mass estimate from host cluster properties

As discussed above in Section 4.1.4, if a SN is spatially coincident with a coeval compact star cluster one can probably assume membership. Hence a measurement of the cluster age and turn-off mass for a coincident Ibc SN is potentially very interesting. [Crockett et al. (2008)] show that the Ic SN2007gr lies on the edge of a bright source, 6.9pc from its nominal centre and that the bright source is probably a compact cluster. The pre-explosion HST images are not of wide enough wavelength coverage to determine a unique age for the cluster, or indeed confirm for certain that it is not an extremely bright single supergiant. A future combined optical and NIR SED of the possible host cluster could give a robust age. [Crockett et al. (2008)] suggest that this could distinguish between two likely
turn-off ages of around 7 and 25 Myr. In principle it may be possible to favour a massive single WR star (around 30M☉) or an interacting, lower mass binary (around 10M☉) from the cluster age.

5.4 The rate of Ibc SNe and interacting binary stars

The relative frequency of discovery of SNe Ibc is strongly suggestive that at least a fraction come from interacting binaries. The $N_{\text{Ibc}}/N_{\text{II}}$ ratio (discussed in Section 2.2) is $0.4 \pm 0.1$ at metallicities of around solar. If we were to assume that this is simply due to higher mass stars producing Ibc by becoming WR stars then the formation of a WR star must occur at initial masses of about 16M☉ and above. This is much too low to be consistent with initial masses for WR stars in the Local Group. In the Galaxy and LMC clusters, the turn off mass to produce WN stars is at least 25M☉ and probably closer to 35-40M☉ to produce WC stars (Massey 2003, Crowther 2007). Also the observed mass-loss rate of 16-20M☉ stars would be somewhat too low to produce WR stars in evolutionary models which adopt these $\dot{M}$ values (see Heger et al. 2003, Hirschi, Meynet, and Maeder 2004, Eldridge and Tout 2004, Crowther 2007).

The high rate of Ibc SNe was recognised as a problem in the 1990’s and interacting binaries were suggested as a common channel (Nomoto, Iwamoto, and Suzuki 1995). Podsiadlowski, Joss, and Hsu (1992) calculated that 15-30% of all massive stars (with initial masses above 8M☉) could conceivably lose mass to an interacting companion and end up as a helium star. They assumed a fraction of stars in binary systems which are close enough to interact of about a third. This latter fraction is still uncertain and recent results suggest it could be more than 60% (Kobulnicky and Fryer 2007). The lack of detection of any massive WR progen-
itors would point towards the binary channel being a common cause of stripped, evolved stars at their life’s end. All that is required is that the primary star in the system is more massive than about $8-10M_{\odot}$, a companion of a few $M_{\odot}$ and an orbital period less than around 100 yrs. Such systems are not uncommon in our galaxy, for example V Sagittae, WR 7a and HD45166 are all binary systems with a H-deficient primary that has probably lost its mass either through Roche-lobe overflow or common envelope evolution. But whether or not they will explode as type Ibc SNe and how common they are by volume are both unanswered questions. If they are common progenitors of type Ibc then they should nearly be as common (within $\simeq 30\%$) as evolved massive stars (blue and red supergiants). Perhaps the final mass-transfer that strips the core occurs very close to the end of nuclear burning (in the last $\sim 10^4$ yrs) and thus the phase lasts such a short time that they are rare objects. Alternatively Nomoto, Iwamoto, and Suzuki (1995) has proposed that common envelope evolution in binaries can result in progressively severe stripping of the envelope of the primary, leading to a sequence of II-L, IIb, Ib, and Ic.

There are theoretical arguments that massive WR stars collapse to form black holes and that, at solar metallicity and below, they do not form bright SN explosions. In related papers Heger et al. (2003) and Fryer (1999) put forward the idea that at around solar metallicity a star which is massive enough to shed its envelope through radiatively driven winds ($\sim 30-60M_{\odot}$ with their adopted mass-loss recipe) ends up with a core mass that is too large to form a neutron star. When a black hole is formed, fall back means little $^{56}$Ni is ejected and an electromagnetically weak explosion follows. By extrapolating mass-loss rates above solar metallicity they suggest that the mass-loss rate could be high enough so that
stars with ZAMS mass $M_{\text{initial}} > 25M_\odot$ produce the canonical core-collapse to a neutron star and successful neutrino driven shock. This is course still uncertain as mass-loss at high metallicities remains unconstrained as do stellar abundances. Fryer et al. (2007) put forward the idea that all bright Ibc could conceivably come from interacting binaries, and massive WR stars could be collapsing quietly to black hole holes with no visible explosion. Eldridge, Izzard, and Tout (2008) illustrate that by mixing single stars and interacting binaries in massive stellar populations they can reproduce the Ibc ratio at solar metallicity and get a lower value of $N_{\text{Ibc}}/N_{\text{II}} \sim 0.1$ at $0.3Z_\odot$, as suggested in the surveys discussed in Section 2.2. This is further encouragement for the observers to improve the metallicity determinations of nearby SNe environments.

5.5 The environments of type Ibc SNe

A strong argument that Ibc SNe actually do come from stars of higher masses than type II-P is their association with H\textsc{ii} emission and areas of high stellar surface brightness in their host galaxies. An early study of the proximity of the Ibc and II SNe with H\textsc{ii} regions suggested the degree of association was not markedly different (Van Dyk, Hamuy, and Filippenko 1996). However a factor of two increase in the numbers of SNe available suggest differences are now discernible. Anderson and James (2009) show that the positions of SNe Ic in late-type galaxies tend to trace the H\textalpha+[N\textsc{ii}] line emission. This contrasts markedly with the locality of SNe II, which are not, on the whole, associated with H\textsc{ii} regions. The SNe Ib also show a higher degree of association with the H\textalpha+[N\textsc{ii}] emission than the SNe II, although somewhat less than for the Ic. As H\textsc{ii} emission requires a young population of ionizing sources (O-stars) the implication is that
the SNe Ic come from a younger population of progenitors than SNe II (with the Ib in between). Kelly, Kirshner, and Pahre (2008) reach a similar conclusion in finding that the SN Ic tend to fall on areas of higher surface brightness than the SNe Ib and II, from surface brightness maps in SDSS host galaxies. The statistics from these studies are impressive, with 69 (type II), 11 (Ib), 24 (Ic) from Kelly, Kirshner, and Pahre (2008) and 100, 22, 34 from Anderson and James (2009). The case for an increasing mass range for progenitors of SNe II-Ib-Ic is supported by both these studies. However as bright H II emission and integrated continuum light is indicative of high stellar surface density and high specific star formation rates, it is also likely to trace cluster and OB-association localities. Clark et al. (2008) point out that the binary fraction in field stars is lower than that found in stellar clusters and OB-associations. While this is still not definitively proven, perhaps there is a propensity for a higher binary fraction in these regions. One might then imagine that these regions could conceivably produce higher numbers of Ibc SNe.

5.6 Ejecta masses from SNe Ibc and GRB related SNe

With the lack of detection of a progenitor of a Ibc event, the only other way to determine a stellar mass is from modelling of the lightcurve and spectral evolution. The type Ic SNe have been subject to intense scrutiny recently due to their link with long-duration GRBs (LGRBs) with ejecta masses now determined for nine Ibc SNe (Mazzali et al. 2006a, Valenti et al. 2008, and references therein). The lowest of these are 1994I, 2002ap and 2007gr with ejecta masses between 1-2.5M⊙. The mass of the remnant left is then critical for an estimate of the CO core that exploded. If we assume a canonical mass of 1.5M⊙ for a neutron star
remnant, then the CO core masses of these objects would be 2.5-4M⊙. These are lower than typically found for the current masses of WC stars in the Galaxy and LMC (Crowther et al. 2002) of between 7-20M⊙. With total energies of around $1 - 4 \times 10^{51}$ ergs s$^{-1}$, these are the least energetic of the Ic SNe that have been modelled. The likely scenario is then that they were not single, massive WC stars but that the CO core of this low mass was formed in an interacting binary. In these models a CO core of 3-5M⊙ corresponds to a primary of initial mass around 8-15M⊙. Although only a few of the nine have low masses, this is due to the high energy events being preferentially selected for detailed modelling and is not a reflection on the relative rates.

The more energetic events, in terms of their kinetic energy and bolometric lightcurves, indicate higher model ejecta masses. The LGRB related SNe (SN1998bw, SN2003dh, SN2003lw) have estimated ejecta masses of 8-13M⊙, while the energetic SN2004aw and SN2003jd (which lack detected LGRBs) were calculated at 3-5M⊙ (Taubenberger et al. 2006, Mazzali et al. 2006b, Valenti et al. 2008). Adding a minimum of 1.5-2.5M⊙ for a NS/BH remnant would suggest reasonable agreement between the progenitor CO core mass and LMC WC stars. Although systematics may affect the masses determined by the lightcurve modelling technique and they are not yet observationally confirmed with an independent method, it does appear that the relative difference in the shapes of Ic SNe are due to an increasing ejecta mass and an increasing mass of the CO star which exploded. The most energetic of these are associated with GRBs. Podsiadlowski et al. (2004) suggested that the rate of energetic broad-lined Ic SNe is similar to the rate of LGRB which might indicate that most (or all) energetic Ic SNe produce GRBs. This assumed that ~5% of all Ibc SNe were
energetic Ic and this is supported in the volume limited numbers of Smartt et al. (2009); of 27 Ibc only one (2002ap) would qualify as a broad-lined Ic. As Podsiadlowski et al. (2004) point out, that the observed rate of production WR stars in galaxies (from stars with initial masses > 40M\textsubscript{☉}) far out weighs (by a factor of \(\sim 10^2\)) the broad-lined Ic SN rate. Thus it is certain that not all WR stars produce broad lined Ic SNe. If we have reason to believe that the normal Ibc population do not, on the whole, come from massive WR stars (see Section 5.1) then what is the fate of these stars? A further complication is that the observed WC/WN ratio is between 0.1 (at SMC metallicity) and 1.2 (solar metallicity; see Crowther 2007 and Massey 2003) but the Ic/Ib rate is 2 ± 0.8 (Section 2.2). Either the WN phase is a transient evolutionary phase for WR stars, or binary systems significantly alter the Ic/Ib ratio significantly.

In summary the observational evidence supports the ideas that a significant fraction of Ibc SNe coming from interacting binaries in which the primary that explodes has a mass lower than what is usually associated with evolution to the massive WR phase. This is supported by the lack of progenitor detections and the low ejecta masses for the least energetic Ic SNe. Although some objects with low ejecta masses clearly have high kinetic energies (SN2002ap for example). However the birth places of Ibc SNe suggest that the Ic SNe, when taken as a population, come from noticeably younger (or denser) regions than the type II SNe. This could imply that they have appreciably higher initial mass. The ejecta masses of the most energetic events would also indicate they could be from massive single stars that form WRs. Hence there are likely two channels at work. The relative contribution of each remains to be determined and the exact relation between core-mass, \(^{56}\text{Ni}\) production, kinetic energy and compact remnant is an area for
future study.
6 The fate of very massive stars

The most massive stars known in the Local Group are LBVs which are evolved blue stars with strong winds and luminosities between $5.5 < \log L/L_\odot < 6.0$ (Humphreys and Davidson 1994). The most extreme have evolutionary masses in the range 80-120$M_\odot$. Their position on the theoretical HRD and comparison with evolutionary tracks implies that they are either core H-burning or He-burning stars which have evolved from the main-sequence (Figure 9). Evolutionary scenarios based on stellar evolution theory and observational inferences from massive stellar populations in the Local Group have generally implied, at least up until now, that they are likely to lose their H and He envelopes and end up as WR-stars (Maeder and Meynet 1994, Heger et al. 2003, Massey 2003). Recently Langer et al. (2007) have proposed that some very massive stars may retain at least part of their H-envelope until their deaths. Although radiatively driven mass-loss occurs during the LBV phase and in the massive O-star progenitor phase, the current measurements of rates are too low to completely drive off the H and He atmospheres, particularly when wind clumping effects are considered (Smith and Owocki 2006). They can lose several solar masses of material in short and sporadic eruptions (Humphreys and Davidson 1994) and the physical cause is not well understood (Pauldrach and Puls 1990, Smith and Owocki 2006, Smith, Vink, and de Koter 2004). Very large ejecta masses of around 10$M_\odot$ in these sporadic outbursts have been suggested along with the idea that only super-Eddington continuum winds or hydrodynamic explosions could be the cause (Smith and Owocki 2006). Thus the ultimate fate of these most massive stars has been uncertain. Their core masses at the end of evolution would suggest that they are likely to form black holes, if the core collapses in a similar way to lower mass objects (Fryer 1999).
Several unexpected and extraordinary discoveries in the last three years have opened up the debate on the physical process that governs the death of these stars. The core-collapse mechanism struggles to explain their nature and novel explosion physics has already been developed.

6.1 SN2005gl: a very massive star

Although Sections 4 and 5 have concentrated on searches for progenitors in galaxies closer than about 30 Mpc, studies of the environments of a small number of SNe at larger distances (40-100 Mpc) were being carried out (Van Dyk, Li, and Filippenko 2003c). The possibility of even HST images being sensitive to individual stars relied on locating very bright and hence very massive progenitors. A remarkable discovery by Gal-Yam and Leonard (2009) shows that a star which is likely one of the most massive and luminous stars we know exist exploded to produce a IIn SN. When SN2005gl was discovered, Gal-Yam et al. (2007) located an HST image of the host galaxy NGC266 taken in 1997. Images in two filters were available (F547M: medium width V-band and F218W: UV band) and alignment with a high resolution image taken with the Keck laser guide star AO system showed a bright point source (only in the F547M band) coincident with the SN. Gal-Yam and Leonard (2009) then showed that the star has disappeared in subsequent HST images with the same filter (see Figure 8). The progenitor was observed with $M_V = -10.3$ and assuming a zero bolometric correction this implies a luminosity of $\log L/L_\odot = 10^6$. The only stars known locally of this luminosity and visual magnitude are the luminous, classical LBVs such as AG Car, AF And, P Cyg and S Dor (see Smith, Vink, and de Koter 2004, for a summary
of LBV luminosities, and Figure 8. SN2005gl was a relatively bright SN IIa which shows distinct evidence of the SN ejecta interacting with a circumstellar shell (Figure 8). The narrow Hα line in the spectrum 8 days after discovery suggests the existence of a shell of H-rich gas with an outflow velocity of around 450 km s$^{-1}$. The later spectra at days 58 and 87 show the broader profile of the SN ejecta moving at around 10,000 km s$^{-1}$. From these spectra and the lightcurve, Gal-Yam and Leonard (2009) estimate that the progenitor lost a modest amount of mass (≈0.03M$_\odot$) to create the circumstellar shell but that the lack of an extended plateau probably points to it having shed a considerable amount of its H-envelope before explosion.

6.2 SN2006jc: a giant outburst followed by core-collapse

The first discovery of a bright optical transient spatially coincident with a subsequent luminous supernova was reported by Pastorello et al. (2007). The SN2006jc was preceded, two years earlier, by a sharply decaying outburst that reached $M_R \simeq -14.1$ and was detected for only a few days. The outburst magnitude and fast decline is similar to the giant outbursts of some LBVs. These outbursts have been recorded in the Galaxy (η Car and P-Cygni) and in the nearby Universe (Section 2.5), but they have generally been thought to be associated with a mass ejection event in which somewhere between a few tenths and few solar masses are ejected. As the known LBVs, which have exhibited this behaviour, still retain their H-envelopes, the material is normally H and He rich. (Foley et al. 2007) and Pastorello et al. (2007) showed that the high velocity ejecta spectrum of SN2006jc is more like a type Ic, with intermediate mass elements O, Mg, Ca (and possibly Na and Si) exhibiting outflow velocities of 4000-9000 km s$^{-1}$. Strong
He lines are persistent, but with a lower velocity of around 2000 km s\(^{-1}\) and weak H is detected at later times. The narrow He\(\text{I}\) lines are circumstellar and this material was ejected from the star in the recent past, although not necessarily in the 2004 outburst. This led to the conclusion that the exploding star was a WC or WO star embedded within a He rich circumstellar envelope (Foley et al. 2007, Pastorello et al. 2007, Tominaga et al. 2008). The outburst in 2004 had a peak luminosity of at least \(\log L/L_\odot \sim 7.5\) and total integrated energy over 9 days of \(> 10^{47}\) ergs. This is similar to the known outbursts of high luminosity LBVs (Humphreys, Davidson, and Smith 1999), but all of these still retain significant hydrogen and helium atmospheres. LBV stars are often helium enriched but are not completely deficient in hydrogen. The progenitor of SN2006jc was a CO core explosion which raises unanswered questions about the outburst. Tominaga et al. (2008) calculate a mass for the WC/WO star of 6.9 M\(_\odot\) and an initial mass of around 40 M\(_\odot\) on the main sequence. Such energetic outbursts have never been associated with WR stars and this may the first observed example of a star transitioning from the LBV phase to the WR phase through sporadic mass ejections. It may be that the \(10^{47}\) ergs outburst ejected the last remnants of its outer He layer (Tominaga et al. 2008, Foley et al. 2007, Pastorello et al. 2007).

### 6.3 Constraints on II-L SNe progenitors

There are very few direct constraints on nearby II-L SNe. This subtype appear to be relatively infrequent (see Table 1) but they may be important in solving the problem of the lack of high mass red supergiants detected as type II-P progenitors. As the II-L by definition have a very short, or non-existent plateau phase they probably have a low mass H-envelope which cannot sustain a lengthy
recombination phase. The H-envelope mass could be reduced through mass-loss or binary mass-transfer. If the former, it could point to them being higher mass progenitors than II-P.

The nearest II-L known, SN1980K in NGC6946 (5.9 Mpc) had a photographic plate taken 49 days before maximum (Thompson 1982). At the position of the SN there is no star, or stellar association visible to a plate magnitude of $M_F \simeq -7.7^m$. The limit does rule out massive red supergiants greater than about 20$M_\odot$, but blue progenitors hotter than 10,000K and between 15-25$M_\odot$ would be permitted. Another nearby type II-L SN1979C fell within a stellar association in M100 and analysis of the stellar population would suggest that if all stars were coeval the turn-off mass for the SN1979C progenitor would be 15-21$M_\odot$ (Van Dyk et al. 1999a). Montes et al. (2000) have estimated the mass-loss history from the SN and find an increased rate at 10,000-15,000yrs before explosion. The total mass loss could be as high as 4-6$M_\odot$ but they suggest this is not inconsistent with the stellar population mass. Absence of evidence is by no means evidence of absence, but to date there are no arguments from direct progenitor studies for high masses for II-L progenitors.

6.4 Are LBVs direct SNe progenitors?

The discovery of several remarkably bright, hydrogen rich (hence type II) SNe has reinvigorated the debate of the physical mechanisms that can produce explosions. The first of these ultra-bright type II SNe recognised was SN2006gy, followed by SN2005ap, SN2008es and SN2006tf. The integrated radiated energies are around $10^{51}$ ergs and the physical cause of the exceptional luminosity is not yet established. The total energy of these explosions has not yet been measured
as the ejecta masses are uncertain, but typical kinetic energies of type II SNe also tend to be of order $10^{51}$ ergs. In the case of SN2006gy and 2006tf (IIn SNe), Smith et al. (2007, 2008) propose that the luminosity results from a physically similar process to that which produces II-P SNe lightcurves (as discussed in Section 4) but with extreme values for radial extent and density. The shock kinetic energy is thermalised in an opaque, dense shell (which acts like a photosphere) of radius $\sim 150$ AU and mass of $\sim 10 - 20 M_\odot$ Smith & McCray (2007). The radius and enclosed mass are too large to be a bound stellar envelope, even when compared to the most extreme red supergiants. Thus Smith et al. (2008) propose that such dense shells were created in LBV-like giant eruptions and mass ejections, within a few years (perhaps up to decades) before final explosion. In this model, the progenitor is required to be a massive LBV, one which is massive enough to have undergone giant outbursts and by implication probably greater than $50 M_\odot$.

Agnoletto et al. (2009) developed a model in which interaction is the luminosity source, with an ejecta mass of 5-15$M_\odot$ impacting 6-10$M_\odot$ of opaque clumps of previously ejected material. Again this suggests an LBV-type progenitor object.

The other two ultra-bright type II SNe (more correctly classed II-L as they show no narrow absorption or emission components) SN2008es and SN2005ap are equally luminous, again with total radiated energies $\gtrsim 10^{51}$ ergs (Quimby et al. 2007, Miller et al. 2009). Gezari et al. (2009) offer an alternative explanation for SN2008es of a progenitor with a lower mass, extended H-rich envelope ($R \sim 6000 R_\odot$) having a steady, dense super-wind with mass-loss rate $\dot{M} \sim 10^{-3} M_\odot$ yr$^{-1}$. For SN2005ap Quimby et al. (2007) suggest the collision shock and thermalization and also the possibility of a jet explosion (GRB-like) within a H-rich massive progenitor.
Lightcurves powered by radioactive decay of $^{56}$Ni were also considered (Smith et al. 2007, Gezari et al. 2009) but this requires a huge mass of $^{56}$Ni in the ejecta ($\sim 20M_\odot$). The sharp decline in the late-time lightcurves and lack of strong [Fe ii] lines now suggests this is unlikely. Such a large $^{56}$Ni mass could only be produced in a pair-instability supernova in which the high temperatures in a massive core (He cores of $\gtrsim 40M_\odot$) induces electron-positron pair production. This absorbs thermal energy, the core collapses further which results in a further temperature rise and runaway thermonuclear burning in a massive core (Woosley and Weaver 1986, Woosley, Heger, and Weaver 2002, for the details of the physics involved and review of the history of this idea see). In theory $10-20M_\odot$ of $^{56}$Ni can be produced and ejected (Heger and Woosley 2002) in a pair-instability supernova or $\sim 5M_\odot$ in a core-collapse of a massive star (Umeda and Nomoto 2008). A modification of this mechanism is pulsational pair-instability in which a massive core undergoes interior instability again due to electron-positron pair production (Woosley, Blinnikov, and Heger 2007). This leads to an explosion which ejects several solar masses of material, but is not enough to unbind the star. Several pulsational explosions can occur and the collisions between the shells could conceivably produce $10^{50}$ ergs. Again, the shock kinetic energy diffuses thermally within an optically thick, high density, compact sphere. This produces the high luminosity rather than it being due to a large mass of $^{56}$Ni. The model of Woosley, Blinnikov, and Heger (2007) requires a large core mass from a star of initial mass 95-130$M_\odot$. The collisions between the massive shells produces radiative energies in a similar manner to that discussed in Smith & McCray (2007).

The radio lightcurve modulations seen in some SNe have been suggested to be due to the interaction of the ejecta with the progenitor stars’ surrounding gas
shells which were ejected in S-Doradus type variability (Kotak and Vink 2006). This would point to stars which had been in the LBV phase close to the epoch of collapse. Additionally a direct LBV progenitor was also proposed for SN2005gj to explain the multiple components in the absorption trough of Hα (Trundle et al. 2008).

The physical mechanism that produces the ultra-bright type IIn and II-L SNe is still controversial and unresolved. Viable explanations are the explosion of the most massive stars we know, while they still retain a significant H-rich envelope or have recently undergone large mass ejections. Such objects are clearly reminiscent of known LBVs in the Local Group. These massive stars are in a position of the HRD that leads stellar evolutionary tracks to suggest they are at the end of core H-burning or perhaps have just entered core He-burning. If they are in fact undergoing core-collapse then their cores are significantly more evolved than we have thought. This would pose difficulties for stellar evolution models and our interpretation of the nature of known LBVs. It is also not yet understood if the core-collapse mechanism (i.e. collapse of an Fe-core and neutrino driven explosion) can account for the energies observed.
7 Explosion parameters and compact remnants

The physics that governs the core-collapse and launch of the shock that destroys the star has been of interest since the luminosities of SNe were first estimated. The current view is that the shock bounce of the proto-neutron star requires reinvigorating and boosting by neutrino energy deposition. (Janka et al. 2007). Successful explosions have been produced numerically, but within restricted mass ranges. Acoustic wave driven explosions have also been proposed to increase the shock energy (Burrows et al. 2006). The observations of progenitors do not give restrictive constraints on the mechanisms by themselves but by comparing with the explosion parameters they are of interest to the core-collapse mechanism.

7.1 $^{56}$Ni production and explosion energies

One of the few direct observational probes of the explosion which can be studied after core-collapse is measuring the amount of radioactive $^{56}$Ni that is synthesised. This nuclide is created by the explosive burning of Si and O as the shock wave heats the surrounding mantle and is mixed through the ejecta. The lightcurves of type Ibc and Ia SNe around peak are determined by the mass of $^{56}$Ni, the total mass of the ejecta and its kinetic energy (Hillebrandt and Niemeyer 2000, Mazzali et al. 2006b, Valentí et al. 2008). Models of the observed lightcurves and spectral evolution of Ic SNe have derived these properties (e.g. Mazzali et al. 2006b, Nomoto et al. 2006, 2008).

The photospheric stage of II-P SNe is powered by the recombination of hydrogen as the photosphere cools but the nebular tail phase luminosity is determined by the $^{56}$Co-$^{56}$Fe decay and its subsequent deposition of $\gamma$-rays and positrons which are thermalised. Thus the bolometric luminosity in the nebular phase of
type II SNe can be used to estimate the original $^{56}$Ni mass. There is a large range in the observed tail phase luminosities of type II-P SNe (e.g. see Figure 10) and the physical interpretation has been differences in the ejected $^{56}$Ni mass (for reference, the $^{56}$Ni mass estimated for SN1987A is $0.075 M_\odot$). Zampieri et al. (2003) and Pastorello et al. (2004, 2006) have measured masses of $^{56}$Ni a factor of 10 lower (than for SN1987A) in 1997D, 1999br, 2005cs. These SNe also show low luminosity plateau magnitudes, low ejecta velocities and hence low kinetic energies. The interpretation of Nomoto et al. (2006), Zampieri et al. (2003) and Pastorello et al. (2004) is that they are initially high mass stars which result in faint explosions (see Figure 11a).

However the initial masses are dependent on the lightcurve model and at least for some faint type II-P SNe there are direct progenitor mass estimates (Figure 11b). For these there is no evidence of a massive progenitor, which allows no confirmation of the massive progenitor and black-hole forming scenario. However there is still a possibility of there being two populations of faint SNe - one from massive progenitors as the lightcurve models and ejecta masses of Zampieri et al. (2003) and Nomoto et al. (2006) propose and one from the lower mass stars. This should be testable as time allows larger numbers of progenitors to be detected and the SN energetics quantified. In fact it should be relatively easy to detect the high mass progenitors. If they are around $20-30 M_\odot$ then they should have $-8 < M_{bol} < -9$, which are easily detectable in the images of the quality discussed in Sections 2.3 & 4. In Figure 11 the lack of a high luminosity branch in the nearby SNe with progenitor information is probably a selection effect as these SNe are intrinsically rare and we have not had the opportunity to search for progenitors of their nearby analogues.
As it stands, the masses from direct detections and limits for progenitors suggests there is an order of magnitude scatter in the mass of $^{56}\text{Ni}$ created in the explosions of stars of seemingly similar masses. This is not well understood within the current paradigms of stellar evolution or explosion physics. Weak explosions from electron capture SNe have been proposed (Kitaura, Janka, and Hillebrandt 2006) but these occur after 2nd dredge up when the progenitors would be S-AGB stars and hence rather luminous, $\log L/L_\odot \simeq 10^5$ (Eldridge and Tout 2004, Poelarends et al. 2008). Eldridge, Mattila, and Smartt (2007) show that SN2005cs for example was unlikely to have been a S-AGB star. The diversity in explosion properties of stars with apparently similar progenitor masses could reflect dependence on the exact density profile above the core, the rotation rate, chemical composition, or stellar magnetic field. As discussed by many modellers (e.g. Woosley and Weaver 1986, Nomoto 1987, Woosley, Heger, and Weaver 2002, Eldridge and Tout 2004) the computation of evolution, and subsequent explosion, of 8-11$M_\odot$ stars is complex due to electron degeneracy phases, thermal pulses and dredge-up.

An example of further diversity in the explosions of stars of probably similar mass is shown in Figure 10. In this case the bolometric lightcurves of the well studied SN1999em, SN2004et and SN2005cs and SN2003gd are compared. The distance to each galaxy is relatively well known and the monitored flux covers from the UV to the NIR in each case. The progenitors have masses between 8-15$M_\odot$ and are likely red supergiants. There appears to be little correlation of kinetic energy, $^{56}\text{Ni}$ mass or plateau luminosity with progenitor mass. The progenitors of SNe 2005cs and 2003gd appear very similar but their $^{56}\text{Ni}$ mass and kinetic energies differ by a factor of around 5. SN2003gd has a similar kinetic
energy to SN1999em but their tail phase luminosity are significantly different with the inferred $^{56}\text{Ni}$ mass a factor of 3 lower in the case of SN2003gd. This large diversity of explosion parameters from apparently quite similar progenitors is puzzling. It will be of great interest to see how the energy and luminosity of SN2008bk compares as it was another explosion of a fairly low mass red supergiant (Section 4.1.3).

The differences between the observed characteristics of II-P SNe in particular has previously been attributed to large differences in the progenitor mass and radii (Hamuy 2003, Nadyozhin 2003, Utrobin and Chugai 2008). However the ejecta masses have not given good agreement with the direct masses of progenitor stars. Future work to reconcile the hydrodynamic ejecta masses and stellar evolutionary masses, which will help quantify the explosion energies better is highly desirable.
7.2 NS and magnetar progenitors: turn-off masses

Figer et al. (2005) suggest that the soft gamma repeater SGR 1806-20 lies within a stellar cluster with an age of $\sim 3 - 4.5$ Myr. Assuming that the progenitor was coeval with the star formation episode that created the cluster this would imply a mass of greater than $\sim 50M_\odot$. SGRs are thought to be magnetars, which are slowly rotating ($P \sim 1$-10 sec) highly magnetized ($B \sim 10^{14}$ G) neutron stars. Vrba et al. (2000) suggest that SGR1900+14 was born within a dense stellar cluster. An age estimate of the stellar population has been prohibitively difficult due to difficulties in identifying a main-sequence turn-off. However the two M5 supergiants have bolometric luminosities which might suggest masses of between $8-12M_\odot$ assuming the largest distance of 15 kpc (based on the RSG parameters of Levesque et al. 2005).

Muno et al. (2006) have discovered an x-ray pulsar only 1.7 arcmin from the core of the massive, young cluster Westerlund 1. The age from the most massive stars in the cluster is $4 \pm 1$ Myrs suggesting a progenitor mass for the X-ray pulsar of $> 40M_\odot$, if it is associated and coeval. The x-ray luminosity and slow rotation period are more consistent with it being a magnetar.

Messineo et al. (2008) further suggest that the $\gamma$-ray source HESS J1813-178 may be part of a coeval association which includes two SN remnants and a cluster of massive stars with ages of 6-8 Myrs. This would imply a minimum mass of 20-30$M_\odot$ for the progenitor. The likelihood of association between the $\gamma$-ray source and the stellar population is the weakest of these three and the nature of the high energy emission is not yet established.

These four coincidences provide some evidence for very high mass progenitors of magnetars (40-50$M_\odot$), but this requires further investigation as at least one
example suggests a lower stellar population mass and the association of HESS J1813-178 with a nearby stellar association is not yet convincing. How neutron stars form from very massive progenitors is puzzling and further work in this area is imperative.
8 An overview and comparison with massive stellar populations

8.1 The lower mass limit for core-collapse

The lower mass limit to produce a SN through core-collapse has theoretically been suggested to lie between 7-11M⊙. The mass estimates and limits from Section 4 (see Figure 4) for the II-P SNe provide a minimum mass estimate of $m_{\text{min}} = 8.5^{+1.1}_{-1.0}$M⊙ and this can be taken as an observational estimate for the minimum mass that can produce a core-collapse. The maximum stellar mass that produces white dwarfs in young stellar clusters has been estimated to be no less than $6.3 - 7.1$M⊙ at 95% confidence by Williams et al. (2009), Rubin et al. (2008). It is not known if the most massive white dwarfs (1-1.2M⊙) have CO or ONe cores. Combining this with the fact that three RSG progenitors of II-P SNe have been unambiguously detected with very similar estimated masses (7-9M⊙; Figures 10 and 4) would suggest a convergence toward $8 \pm 1$M⊙ for the lower limit to produce a SN. It should be noted that the WD masses and the RSG progenitor masses both depend on stellar evolutionary models and also WD cooling tracks and the bolometric luminosity model for RSGs.

The models of Poelarends et al. (2008) and others (see references therein) suggest that in the range 7.5-9.25M⊙ they become Super-AGB stars (S-AGB) and form an oxygen-neon core (Nomoto 1984). The most massive (9 - 9.25M⊙) can reach the Chandrasekhar limit and explode as ECSNe (see Section 7.1) while above 9.25M⊙ normal Fe core collapse occurs. The stellar models predict high luminosities for the S-AGB progenitors of log $L/L_\odot \sim 5.0$ dex, significantly higher than any of the progenitors observed and above most of the upper limits. Poelarends et al. (2008) suggest that only a few (~3%) of SNe are likely to be ECSNe. We cer-
tarily do see weak explosions with low ejecta masses of $^{56}$Ni (e.g. see Figure 11) but in the cases of 2005cs and 2003gd the progenitor was not a luminous S-AGB star (Eldridge, Mattila, and Smartt 2007). It maybe that these were weak EC-SNe as the $^{56}$Ni and explosion energies were similar to those of the explosion models of Kitaura, Janka, and Hillebrandt (2006), but the stars did not undergo 2nd dredge-up to become luminous.

As discussed in Section 4.5 the possibility remains that the transients SN2008S, NGC300-OT2008 and M85-OT2006 could be examples of ECSNe. (Thompson et al. 2009) suggest that they might be relatively common explosions and have gone undetected until recently. They also point out that the rarity of the stellar analogues in nearby galaxies would suggest the dust enshrouded phase is short. It remains to be seen if the rate and explosion energies of these events are compatible with predicted SNe from SAGB star models.

### 8.2 Comparison with Local Group massive stellar populations

Within the Galaxy and the Local Group there is now a wealth of studies of evolved massive stars, both hot and cool (Massey 2003) and this population is a reasonable comparator sample to compare with the SN progenitors we have discussed.

The effective temperatures and bolometric luminosities of Galactic and Magellanic Cloud RSGs have been revised with new model atmospheres (Levesque et al. 2005, 2006). Their inferred luminosities have been substantially reduced so that they appear up to $\log L/L_\odot < 5.6$ which corresponds to an initial evolutionary mass of $30M_\odot$. It is likely that this is their final resting place before explosion as the minimum initial mass for a star into a H-deficient WR star is 25-30$M_\odot$. 


at around solar metallicity. Massey, DeGioia-Eastwood, and Waterhouse (2001) studied the WR population in twelve Galactic clusters and show that at solar metallicity the minimum initial mass to produce a WR through single star evolution is above 25$M_\odot$. This rises to above 30$M_\odot$ in the LMC. Crowther (2007) point out that there are few Milky Way clusters apart from Westerlund 1, that host both WRs and RSGs. This implies that they come from quite separate progenitor mass ranges. Thus Local Group studies seem to have established, with some measure of confidence, that RSGs evolve from single stars with masses up to around 25-30$M_\odot$. At solar metallicity it is likely that stars of 25$M_\odot$ and above can form WN stars (with more massive objects becoming WC stars). At LMC metallicity this initial mass for WR formation is 30$M_\odot$. Hence one would expect RSGs in the range 8 to 25-30$M_\odot$ to be viable progenitors for type II-P SNe. Evolutionary models can reproduce this separation between the RSGs and WR stars by including suitable mass-loss rates (see Figure 9 for example).

8.3 The red supergiant problem

After just the first few years of intensive systematic searching for progenitors the lack of easy detection of moderately massive and very massive stars became an interesting issue (Smartt et al. 2003). The compilation of progenitor masses produced by Li et al. (2007) showed an obvious trend and lack of high mass stars. The volume and time limited survey of Smartt et al. (2009) allows a statistical analysis of the mass ranges that produce type II SNe and type II-P in particular. As discussed in Section 4, the 20 II-P SN progenitors can be adequately fit with a Salpeter IMF, a minimum mass of $m_{min} = 8.5^{+1.1}_{-1.5} M_\odot$ and a maximum mass of $m_{max} = 16.5 \pm 1.5 M_\odot$. Comparing this to the Local Group massive stellar pop-
lations immediately raises the question of the lack of detected RSG progenitors with initial masses between 17-30M\textsubscript{☉}. Smartt \textit{et al.} (2009) term this the “red supergiant problem”. There are a number of possible explanations:

- The galaxy integrated IMF of massive stars could be significantly steeper than $\gamma = -2$. It would need to be at least $\gamma = -3$ to reduce the lack of massive RSGs to a statistically insignificant number. (Weidner and Kroupa 2006) argue that galaxy integrated IMFs could be steeper than Salpeter due to the maximum stellar mass being linked to its natal cluster mass.

- All massive stars above 17M\textsubscript{☉} could produce IL-L, IIn and Ibc SNe. The relative frequencies of the II-P SNe compared to all other core-collapse types match the stellar numbers from an IMF between 8.5-17M\textsubscript{☉}. For this to happen the II-L and IIn SNe must play an important role which would mean severe mass loss occurs during the last stages of evolution of all massive stars.

- Related to this, perhaps the metallicities of the progenitor stars have been underestimated. If mass-loss rates can be extrapolated to higher metallicities than solar (and there is no evidence at present that they can be) then perhaps WR stars can be produced from lower masses than currently estimated at solar to LMC metallicity.

- Perhaps massive RSGs undergo severe mass-loss during the last 1-5% of their lifetimes and become obscured in a dusty envelope which is optically thick at visible and NIR wavelengths (dusty red supergiants are known in the LMC; van Loon \textit{et al.} 2005). Hence the detections and limits reviewed in Section4 could be biased against these stars, although the explosion would need to fully destroy the dust envelop as the SNe themselves do not
appear extincted.

- The massive RSGs that are visible in the Local Group between \( \log L/L_\odot = 4.0 - 5.5 \) dex and \( M_{\text{initial}} \sim 17 - 30M_\odot \) do end their lives in this evolutionary phase. But they produce SNe so faint that they have not been detected yet. An explanation for this is that their cores form black-holes with no, or extremely weak, explosions (Fryer 1999, Heger et al. 2003).

If any one of these five explanations is the main reason then it has important implications for both SN studies and massive stellar evolution. If a steep, galaxy integrated IMF is the cause it would have far reaching implications (Weidner and Kroupa 2006). One could imagine that it is a combination of the first four and that we could stretch each of the current best estimates of the IMF, initial mass for WR formation, metallicity and metallicity dependent mass-loss and RSG extinctions by a reasonable amount so that the cumulative effect could account for the observations. All the effects would need to conspire to work in unison however.

8.4 Mass ranges for progenitors

The most intriguing possibility is that we are seeing the first observational signals for the stellar mass range that form black-holes in core collapse. This is perhaps the explanation that would cause least contradiction with known parameters of massive stellar populations. Models have predicted that between about \( Z_\odot \) and \( 0.5Z_\odot \), stars with initial masses above \( 25M_\odot \) may not be able to explode through the presumed core bounce and neutrino driven mechanism. This might suggest that red supergiants above \( 25M_\odot \) and massive WR stars from initial masses above \( 30M_\odot \) collapse quietly to form black holes and either very faint SNe or none at all (Fryer 1999, Heger et al. 2003). In Section 5 one could draw a conclusion
from the review of the limits on Ibc SNe and the measured ejecta masses that all Ibc SNe (which are not broad-lined or associated with GRBs) arise from interacting binaries from progenitors with initial masses 8-15\(M_\odot\). It could be that the more massive cores form black-holes and produce Ic SNe and GRBs through the collapsar mechanism. In this case the difference between quiescent collapse and a jet induced explosion would be angular momentum of the CO star. This would mean virtually all (probably 95%; see Podsiadlowski et al. 2004) local WR stars do not produce Ibc SNe. At first thought this is perhaps surprising and controversial but this is not in serious conflict with any of the restrictive observational studies of SNe progenitors reviewed here. The case of SN2008ax suggests that single WN stars (of initial mass around 25\(M_\odot\)) can produce bright IIb SNe so there may not be a sharp mass cut-off between the two types and it may be smeared due to other effects like metallicity, rotation and mass-loss.

An interesting area for future work would be a survey for quietly disappearing massive stars as suggested by Kochanek et al. (2008).

Attempts have been made in the past to extend the simple picture of the “Conti scenario” of massive stellar evolution in which mass-loss drives the schematic evolutionary phases of massive stars (Conti 1976). Variations on such extensions were discussed by Massey (2003), Crowther (2007) and Gal-Yam et al. (2007) for example. However these are overly simplified when one considers the added effects that metallicity, rotation and binarity can play. This is not a criticism of the schemes, merely a statement that a one dimensional evolutionary route which is based on observational evidence is probably not sufficient. Theoretical stellar population studies can quantify the different effects of binary fractions, rotational velocity distributions and metallicity with parameterized values giving
fractions of the SN types and tree diagrams (e.g. Podsiadlowski, Joss, and Hsu 1992). Hence an attempt is made in Figure 12 to show the paths to core-collapse that match what has been presented in this review. It is meant to illustrate the diversity and complexity of phenomena that are observed as well as giving a likely path. I should stress that this is not meant to be definitive and there will be inevitable adjustments to the diagram as time progresses (particularly with regard the new types of transients) but it summarizes the results reviewed here and the bulk of the local SN population. One problem with the figure is that it does not adequately deal with metallicity effects and as Modjaz et al. (2008) show, metallicity may play a critical role in defining the explosion mechanism and GRB production.

9 Summary points

1. The progenitors of II-P SNe have been confirmed as red supergiants, although there has been a surprising lack of high mass stars detected. The three best detections still await confirmation that the progenitor stars have indeed disappeared. The lack of high-mass progenitors has interesting implications for stellar evolution and explosion mechanisms. The minimum mass that produces SNe seems to be converging toward $8 \pm 1M_\odot$.

2. It is almost certain that interacting binaries play an important role in influencing the relative rates of types within SN populations. The progenitor system of the SN1993J (a IIb SN) is well characterised and it appears very likely that a significant fraction of Ibc SNe come from interacting binaries.

3. There is a plausible candidate for a WR progenitor (probably a WN star) of SN2008ax. This was a IIb hence indicating that different channels can
produce similar, but not identical SNe. So far there is no confirmation that massive WR stars produce the majority of Ibc SNe in the local Universe. There are arguments supporting them as progenitors of broad-lined, highly energetic Ic SNe which are related to GRBs.

4. Evidence now exists that LBVs or stars showing LBV like characteristics die in luminous explosions. The recent discoveries of the brightest hydrogen-rich SNe known also suggests high mass LBV type progenitors. The explosion mechanism which produces these is not easy to reconcile with an Fe-core collapse. New physical mechanisms are probably required.

5. Three low-luminosity transients have been discovered which may have dust embedded massive star progenitors. Their nature is currently uncertain but it is possible they are ECSNe in Super-AGB stars.

10 Future issues and prospects

• Apart from extraordinarily bright progenitors from rare SNe, it has been difficult to detect progenitors beyond about 10 Mpc. Hence the greatest potential for future discovery in this field will come from a concerted effort to gather deep, multi-wavelength (from the UV to mid-IR) wide-field imaging of nearby galaxies for future SN progenitor characterisation. This can be a combination of space and ground-based images. The SNe themselves require rapid and intense follow-up to characterise their explosions.

• The new transients discovered at the extrema of the SN spectrum (low and high luminosity) require further physical understanding. It may be that the canonical Fe-core collapse mechanism is unable to explain the full range of explosion parameters and alternative explosion physics is required. This is
an area ripe for intense theoretical and observational effort.

- The rare ultra-bright events, intrinsically faint explosions and SNe in low-luminosity metal poor hosts are likely to be discovered in much larger numbers with future deep, wide-field optical surveys such as Pan-STARRS, SkyMAPPER, Palomar Transient Factory and eventually LSST. Potentially new types of stellar explosion could be discovered by combining optical detections with LOFAR, Fermi, Advanced LIGO and neutrino experiments.

- Exactly which type of stars produce stellar mass black-holes is not yet understood and the lack of high mass progenitors may suggest there is a population of black-hole forming SNe which so far have eluded discovery. Searches for faint events, or perhaps no explosions at all are interesting areas for future effort.

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Key Terms and Acronyms

**Acronyms**

**CCSN** Core collapse supernova

**RSG** Red supergiant

**BSG** Blue supergiant

**IMF** Initial mass function

**Bolometric lightcurves:** Integrated flux from the UV to the infra-red usually 0.3-2.5 µm, as a function of time, to monitor the total radiated energy.

**Type II-P SNe:** SNe showing P-cygni H-lines and a long plateau in the lightcurve. Expanding photosphere phase powered by recombination of hydrogen.

**Type Ibc SNe:** Classification into Ib or Ic categories can be ambiguous, Ibc is often used as an umbrella term for both.

**Electron Capture core-collapse:** A stellar core of ONeMg reaches the Chandrasekhar limit. Electron capture by $^{24}$Mg and $^{20}$Ne triggers collapse before O and Ne are ignited.

**Luminous Blue Variables:** Massive luminous stars with H and He rich atmospheres and strong winds. Variable photospheric temperatures and can undergo luminous outbursts.

**SN impostors:** Some faint IIn SNe are actually giant eruptions of LBVs rather than core-collapse explosions - termed “SN impostors”

**Wolf Rayet stars:** Evolved massive stars that have lost their envelopes through
radiatively driven winds. They have high mass-loss rates, low He and H content and are likely of original mass more than $25-30M_\odot$

**WN** Nitrogen sequence Wolf-Rayet  
**WC** Carbon sequence Wolf-Rayet  
**WO** Oxygen sequence Wolf-Rayet  

**Gamma ray bursts:** Flashes of electromagnetic radiation with durations of order of seconds and photon energies $\sim 100$ keV. Isotropically distributed the vast majority are at cosmological distances.  

**Long duration GRBs:** GRBs are broadly categorized into long-soft bursts (LGRBS; typical duration $\sim 20s$) and short-hard bursts ($\sim 0.3s$). Total $\gamma$-rays energy in LGRBs is $\sim 10^{51}$ erg.  

**Type Ic-BL:** The nearest long duration bursts are coincident with highly energetic type Ic SNe - called "broad-lined" Ic or hypernovae.  

**Ultra-bright type II SNe:** A newly discovered group of SNe which have enormous luminosities, typically $10^{51}$ ergs integrated, $\sim 100$ times more than normal CCSNe.

**Reference Annotations**

**Crowther 2003:** Extensive review article on the physical parameters of massive WR stars.  

**Gal-Yam & Leonard 2009:** Discovery of a very luminous star, probably an LBV, as the progenitor of a IIIn SN and evidence that it has since disappeared.  

**Heger et al. 2003:** Theoretical models of stellar evolution are linked to the type of SN and remnants produced as a function of metallicity.  

**Massey 2003:** Review of the massive stellar populations in the Local Group.
Pastorello et al. 2007: First discovery of a luminous outburst before the collapse of a massive star and subsequent SN.

Smartt et al. 2009: Volume and time limited search for progenitors of II-P SNe, consistent analysis and statistical results for progenitor mass ranges.

Smith et al. 2007: First paper on the new class of ultra-bright type II SNe.

Woosley & Bloom 2006: Review of the supernova - gamma ray burst connection
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Table 1: The relative frequency of core-collapse supernova types reported in 4 different studies. SECM (Smartt et al. 2009), LWVetal07 (Li et al. 2007), VLF08 (van den Bergh, Li, and Filippenko 2005), PSB08 (Prieto, Stanek, and Beacom 2008), CET99 (Cappellaro, Evans, and Turatto 1999). The uncertainties are simple Poissonian errors and the total number of objects in each survey is listed in the Sample Size row. SECM08 and LWVetal07 are volume limited estimates with distance limits of 28 Mpc and 30 Mpc, covering different time periods. VLF05 is based on LOSS discoveries within about 140 Mpc. The PSB08 sample is between about 40–170 Mpc and CET99 combines various surveys mostly within 100 Mpc.

| Sample | Type | SECM08 | LWVetal07 | VLF05 | PSB08 | CET99 |
|--------|------|--------|-----------|-------|-------|-------|
|        | II-P | 58.7±8.0% | 67.6±10%  | 62.9±4.7% | 75.5±9.8% | 77.7±10.8% |
|        | II-L | 2.7±1.7%   |           |       |       |       |
|        | IIn  | 3.8±2.0%   | 4.4±2.5%  | 9.2±1.8% |       |       |
|        | IIb  | 5.4±2.7%   | 1.5±1.5%  | 3.2±1.0% |       |       |
|        | Ib   | 9.8±3.3%   |           |       |       |       |
|        | Ic   | 19.6±4.5%  | 26.5±6.2% | 24.7±3.0% | 24.6±5.6% | 22.3±5.8% |
|        | Sample size | 92 | 68 | 277 | 77 | 67 |
Figure 1: The colour combined HST ACS image of SN1993J at 10 yrs after explosion from Maund et al. (2004). The progenitor of SN1993J was a bright source in the $U$ and $B$ bands which could either have been due to a surrounding OB-association or binary companion in the lower resolution ground-based pre-explosion images of Aldering et al. (1994). The faint blue stars E, F and G did contribute to the $UB$-band excess in the pre-explosion images but they cannot account for all the progenitors flux. A spectrum of the SN1993J source shows $\text{H} \text{I}$ absorption lines due to a B-type supergiant star coincident with the SN1993J remnant and this is likely the companion to the K-type supergiant that exploded and the main source of $UB$-band flux in the pre-explosion images (Maund et al. 2004). The exposures were taken through two near-UV filters (250W, 2100 seconds and 330W, 1200 seconds) shown in purple and blue, a blue filter (435W, 1000 seconds) shown in green and a green filter (555W, 1120 seconds) shown in red (Image credit: European Space Agency and Justyn R. Maund)
Figure 2: HR diagram illustrating the evolution of the binary system that produced SN1993J. The blue lines show the evolution of the stars before mass transfer, the red lines during the mass transfer phase. The numbers give the stellar masses on the main-sequence and at the point of explosion of the K-type primary (Podsiadlowski, Joss, and Hsu 1992, Maund et al. 2004).
Figure 3: (a)+(b): Colour image of the progenitor of SN2008bk. The pre-explosion image (a) is a combination of VLT optical and NIR images and the progenitor is identified as a bright red point source. The Adaptive-Optics NACO $K_s$ image (near diffraction limited resolution of 0.1 arcsec) used for precise differential astrometry was taken roughly two months after explosion. Both images are from Mattila et al. (2008).

(c)+(d): Colour image of the progenitor of SN2005cs. The pre-explosion HST ACS-WFC image (c) shows the red supergiant progenitor found to be coincident with SN2005cs by Maund, Smartt, and Danziger (2005) and Li et al. (2006). The ACS-HRC image (d) shows SN2005cs as a bright blue source. These images of SN2005cs are archive data taken by Filippenko et al. (HST program GO10182; F330W images taken 46-50 days after explosion) and Li et al. (SNAP 10877; F555W and F814W taken at 530 days after explosion.

(e)+(f): Colour composite showing the progenitor of SN2003gd using the data presented in Smartt et al. (2004) and Van Dyk, Li, and Filippenko (2003a) and supplemented with a late-time F450W archive image from SNAP10877. As the SN is not detected in that image, it can be used to construct the pre-explosion colour composite. The image of SN2003gd shown in (f) was taken from Smartt et al. (2004), taken about 137 days after explosion. These examples show unambiguous RSG progenitors of three nearby type II-P SNe.

Image Credit: David R. Young and R. Mark Crockett.
Figure 4: (a) The progenitors of SN 2003gd (black error bar) and SN 2005cs (blue shaded region with the STARS evolutionary tracks at $Z = 0.02$ overplotted from masses $6-30M_\odot$). The 6 and $8M_\odot$ tracks have the 2nd-dredge up phase indicated with the extended dotted track. The red points are the Milky Way red supergiants from Levesque et al. (2005).

(b): The progenitor of SN 2008bk with the LMC RSGs of Levesque et al. (2006) and the STARS tracks at $Z = 0.008$. 
The progenitor of SN2004et was first proposed to be a high mass yellow supergiant (Li et al. 2005), identified by the cross-hairs in the CFHT pre-explosion $R$–band image. However the WHT image (b) in the centre panel 4 years after discovery shows the same source visible at the same $BVRI$ magnitudes. A near diffraction limited $K$–band image from Gemini North clearly reveals that the object identified as the progenitor of SN2004et was not a yellow supergiant but a cluster of massive stars. The progenitor originated within this small association and provides a farewell progenitor progenitor scenario.
Figure 6: (a): A cumulative frequency plot of the masses of II-P progenitors, taken from Smartt et al. (2009). The right-hand axis is a simple number count and the SNe are ordered in increasing mass or mass limit. The solid line is a Salpeter IMF ($\alpha = -2.35$) with a minimum mass of $8.5M_\odot$ and maximum mass of $16.5M_\odot$ which is the most likely fit to the data. The dotted line is a Salpeter IMF but with a maximum mass of $30M_\odot$. The SNe are grouped in metallicity bins $\log O/H + 12 = 8.3 - 8.4$ (yellow), $8.5 - 8.6$ (red), $8.7 - 8.9$ (purple). (b): The maximum likelihood analysis of the II-P progenitor sample gives the most likely value for initial and final mass and the likelihood contours (also from Smartt et al. 2009). The dashed lines are those calculated with detections only and the solid lines represent the contours calculated including the upper masses.
Figure 7: The $BVR$ magnitudes (blue, green, red symbols) of WR stars in the LMC (circled dots are likely binaries) from Massey (2002). The magnitude limits for all Ibc SNe as discussed in Section 5 are shown on the right. If these massive stars are the progenitors of local Ibc SNe then there is only a 10% chance we have not detected any by chance. The arrows are colour coded blue, green red to signify psuedo-$BVR$ limits respectively. Adapated from Crockett (2009).
Figure 8: The upper panels show the detection of the progenitor of SN2005gl in a 1997 pre-discovery HST F547M image (within the white circle). The SN is shown in the middle panel from 2005 and is coincident with the bright progenitor object from 1997. The repeat HST image taken in 2007 shows the progenitor star has disappeared (again, position denoted by the white circle). The lower panel shows the evolution of the Hα profile of SN2005gl, classified as a IIn. Early in the evolution, the profile is narrow suggesting excitation of a dense circumstellar medium and the broad eject become visible later. All material is from Gal-Yam and Leonard (2009).
Figure 9: The HRD of the STARS evolutionary tracks (Eldridge & Tout 2004). The location of the classical LBV region from Smith, Vink, and de Koter (2004) is illustrated. SN2005gl had a luminosity of at least $\log L/L_\odot \approx 10^6$, which puts it in the LBV region indicated, or at even higher luminosities if it was hotter and hence had a significant bolometric correction. The region where we should see WR progenitors is shown and the only progenitor detected close to this region is that of SN2008ax. The RSG region in which observed progenitors have been detected is shown again for reference.
Figure 10: Bolometric lightcurves of II-P SNe. These four are likely to have had similar progenitor stars and the progenitors of SN2003gd and SN2005cs appear to be identical. There is a large diversity in bolometric luminosity, kinetic energy and $^{56}$Ni mass from similar progenitors, hinting at intrinsic differences in the explosions. Data sources are SN1999em: Elmhamdi et al. (2003); SN2003gd: Hendry et al. (2005); SN2005cs: Pastorello et al. (2009); SN2004et: Misra et al. (2007).
Figure 11: $^{56}$Ni mass vs main-sequence initial mass with the upper panel taken from Nomoto et al. (2006) and the lower plot from Smartt et al. (2009). The initial masses in this plot are estimated from the ejecta masses derived from lightcurve modelling. The lower plot shows the $^{56}$Ni masses for nearby SNe for which there are reliable restrictions on the progenitor masses from direct constraints.
Figure 12: A summary diagram of the likely evolutionary scenarios and end states of massive stars, based on the observational evidence presented in this review. The acronyms are neutron star (NS), black hole (BH), pair instability supernova (PIS). The probable rare channels of evolution are shown in light brown. The faint SNe are proposed and have not yet been detected.