Progenitors of Core-Collapse Supernovae

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massive stars, stellar evolution, supernovae

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 (SN) has converged to $8 \pm 1\ M_{\odot}$ 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 SNe arise from moderate mass interacting binaries. The highly energetic, broad-lined Ic SNe are likely produced by massive, Wolf-Rayet progenitors. There is some evidence to suggest that the majority of massive stars above $\sim 20\ M_{\odot}$ may collapse quietly to black holes and that the explosions remain undetected. The recent discovery of a class of ultrabright type II SNe and the direct detection of some progenitor stars bearing luminous blue variable characteristics suggest some very massive stars do produce highly energetic explosions. The physical mechanism is under debate, and these SNe pose a challenge to stellar evolutionary theory.

1. INTRODUCTION

CCSN: Core-collapse supernova

Gamma-ray burst (GRB): A flash of electromagnetic radiation with a duration on the order of seconds and photon energies of ∼100 keV

Ultrabright type II SNe: A newly discovered group of SNe that have enormous luminosities, typically 10^{51} ergs integrated, ∼100 times more than normal CCSNe

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 O ejected by every 15–$M_{\odot}$ star (Thielemann, Nomoto & 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 Fe and further nuclear burning no longer provides thermal pressure to support the star. Given the astrophysical knowledge at the time, Baade & Zwicky (1934) made a great leap of faith when they predicted their newly named SNe in external galaxies were the deaths of massive stars that produced neutron stars (NSs) and high energy cosmic rays. This paradigm has stood for more than seventy years, and great efforts have been invested to understand SNe and their remnants. A major goal has been theoretically predicting what type of stars can produce Fe or O-Mg-Ne cores and collapse to give these explosions (see, for example, a nonexhaustive list of recent work generated by Woosley, Heger & Weaver 2002; Heger et al. 2003; Eldridge & Tout 2004; Hirschi, Meynet & 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 1.4–$M_{\odot}$ 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-NS does not inject enough energy to produce a shock with enough momentum to reach the surface (Woosley & Weaver 1986, Janka et al. 2007). At the extreme temperatures and densities in the collapsing core, neutrinos of all three flavors are created with a total luminosity of around 3×10^{53} ergs. Deposition of a small fraction of the 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-NS (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 these theories with, presumably, a strong neutrino and gravitational wave signal. The youngest SN remnant in the galaxy G1.9+0.3 is of order 150 years 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. SNe 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 & Niemeyer 2000). The energetically most extreme CCSNe are those associated with gamma-ray bursts (GRBs) with kinetic energies of $2\text{–}5 \times 10^{52}$ ergs (Woosley & Bloom 2006). A new class of ultrabright type II 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 $\sim 10\ M_{\odot}$ (Humphreys & 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 & Hsu 1992; Heger & Langer 2000; Eldridge & Tout 2004; Hirschi, Meynet & Maeder 2004; Yoon & Langer 2005).

The past decade has seen direct discoveries of many SN progenitors and an explosion in the numbers and diversity of SNe discovered. This review discusses the remarkable and rapid recent progress in identifying massive stars that have subsequently exploded. For every nearby CCSN that 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 being identified. Extraordinary theoretical progress has been made since Baade & Zwicky (1934) by comparing stellar evolution models to lightcurve models of SN observations. Multiwavelength 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.

Type Ic-BL: The nearest long-duration bursts are coincident with highly energetic type Ic SNe (also called broad-lined Ic or hypernovae)

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). His article points out that the approach 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 during the past 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 H features (either in emission or absorption). Type Ia SNe also show no He features but have a characteristic Si absorption feature. Type Ib SNe have unambiguous signatures of He and type Ic SNe show no H or He. 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 H lines, and a further subclassification 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 SNe, which exhibit a linear decay after peak brightness. The type IIn SNe show H emission lines, which usually have multiple components of velocity and always have a strong "narrow" profile. There are often variations on these major subcategories; for example, SN1987A is usually referred to as a plateau-type event but was clearly peculiar. The type Ic-BL SNe, which are associated with long gamma-ray bursts (Woosley & Bloom 2006), all show much broader lines than typical Ic SNe. They have been referred to as "hypernovae" or broad-lined Ic SNe, owing to their large inferred kinetic energies. It can often be hard to distinguish between the Ib and Ic SNe and it is often useful to term the group Ibc SNe; such terminology is used in this review (see also Filippenko 1997). Finally the IIb SNe are those that 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

IMF: Initial mass function

Type Ibc SNe: An umbrella term for classification into either Ib or Ic categories, as classification into one or the other can be ambiguous

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 cataloged 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 among the most prodigious SN hunters working outside professional astronomical institutions). How many nearby SNe are missed owing to dust extinction in their hosts, or intrinsically faint luminosities, or neglected faint host galaxies, is still an open question. In addition, 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 favors the formation of lower-mass stars is now well established as existing for massive stars in the local Universe (Massey 2003, Elmegreen 2009). 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 distinguishes the measurement of 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 1** lists the relative frequency of each subtype from five different studies.

The most reliable measurement of the local SN rate is still that of Cappellaro, Evans & 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 Li et al. (2007) and van den Bergh, Li & 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 Cappellaro, Evans & Turatto (1999) in separating the IIn and IIb SNe from the overall type II

Table 1 The relative frequency of core-collapse supernova types reported in five different studies: SECM (Smartt et al. 2009), LWVetal07 (Li et al. 2007), VLF08 (van den Bergh, Li & Filippenko 2005), PSB08 (Prieto, Stanek & Beacom 2008), and CET99 (Cappellaro, Evans & 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, respectively, covering different time periods. VLF05 is based on LOSS discoveries within about 140 Mpc. The PSB08 sample is between about 10–170 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%	26.5 ± 6.2%	24.7 ± 3.0%	24.6 ± 5.6%	22.3 ± 5.8%
Ic	19.6 ± 4.5%				
Sample size	92	68	277	77	67

class. Smartt et al. (2009) have compiled all SN discoveries in the literature in a fixed 10.5-year period within galaxies with recessional velocities $V_{\rm vir} < 2000$ km s^{-1} (corrected for Virgo infall, this implies a distance of 28 Mpc, assuming $H_0 = 72$ km s^{-1} Mpc $^{-1}$) and reassessed all available data on the 92 CCSNe 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. Within the Poisson statistical uncertainties there is no clear discrepancy between them. Prieto, Stanek & Beacom (2008) caution that their sample of SNe in SDSS star-forming galaxies suggests that the ratio of the frequency of Ibc to II ($N_{\rm Ibc}/N_{\rm II}$) goes down from 0.4 $\pm$ 0.1 at solar metallicity ($Z_\odot$) to 0.1 $\pm$ 0.1 at a metallicity of 0.3 $Z_\odot$. The results in **Table 1** effectively average over metallicities between about 0.3–2 $Z_\odot$ (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 subtype resolution, more statistics, and more accurate nebular O abundances of the SN environments.

An important point to keep in mind is that we do not know how complete the local samples of SNe are. At the distance limits of 28–30 Mpc (distance modulus : $\mu \simeq 32.3$), 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 $m_{\rm CCD} \sim 19$. However this is far from clear, and there are arguments put forward recently that we may even be missing events within 10 Mpc (Smartt et al. 2009, Thompson et al. 2009). The physical interpretation of the relative frequencies and the possibility of missing events are 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 ∼20 Mpc has become fairly routine with 15 years of postrefurbishment *Hubble Space Telescope* (HST) operations. The HST Key Project on the Extragalactic Distance Scale 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 ∼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 are 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 progenitor's 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 infrared. The distance limit within which massive stars have been quantitatively studied is reduced by a factor of approximately six compared to HST campaigns. The

Araucaria Project has studied Cepheids and massive blue supergiants (BSGs) in spirals between 2–4.4 Mpc (Garcia-Varela et al. 2008, Kudritzki 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). Although 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 millions of years is probably common place in star-forming galaxies. (Chandar, Fall & 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 (RSG) population of M81 in the near-infrared (NIR), showing that the most massive 10–20-$M_{\odot}$ stars peak at magnitudes $M_K = -11.5$. Using accurate stellar photometry from a 4-m 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.

BSG: Blue supergiant

RSG: Red supergiant

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

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 worldwide. 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 & Filippenko (1996), suggesting that there was no obvious trend for Ibc SNe to be more closely associated with giant HII 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. 1999a). By the late 1990s, the HST archive, along with the highest resolution ground-based image archives, was 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 & Filippenko 2003b). Extensive searches of the HST archive were carried out by both groups (Van Dyk, Li & Filippenko 2003a; Maund & 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 (see Sections 4 and 5). The first unambiguous discovery of a stellar progenitor in these painstaking searches of the HST archive that allowed the stellar progenitor to be quantified was for SN2003gd (Van Dyk, Li & Filippenko 2003c; Smartt et al. 2004), showing the expected RSG 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 milliarcsec; 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 that 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 Sections 3, 4, and 5. Smartt et al. (2009) reviewed all SNe discovered within 28 Mpc in a 10.5-year 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 has been extending this search for the precursor objects and systems to both the *Spitzer* and *Chandra* archives (see Section 4.5; Nelemans et al. 2008, Prieto et al. 2008).

Luminous blue variable (LBV): A massive luminous star having a H- and He-rich atmosphere with strong winds and variable photospheric temperatures, and can undergo luminous outbursts

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 25–30 $M_{\odot}$

Supernova impostors: Some faint IIn SNe that are actually giant eruptions of LBVs rather than core-collapse explosions

2.5. Supernova Impostors and Their Progenitors

The most massive stars very likely pass through a luminous blue variable (LBV) phase during their lifetime and 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 on the way to becoming Wolf-Rayet (WR) stars (see Section 6; see 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 characterization of these precursor stars are not discussed in detail here, although we discuss the possibility that LBVs die in a complete destructive explosion in Section 6. The likely LBV giant eruptions that were originally given SN designations and have progenitors identified are SN 1961V (Goodrich et al. 1989; Van Dyk, Filippenko & Li 2002), SN 1954J (Van Dyk et al. 2005; Smith, Humphreys & Gehrz 2001), SN1978K (Ryder et al. 1993), SN1997bs (Van Dyk et al. 2000), and SN2002 kg and SN2003 gm (Maund et al. 2006). A complete list of nearby events is given by Smartt et al. (2009), who suggest 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 they surprised the SN and massive star communities by not matching the canonical precollapse 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 ($d = 3.6$ Mpc, Freedman et al. 2001) 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. Its photometric and spectroscopic evolution were both peculiar, although it matched SN1987K and many similar examples have been found since 1993 (Matheson et al. 2000). 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 (Matheson et al. 2000). The lightcurve was well matched with models of an explosion of a He core of mass 4–5 $M_{\odot}$ that had a residual low mass H-envelope (of around 0.2 $M_{\odot}$). 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 ($\sim 500 R_{\odot}$) 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 4–5 $M_{\odot}$ He core; a primary star of initial mass around 15 $M_{\odot}$ becomes a He-core–burning RSG that fills its Roche lobe and loses around 10 $M_{\odot}$ during mass transfer.

A progenitor object coincident with the position of SN1993J was rapidly identified and a detailed study of its $UBVR_CI_C$ spectral energy distribution from a homogeneous set of deep images emerged. Aldering, Humphreys & Richmond (1994) found that the SED could only be fit with two components. A RSG of spectral type G8-K5I matched the VR_CI_C colors 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 colors 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_C) 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 owing to strong nebular lines produced by interaction of the ejecta with circumstellar material (CSM) (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. (2002) analyzed 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. (2002) presented a sum of the fluxes of the neighboring bright stars (stars A, B, C, and D in **Figure 1**), employing both a simple sum and Gaussian-weighted estimate. As Aldering, Humphreys & Richmond (1994) used a careful point spread function (PSF) fitting method, the latter is probably most accurate. They found that the combined fluxes of the neighboring 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. (2002) 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 KeckI telescope. The ACS image is shown in **Figure 1** with SN1993J still quite bright at this epoch ($M_B \simeq -8$). They estimated the total flux contributions of the neighboring sources (stars A-G in **Figure 1**) and found results similar to Van Dyk et al. (2002). 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. (2002) 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

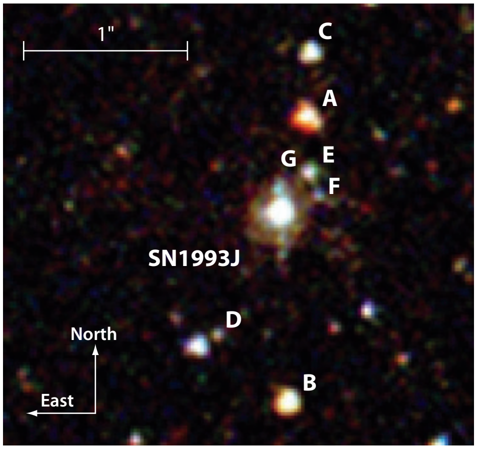


Figure 1

The color-combined *Hubble Space Telescope* ACS image of SN1993J at 10 years after explosion from Maund et al. (2004). The progenitor of SN1993J was a bright source in the *U* and *B* bands that 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 of the progenitor's flux. A spectrum of the SN1993J source shows HI 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 (250 W, 2100 s and 330 W, 1200 s) shown in purple and blue, a blue filter (435 W, 1000 s) shown in green, and a green filter (555 W, 1120 s) shown in red [Image credit: European Space Agency. Adapted and reprinted by permission from Macmillan Publishers Ltd: Nature (Maund et al. 2004), copyright 2004.]

& Richmond (1994) note that their PSF fit to the *B*-band leaves residuals to the north and south and, comparing their figure 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 HI 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 **Figure 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 & 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 years. The mass-transfer rate is initially high (reaching a peak of $4 \times 10^{-2}\ M_{\odot}$ 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 years to go before collapse. The extensive radio monitoring campaign of Weiler et al. (2007) suggests a sudden increase in the progenitor's mass-loss rate ~8000 years 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.

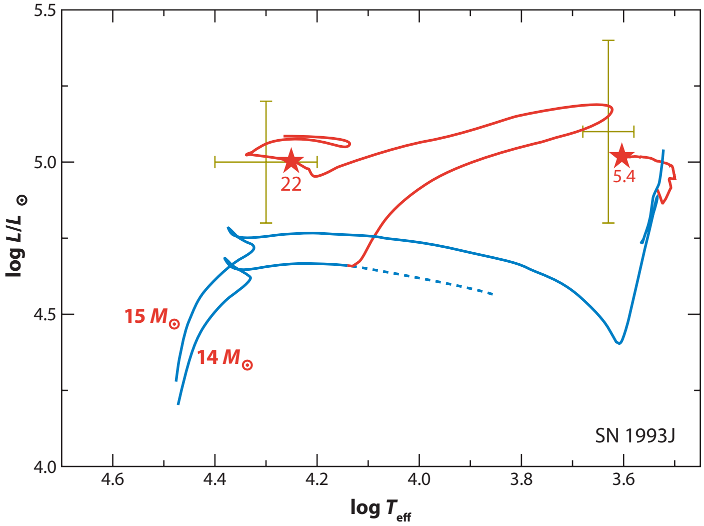


Figure 2

A Hertzsprung-Russell diagram illustrating the evolution of the binary system that produced SN1993J. The blue lines show the evolution of the stars before mass transfer, whereas the red lines are representative of the time 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. [Reprinted by permission from Macmillan Publishers Ltd: *Nature* (Maund et al. 2004), copyright 2004. The model comes originally from Podsiadlowski, Joss & Hsu 1992.]

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 & 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 a BSG (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 (see also Nomoto, Iwamoto & Suzuki 1995). However, as will be discussed in Section 5.2, it is possible that some IIb SNe come from massive single WN-type stars.

3.2. The Nearest Progenitor: SN1987A

WN: Nitrogen-sequence Wolf-Rayet

The most famous stellar progenitor of a SN is Sk −69°202, which collapsed to give SN1987A in the Large Magellanic Cloud (LMC). White & Malin (1987) showed this star to be coincident with the SN very soon after discovery, and a trawl through the photographic plate material of 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 $T_{\rm eff} \simeq 15{,}750$ (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 expand (Graves et al. 2005, Kjær et al. 2007). Extensive analysis and discussion of the event already exist (e.g., Arnett 1987, Arnett et al. 1989), and this section focuses 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 BSG. 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 $-69°202$. This implies a He-core mass in the region of $5^{+2}_{-1}\,M_{\odot}$, which can be produced from a star of initial mass in the region of 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 BSGs 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 years before explosion and the chemical abundances in the ring, as well as 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 BSG, remarkably similar in its predicted parameters to Sk $-69°202$. A similar idea was proposed by de Loore & Vanbeveren (1992), and in this case there should be a double NS-NS system embedded in the remnant of SN1987A. This model, however, does not 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-years dynamical age of the rings. Morris & Podsiadlowski (2007) invoke a wide binary model of a 15–16-$M_{\odot}$ primary and a lower mass 3–6-$M_{\odot}$ star with an orbital period of more than 10 years. Unstable mass-transfer results in a common envelope phase and their three-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 axisymmetric shape of the surrounding nebular rings. Chita et al. (2008) employ hydrodynamic calculations of the stellar wind properties of a 12-$M_{\odot}$ star that had an initial rotational velocity of 300 km s^{-1}. However the model star ends its life as a RSG, which doesn't match Sk $-69°202$. The preSN rotating model of a 20-$M_{\odot}$ star derived by Hirschi, Meynet & Maeder (2004) can end its life in the blue, but the model star has a low H content and would probably result in a IIb or Ib SN rather than a type II. There are four Galactic BSGs with similar circumstellar nebulae to Sk $-69°202$ (Smith, Bally & 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 N to C and O ($N/C \simeq 5$ and $N/O \simeq 1$, 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 24 B-type supergiants in the LMC were recently presented by Hunter et al. (2008). The CNO ratios ranged from $0.2 \lesssim N/C \lesssim 8$ and $0.03 \lesssim N/O \lesssim 1$. 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 $\sim$300 km s^{-1}

or postRSG dredge-up. At least 25% of the highly processed LMC B-supergiants are binaries, although their orbital parameters remain undetermined. Although 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 studies 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$40 $R_{\odot}$, compared to typical RSG radii of 500–1000 $R_{\odot}$ resulted in the distinctive bolometric and visual lightcurve of SN1987A. At the time it was thought that, owing to it being relatively faint for a type II SN ($M_V \simeq -15.5$ 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 RSG 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 2004 am (M82; 3.3 Mpc), 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, 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 SN (Bauer et al. 2008). In addition, a number of faint, nearby transients have been discovered that 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

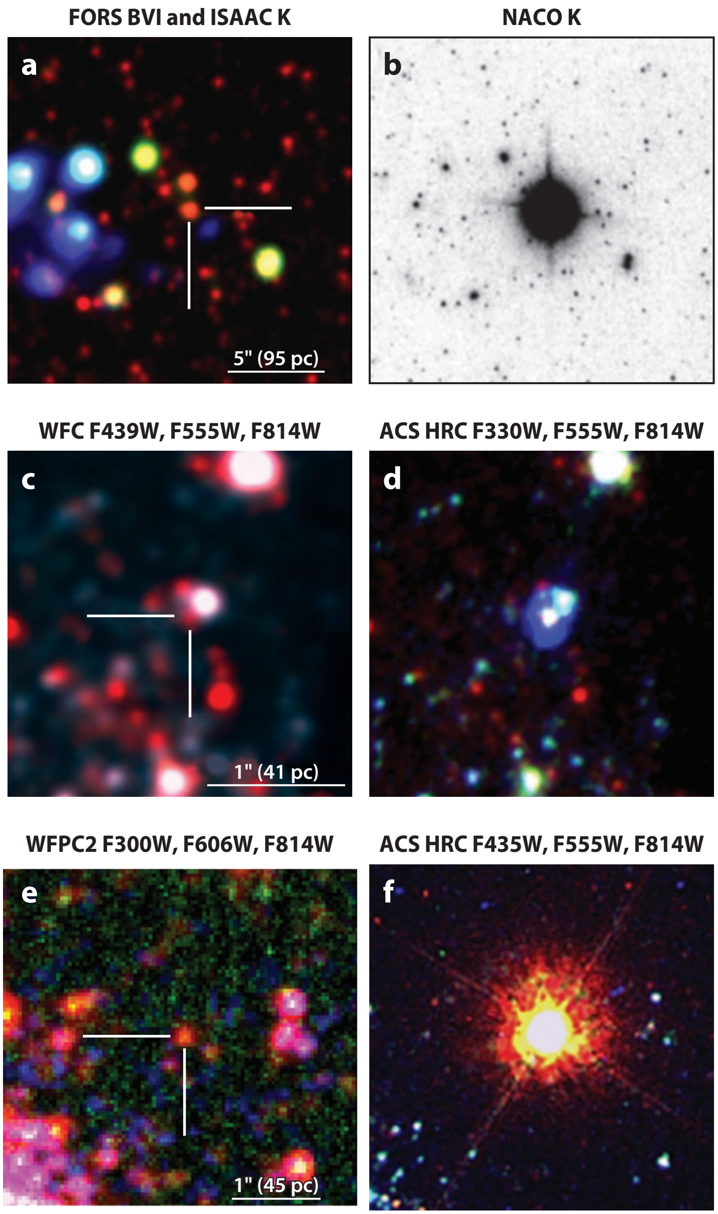
It has been suspected for many years that the type II-P SNe are the most common explosions, by volume, in the Universe. The rates compiled in Section 2.2 now quantifiably endorse this perception. Perhaps surprising is how rare the brighter type II-L SNe are. The lightcurves of II-P have generally been 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) all 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 Fe 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 8–30 $M_{\odot}$ should begin He-core burning when they have expanded and cooled to become RSGs and that further nuclear burning phases should occur while they are RSGs. 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 500–1500 $R_{\odot}$. Even the addition of rapid rotation ($V_{\rm rot} \sim 300$ km s^{-1}) in the stellar models still results in 8–20-$M_{\odot}$ stars becoming RSGs during core-He burning and beyond (Hirschi, Meynet & Maeder 2004), as long as they avoid chemically homogeneous evolution (Yoon & Langer 2005). The recently detected UV-flash from young II-P SNe has been interpreted as the shock breakout signature in a RSG progenitor (Gezari et al. 2008, Schawinski et al. 2008). This further strenghtens 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 SN 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 data set 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 characterization of the progenitor and the SN explosion. A "gold" event should have enough information to estimate a color 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 characterized. SN2003gd, SN2005cs, and SN2008bk all have unambiguous and reliable detections ($>10\sigma$) in one or more bands. All three are almost certainly RSGs. 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 that is around 3–5σ or have no detailed study of the SN evolution (SNe 1999ev and 2004A and 2004et). The "bronze" events 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 on 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 that 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 $\pm$ 0.1 $M_{\odot}$). M74 had been imaged by WFPC2 on HST (3100s in F606W) and GMOS on Gemini North (480–960s in $g'r'i'$) 6 to 9 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 researchers favored the brighter star (Van Dyk, Li & Filippenko 2003c). Images of the SN with HST showed that this single point source was coincident with the SN to within 13 $\pm$ 33 milliarcsec, which corresponds to 0.6 $\pm$ 1.5 pc at the distance of M74 (Smartt et al. 2004). The images are shown in **Figure 3**; the progenitor is identified at $V = 25.8 \pm 0.15$. It is almost certain the progenitor has been identified; if not, then the progenitor must have been fainter than $V \simeq 27.1$, which both Van Dyk, Li & Filippenko (2003c) and Smartt et al. (2004) note would put the progenitor mass uncomfortably below the core-collapse limit and probably around 5 $M_{\odot}$. The I-band magnitude of the progenitor has been estimated by both Smartt et al. (2004) and Van Dyk, Li & Filippenko (2003c). 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 RSG within the range K5-M3Ib and the position on an HR diagram is shown in **Figure 4**. The distance to this galaxy is still, perhaps surprisingly, not reliably determined, with estimates ranging from 7.5 to 10.2 Mpc (reviewed by Hendry et al. 2005). It would be desirable to establish the distance 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 of $8^{+4}_{-2}\,M_{\odot}$. The progenitor's estimated location on an HRD is similar to RSGs in Milky Way clusters, with the Galactic stars shown for comparison in **Figure 4**. 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 color mosaic image of the galaxy made from four filters (F435W, F555W, F658N, F814W). Rather fortuitously, SN 2005cs was discovered close to explosion on June 28, 2005. Additionally, the galaxy had also been imaged by HST's NICMOS instrument in five NIR 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 & Danziger 2005; Li et al. 2006). The two studies identified the same object in the ACS F814W images as the likely progenitor (see **Figure 3**) . Although only detected in one band, the limits from the other wavelengths constrain the progenitor to be a RSG, later than approximately K3-type. Similar to SN2003gd, the star was quite low in luminosity and low in mass, with the two *I*-band measurements of 23.3 $\pm$ 0.2 and 23.5 $\pm$ 0.2 in reasonable agreement. The likely position of the progenitor on an HRD is shown in **Figure 4**, suggesting a mass of approximately 8 $\pm$ 2 $M_\odot$ (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 SN (see Section 7.1).

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

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 & Smartt (2007) investigated the possibility that SN 2005cs was the explosion of a massive asymptotic giant branch star (or super-AGB star, SAGB) that underwent electron-capture core-collapse. They suggested this to be unlikely, from the restrictions on the photospheric temperature implied from the NIR colors.

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 milliarcsec of the SN position, corresponding to 0.8 pc (**Figure 4**). The progenitor source is a strong detection in the *IJHK*

Figure 3

(*a*,*b*) Images of the progenitor of SN2008bk, reproduced by permission of the AAS and color enhanced by D.R. Young and R.M. Crockett. (*a*) The pre-explosion image is a combination of VLT optical and near-infrared images, and the progenitor is identified as a bright red point source. (*b*) 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*) Color images of the progenitor of SN2005cs (constructed by D.R. Young and R.M. Crockett). (*c*) The pre-explosion HST ACS-WFC image shows the red supergiant progenitor that was found to be coincident with SN2005cs by Maund, Smartt & Danziger (2005) and Li et al. (2006). (*d*) The ACS-HRC image shows SN2005cs as a bright blue source. These images of SN2005cs are archive data (HST program GO10182; F330W images taken 46–50 days after explosion and SNAP 10877; F555W and F814W taken at 530 days after explosion). (*e*,*f*): Color composites showing the progenitor of SN2003gd using the data presented in Smartt et al. (2004) and Van Dyk, Li & Filippenko (2003c) and supplemented with a late-time F814W archive image from GO11229. As the supernova is not detected in that image, it can be used to construct the pre-explosion color composite. (*f*) The image of SN2003gd was taken approximately 137 days after explosion (from Smartt et al. 2004). These examples show unambiguous red supergiant progenitors of three nearby type II-P SNe. Both *e* and *f* are reprinted with permission from AAAS and color enhanced by D. R. Young and R. M. Crockett.

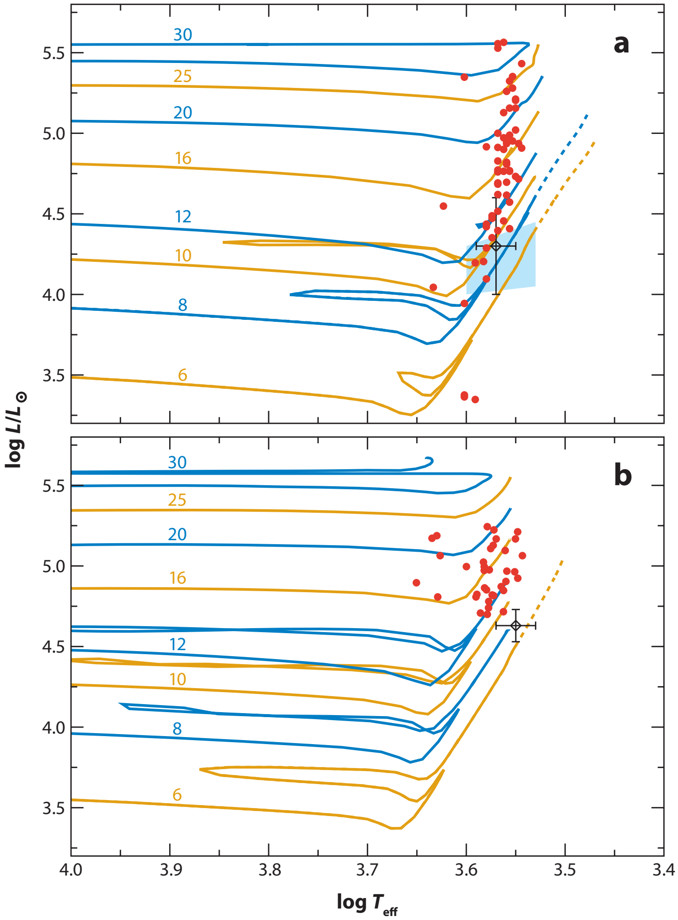


Figure 4

(*a*) The progenitors of SN 2003gd (*black error bar*) and SN 2005cs (*blue shaded region*) with the STARS evolutionary tracks (Eldridge & Tout 2004) at $Z = 0.02$ overplotted from masses 6–30 $M_\odot$. The 6- and 8-$M_\odot$ tracks have the second 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 SN2008bk with the Large Magellanic Cloud red supergiants of Levesque et al. (2006) and the STARS tracks at $Z = 0.008$.

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 RSG of initial mass 8.5 ± 1.0 $M_\odot$. 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 star-forming regions of their host galaxies but, perhaps somewhat surprisingly, are rarely coincident with bright star clusters (Van Dyk, Li & Filippenko 2003a; Maund & Smartt 2005). Quantitatively, it is probably 10% or less. Smartt et al. (2009) show that in their volume-limited sample of 20 II-P SNe, only 2 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 Myears and, hence, an initial mass for the progenitor of around 15 $M_{\odot}$. Using different photometry and population synthesis models, Wang et al. (2005) suggested an age of 20 Myears and a main-sequence mass of 12 $M_{\odot}$. A detailed multiwavelength 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 12–20 $M_{\odot}$.

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} Myears recently estimated by Lançon et al. (2008). In both these clusters there is a clear sign of a RSG population either from their *JHK* colors or the absorption lines in the 0.8–2.4-μm 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. In one case, the study of the SN itself is poor. The progenitor of SN1999ev is a 4.8-σ detection in a prediscovery HST image of NGC4274 (d = 15.1 ± 2.6 Mpc). It is detected at $m_{F555W} = 24.64 \pm 0.17$ or $M_V \simeq -6.5 \pm 0.3$ (Maund & 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 SN but it is not certain. If it was a RSG then Maund & Smartt (2005) suggest a likely progenitor mass of 15–18 $M_{\odot}$.

There is also a probable detection (4.7-σ 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 SN. The putative progenitor is detected in a single filter (F814W) in an HST pre-explosion image at $M_I \simeq -7.2$. The nondetection in a fairly deep F606W image suggests the progenitor was a red star, likely a supergiant later than mid-G-type, which led Hendry et al. (2006) to suggest a RSG progenitor of mass 9^{+3}_{-2} $M_{\odot}$.

Li et al. (2005) have claimed that the progenitor of the II-P SN2004et 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 color 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 $9^{+5}_{-1} M_{\odot}$.

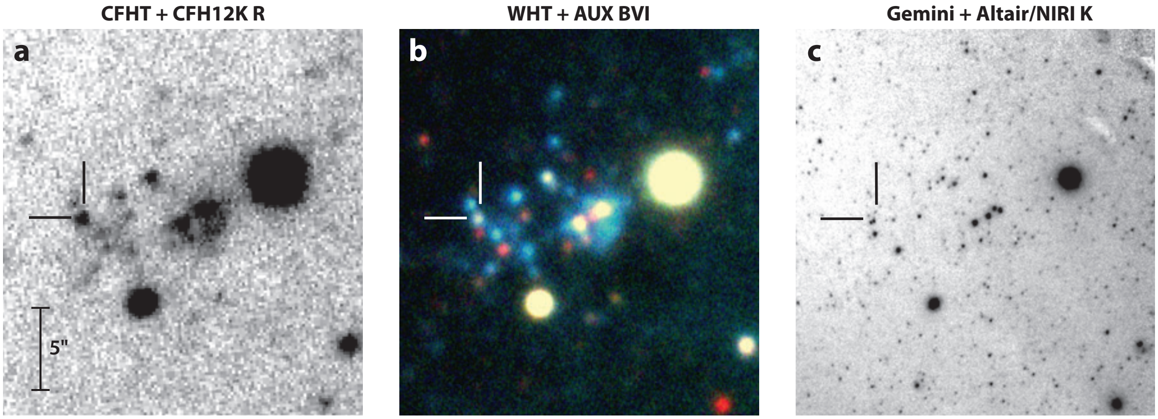


Figure 5

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 (*a*). However, the WHT image (*b*) four years after discovery shows the same source visible at the same *BVR* magnitudes. A near-diffraction-limited *K*-band image (*c*) from Gemini North clearly reveals that the object originally identified as the progenitor of SN2004et was not a yellow supergiant but a cluster of massive stars. The red supergiant progenitor originated within this small association and no evidence for yellow supergiant progenitors now exists. Images from Crockett (2009).

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 that 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 nondetections can be used to statistically constrain the parent population.

The detection of two progenitors in Virgo cluster galaxies was asserted by Li et al. (2007), in which they suggested the identification of a RSG 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, 8 are the gold and silver SNe discussed above and 12 have no progenitor detected. Of these 12, 2 are SN 2006my and SN 2006ov, which are 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 RSGs (which seems well justified by the gold detections and the theory of the recombination-powered plateau; see Section 4.1), 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 nondetections now appears to be significant.

Van Dyk, Li & Filippenko (2003a) 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 masses of II-P progenitors.

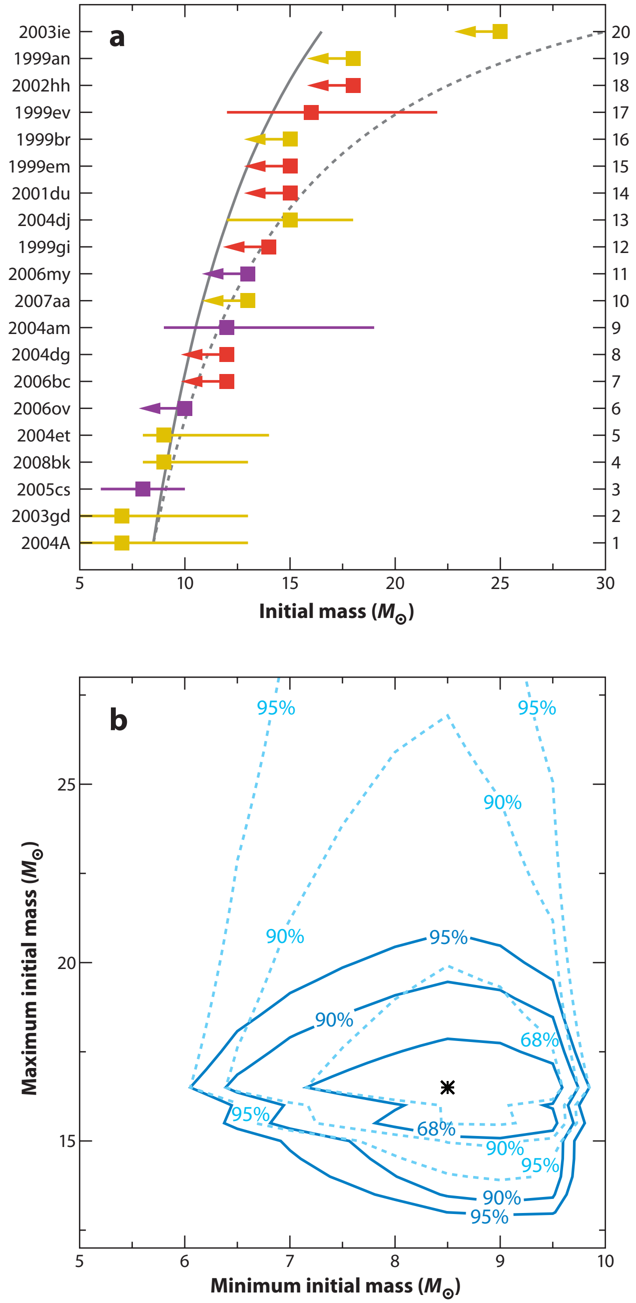
4.4. The Masses of the Progenitor Population and the Initial Mass Function

The 12 upper mass limits presented in Smartt et al. (2009) (see their table 2) together with the 8 estimates of progenitor masses are summarized in **Figure 6*a***. The mass distribution can be adequately fit with a Salpeter IMF of slope $\alpha = -2.35$, assuming a minimum mass of $8.5 \pm 1.0\ M_{\odot}$. But this fit requires a fixed maximum mass of 16–17 $M_{\odot}$. 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 minimum stellar mass for a type II-P SN to form is $m_{\rm min} = 8.5^{+1}_{-1.5}\ M_{\odot}$, and the maximum mass for II-P progenitors is $m_{\rm max} = 16.5 \pm 1.5\ M_{\odot}$ (**Figure 6*b***). 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 2009). The $m_{\rm min}$ 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 SN has interesting implications, which are 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 & 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 RSGs with luminosities very similar to the rotating models of Hirschi, Meynet & Maeder (2004) and Heger & 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 of 2) are used, this could indeed affect the masses. Mass-loss in the RSG stage is particularly uncertain. A major uncertainty in the stellar models is the treatment of convective core overshooting. Increasing the overshooting increases 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, color 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 SN designation owing to its uncertain nature. Bond et al. (2009) proposed it could be the outburst of a relatively massive OH/IR star rather than a true supernova explosion. Just three months earlier, a stellar eruption in NGC6946 showed similar photometric properties and narrow emission lines, and this time it was given a SN designation; it is known as SN 2008S. It has been given the label of a SN 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 3.5–8.0 μm), coincident with both the eruptions. Neither progenitor was visible in deep optical images, which led the researchers to suggest that these were the result of core collapse of massive stars that 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 $T_{\mathrm{dust}} \sim 440$–300 K, luminosities of between $\log L/L_{\odot} \sim 4.5 - 5.0$, and black-body radii of $R_{\mathrm{BB}} \sim 150$–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 8–15 $M_{\odot}$, or possibly lower mass stars (5–8 $M_{\odot}$) that have gone through second dredge-up (see **Figure 4** and Eldridge, Mattila & 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 multiwavelength images of the Local Group spiral M33 for possible counterparts and found this type of object extremely rare. It appears that fewer than ten similar objects exist in this galaxy and 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 & Hillebrandt 2006).

The progenitors would be SAGB stars, having undergone second 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 are forthcoming. Three ways to provide evidence for the ECSN 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 postexplosion MIR evolution may be comparable to SN2008S and NGC300-OT2008, suggesting a common origin. Whether or not all three transients are really of the same nature and whether or not they are ECSNe from dust obscured SAGB stars still

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 supernovae are ordered in increasing mass or mass limit. The solid line is a Salpeter IMF ($\alpha = -2.35$) with a minimum mass of 8.5 $M_{\odot}$ and maximum mass of 16.5 $M_{\odot}$, which is the most likely fit to the data. The dotted line is a Salpeter IMF but with a maximum mass of 30 $M_{\odot}$. The supernovae 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 (*star symbol*) 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.

remain 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. 2009) will guide future discussion.

WC: Carbon-sequence Wolf-Rayet

WO: Oxygen-sequence Wolf-Rayet

5. THE PROGENITORS OF Ibc SUPERNOVAE

The simple fact that Ibc SNe do not, on the whole, show evidence for H ejected at velocities similar to the intermediate-mass elements is convincing evidence that the exploding star did not have a H atmosphere. It is likely that some Ib SNe do show evidence of H absorption features in their early photospheric spectra (Branch et al. 2002), and there is almost certainly a continuum of H-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 WR stars (Gaskell et al. 1986), as these are massive evolved stars that have shed most, if not all, of their H envelope. An alternative scenario is that the Ibc SN progenitors are stars of much lower initial mass in close binaries that have had their envelopes stripped through interaction (Roche lobe overflow, or common envelope evolution; Podsiadlowski, Joss & Hsu 1992; Nomoto, Iwamoto & Suzuki 1995). This section reviews 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 H atmosphere.

5.1. Searches for Ibc Progenitors

There are 10 SNe classified as Ibc that have deep pre-explosion images available and none of them have a progenitor detected. Maund & Smartt (2005) and Maund, Smartt & 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 & Filippenko (2003a) 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 **Figure 7**, the magnitude limits cannot rule out a massive WR star progenitor. However, let us 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 assumes 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 is discussed below. The following two sections discuss interesting events in which a possible WN progenitor has

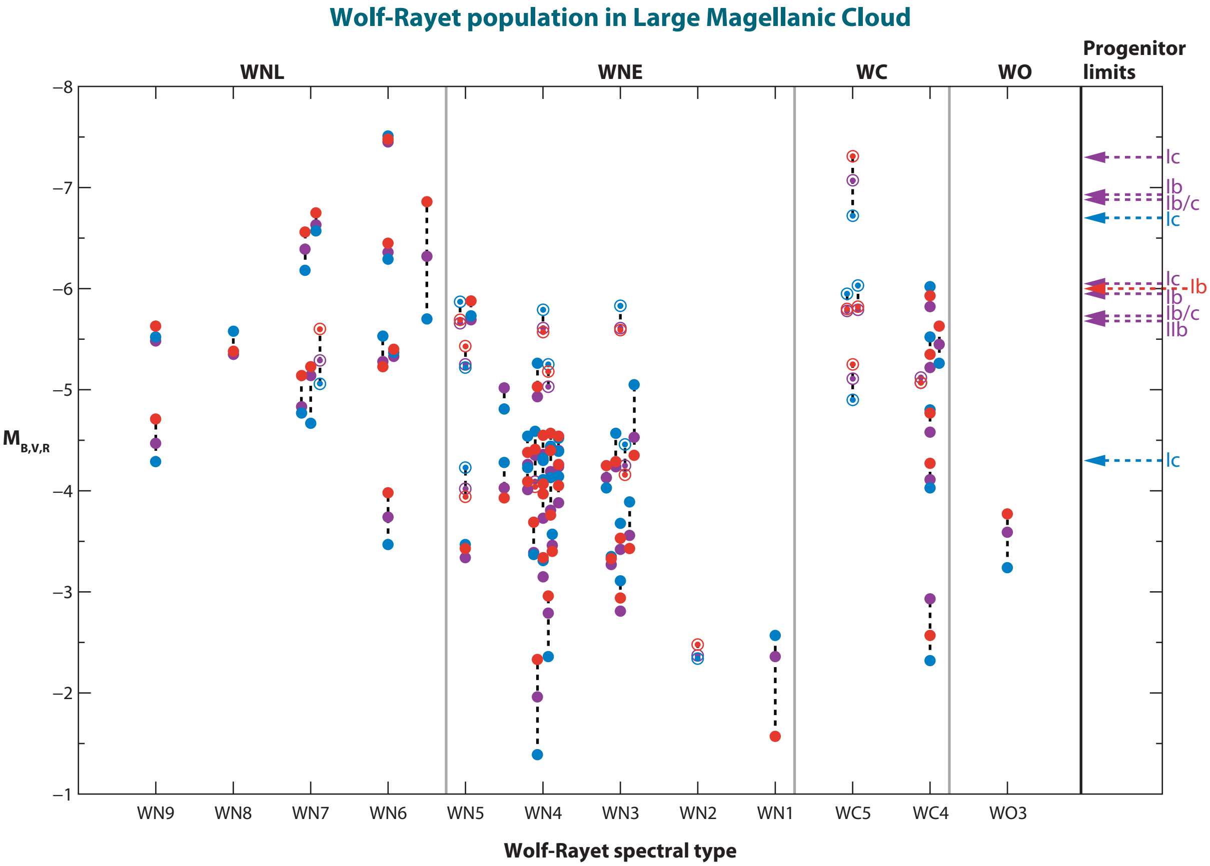


Figure 7

The *BVR* magnitudes (*blue*, *purple*, *red symbols*) of Wolf-Rayet stars in the Large Magellanic Cloud (*circled dots* are likely binaries) from Massey (2002). The magnitude limits for all Ibc supernovae, as discussed in Section 5, are shown on the right. If these massive stars are the progenitors of local Ibc supernovae, then there is only a 10% probability we have not detected any by chance. The arrows are color coded blue, purple, and red to signify psuedo-*BVR* limits, respectively. Adapted from Crockett (2009).

been detected and a possible host cluster has been identified. They represent two of the best opportunities for characterizing the local IIb-Ib-Ic populations.

5.2. SN2008ax: A Late Nitrogen-Sequence Wolf-Rayet 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 Hα absorption feature in the spectrum faded rapidly, and by 56 days nearly all traces of H had disappeared from the spectrum, which became He dominated. Crockett et al. (2008a) showed that the SN was coincident to within 22 milliarcsecs 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

Bolometric lightcurves: Integrated flux from the ultraviolet to the infrared usually 0.3–2.5 μm, as a function of time, to monitor the total radiated energy et al. (2008a) 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 colors and Crockett et al. (2008) show that it is difficult to come up with a binary system that has a combined color 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 neighboring stars. The object is consistent with a single PSF, but at a distance of nearly 10 Mpc, the PSF width corresponds to about 6 pc. Crockett et al. (2008a) 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 colors are quite consistent with it being such a stripped massive star and possibly of initial mass between 25–30 $M_{\odot}$. 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. (2008a) show reasonable agreement with the final position of the progenitor in color 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 SN, but a IIb SN in which clear evidence of H was seen, although the transformation to a Ib SN 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. (2008b) show that the Ic SN2007gr lies on the edge of a bright source, 6.9 pc from its nominal center 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. (2008b) suggest that this could distinguish between two likely turn-off ages of around 7 and 25 Myear. In principle, it may be possible to favor a massive single WR star (around 30 $M_{\odot}$) or an interacting, lower mass binary (around 10 $M_{\odot}$) from the cluster age.

5.4. The Rate of Ibc Supernovae 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 $N_{\mathrm{Ibc}}/N_{\mathrm{II}}$ ratio (discussed in Section 2.2) is 0.4 ± 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 16 $M_{\odot}$ and above. This is much too low to be consistent with initial masses for WR stars in the Local Group. In Galaxy and LMC clusters, the typical turn off mass to produce WN stars is at least 25 $M_{\odot}$ and probably closer to 35–40 $M_{\odot}$ to produce WC stars (Massey 2003, Crowther 2007). Also, the observed mass-loss rate of 16–20 $M_{\odot}$ stars would be somewhat too low to produce WR stars in evolutionary models that adopt these $\dot{M}$ values (see Heger et al. 2003; Eldridge & Tout 2004; Hirschi, Meynet & Maeder 2004; Crowther 2007).

The high rate of Ibc SNe was recognized as a problem in the 1990s, and interacting binaries were suggested as a common channel (Nomoto, Iwamoto & Suzuki 1995). Podsiadlowski, Joss & Hsu (1992) calculated that 15–30% of all massive stars (with initial masses above 8 $M_{\odot}$) could conceivably lose mass to an interacting companion and end up as a He star. They assumed a fraction of stars in binary systems that 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 & Fryer 2007). The lack of detection of any massive WR progenitors would point toward 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 be more massive than about 8–10 $M_{\odot}$, the companion must be of a few solar mass, and it must have an orbital period less than around 100 years. 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 $\sim 10^4$ years), and thus the phase lasts such a short time that they are rare objects. Alternatively, Nomoto, Iwamoto & Suzuki (1995) have 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, IIn, 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 that is massive enough to shed its envelope through radiatively driven winds ($\sim$30–60 $M_{\odot}$ with their adopted mass-loss recipe) ends up with a core mass that is too large to form a NS. 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 mass >25 $M_{\odot}$ produce the canonical core-collapse to a NS and successful neutrino driven shock. This is, of 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 holes with no visible explosion. Eldridge, Izzard & Tout (2008) illustrate that by mixing single stars and interacting binaries in massive stellar populations they can reproduce the lbc SNe ratio at solar metallicity and get a lower value of $N_{\mathrm{Ibc}}/N_{\mathrm{II}} \sim 0.1$ at 0.3 $Z_{\odot}$, as suggested in the surveys discussed in Section 2.2. This is further encouragement for the observers to improve the metallicity determinations of nearby SN environments.

5.5. The Environments of Type Ibc Supernovae

A strong argument that Ibc SNe actually do come from stars of higher masses than type II-P is their association with Hɪɪ 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 Hɪɪ regions suggested the degree of association was not markedly different (Van Dyk, Hamuy & Filippenko 1996). However, a factor of two increase in the available numbers of SNe suggests differences are now discernible.

Anderson & James (2008) show that the positions of SNe Ic in late-type galaxies tend to trace the Hα + [Nɪɪ] line emission. This contrasts markedly with the locality of SNe II, which are not, on the whole, associated with Hɪɪ regions. The SNe Ib also show a higher degree of association with the Hα +[Nɪɪ] emission than the SNe II, although somewhat less than for the Ic. As Hɪɪ 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 & 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), and 24 (Ic) from Kelly, Kirshner & Pahre (2008) and 100, 22, and 34 from Anderson & James (2008). The case for an increasing mass range for progenitors of SNe II-Ib-Ic is supported by both these studies. However as bright Hii emission and integrated continuum light are 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. Although 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.

Long-duration GRB: A long-soft gamma-ray burst (typical duration ∼20 s; as opposed to a short-hard gamma-ray bursts, ∼0.3 s). Total gamma-ray energy is typically $\sim 10^{51}$ erg

5.6. Ejecta Masses from Ibc Supernovae and Gamma-Ray-Burst–Related Supernovae

With the lack of detection of a progenitor of a Ibc event, the only other way to determine a stellar mass is from modeling of the lightcurve and spectral evolution. The type Ic SNe have been subject to intense scrutiny recently owing 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 1–2.5 $M_\odot$. 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 1.5 $M_\odot$ for a NS remnant, then the CO core masses of these objects would be 2.5–4 $M_\odot$. These are lower than typically found for the current masses of WC stars in the Galaxy and LMC (Crowther et al. 2002) of between 7–20 $M_\odot$. 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 3–5 $M_\odot$ corresponds to a primary of initial mass around 8–15 $M_\odot$. Although only a few of the nine have low masses, this is due to the high-energy events being preferentially selected for detailed modeling 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 8–13 $M_\odot$, whereas the energetic SN2004aw and SN2003jd (which lack detected LGRBs) were calculated at 3–5 $M_\odot$ (Mazzali et al. 2006b, Taubenberger et al. 2006, Valenti et al. 2008). Adding a minimum of 1.5–2.5 $M_\odot$ 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 modeling technique and they are not yet observationally confirmed with an independent method, it does appear that the relative differences in the shapes of SNe Ic lightcurves are due to an increasing ejecta mass and an increasing mass of the CO star that 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 (SN2002ap) would qualify as a broad-lined Ic. As Podsiadlowski et al. (2004) point out, the observed rate of production of WR stars in galaxies (from stars with initial masses of >40 $M_\odot$) far outweighs (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.

In summary, the observational evidence supports the idea that a significant fraction of Ibc SNe come 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. However, some objects with low ejecta masses clearly have high kinetic energies (SN2002ap, for example). 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}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 & Davidson 1994). The most extreme have evolutionary masses in the range of 80–120 $M_\odot$. Their position on the theoretical HRD and comparison with evolutionary tracks imply that they are either core H-burning or He-burning stars that have evolved from the main sequence (**Figure 8**). 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 & 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 & Owocki 2006). They can lose several solar masses of material in short and sporadic eruptions (Humphreys & Davidson 1994), and the physical cause is not well understood (Pauldrach & Puls 1990; Smith, Vink & 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 & 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; Woosley, Heger & Weaver 2002; Heger et al. 2003; Nomoto et al. 2006). Several unexpected and extraordinary discoveries in the past 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

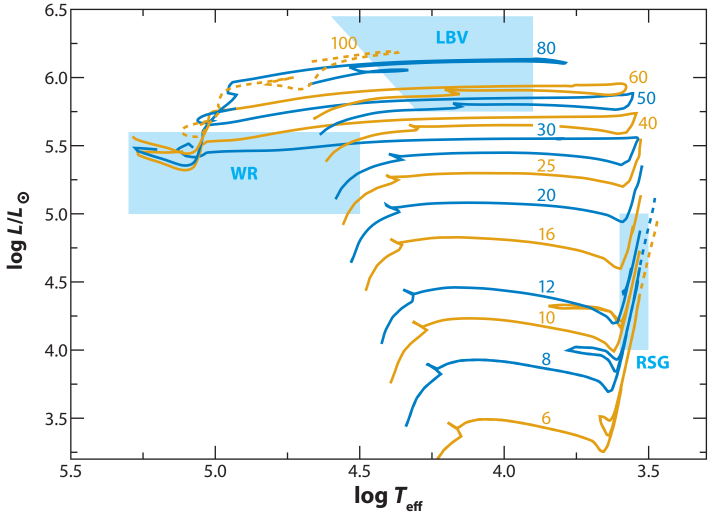


Figure 8

The Hertzsprung-Russell diagram of the STARS evolutionary tracks (Eldridge & Tout 2004). The location of the classical luminous blue variable (LBV) region from Smith, Vink & de Koter (2004) is illustrated. SN2005gl had a luminosity of at least log $L/L_{\odot} \simeq 6$, 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 Wolf-Rayet (WR) progenitors is shown, and the only progenitor detected close to this region is that of SN2008ax. The red supergiant (RSG) region in which observed progenitors have been detected is shown again for reference.

(40–100 Mpc) were being carried out (Van Dyk, Li & Filippenko 2003a). 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 & Leonard (2009) shows that a star—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 & Leonard (2009) then showed that the star has disappeared in subsequent HST images with the same filter (see **Figure 9**). 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 & de Koter 2004 for a summary of LBV luminosities, and **Figure 8**). SN2005gl was a relatively bright SN IIn that shows distinct evidence of the SN ejecta interacting with a circumstellar shell (**Figure 9**). 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 & Leonard (2009) estimate that the progenitor lost a modest amount of mass ($\sim$0.03 $M_{\odot}$) 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.

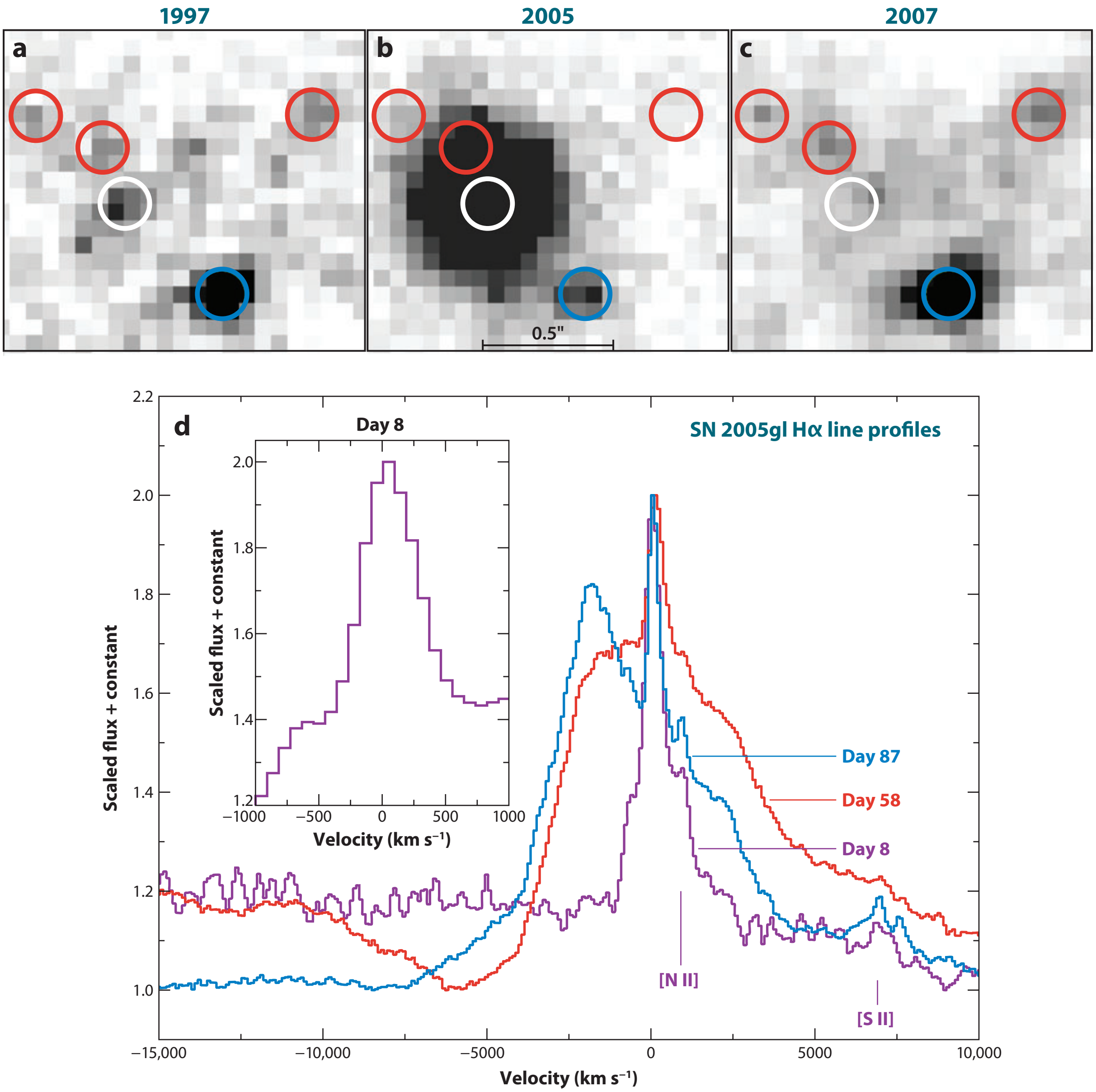


Figure 9

Upper panels *a–c* show the detection of the progenitor of SN2005gl. (*a*) Detection of the progenitor in a 1997 prediscovery HST F547M image (within the *white circle*; other objects used for alignment are circled in *red* and *blue*). (*b*) An image of the supernova taken in 2005 shows that it is coincident with the bright progenitor object from 1997. (*c*) 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 ejecta become visible later. Reprinted by permission from Macmillan Publishers Ltd: *Nature*, copyright 2009 (Gal-Yam & Leonard 2009).

6.2. SN2006jc: A Giant Outburst Followed by Core-Collapse

The first discovery of a bright optical transient spatially coincident with a subsequent luminous SN 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 are 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 behavior, still retain their H-envelopes, the material is normally H and He rich. Foley et al. (2007) and Pastorello et al. (2008) showed that the high-velocity ejecta spectrum of SN2006jc is more like a type Ic SN, with intermediate mass elements O, Mg, and 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 HeI 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 $\gtrsim 10^{47}$ ergs. This is similar to the known outbursts of high-luminosity LBVs (Humphreys, Davidson & Smith 1999), but all of these still retain significant H and He atmospheres. LBV stars are often He enriched but are not completely deficient in H. 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 be 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 (Foley et al. 2007; Pastorello et al. 2007, Tominaga et al. 2008).

6.3. Constraints on II-L Supernovae Progenitors

There are very few direct constraints on nearby II-L SNe. This subtype appears to be relatively infrequent (see **Table 1**), but they may be important in solving the problem of the lack of high mass RSGs detected as type II-P progenitors. As the II-L by definition have a very short, or nonexistent, plateau phase they probably have a low-mass H-envelope that 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 RSGs greater than about 20 $M_\odot$, but blue progenitors hotter than 10,000 K 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. 1999b). Montes et al. (2000) have estimated the mass-loss history from the SN and find an increased rate at 10,000–15,000 years 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 Luminous Blue Variables Direct Supernovae Progenitors?

The discovery of several remarkably bright, H-rich (hence, type II) SNe has reinvigorated the debate of the physical mechanisms that can produce explosions. The first of these ultrabright type II SNe recognized 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 thermalized 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 RSGs. 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 that 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 ultrabright type II SNe (more correctly classed II-L as they show no narrow absorption or emission components) SN2005ap and SN2008es 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 superwind with mass-loss rate $\dot{M} \sim 10^{-3}\ M_{\odot}\ \mathrm{year}^{-1}$. For SN2005ap, Quimby et al. (2007) suggest a 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$20 $M_{\odot}$). The sharp decline in the late-time lightcurves and lack of strong [Fe II] lines now suggest 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 $\gtrsim$ 40 $M_{\odot}$) induce electron-positron pair production. This absorbs thermal energy, and the core collapses further, which results in a further temperature rise and runaway thermonuclear burning in a massive core (Woosley & Weaver 1986; see also Woosley, Heger & Weaver 2002 for the details of the physics involved and review of the history of this idea). In theory, 10–20 $M_{\odot}$ of ^{56}Ni can be produced and ejected (Heger & Woosley 2002) in a pair-instability supernova or $\sim$5 $M_{\odot}$ in a core-collapse of a massive star (Umeda & 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 & Heger 2007). This leads to an explosion that 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 & Heger (2007) requires a large core mass from a star of initial mass 95–130 $M_{\odot}$. The collisions between the massive shells produce radiative energies in a similar manner to that dicsussed 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 & Vink 2006). This would point to stars that 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 ultrabright type IIn and II-L SNe is still controversial and unresolved. Viable explanations are the explosion of the most massive stars we know, though 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 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-NS 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 that can be studied after core-collapse is measuring the amount of radioactive ^{56}Ni that is synthesized. 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 & Niemeyer 2000; Mazzali et al. 2006a,b; Valenti et al. 2008). Models of the observed lightcurves and spectral evolution of Ic SNe have derived these properties (e.g., Mazzali et al. 2006; Nomoto et al. 2006, 2008).

The photospheric stage of II-P SNe is powered by the recombination of H as the photosphere cools but the nebular tail phase luminosity is determined by the $^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$ decay and its subsequent deposition of gamma-rays and positrons, which are thermalized. 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, and 2005cs. These SNe also show low luminosity plateau magnitudes, low ejecta velocities and, hence, low kinetic energies. The interpretations of Nomoto et al. (2006), Zampieri et al. (2003) and Pastorello et al. (2004) are that they are initially high mass stars that result in faint explosions (see **Figure 11*a***).

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 11*b***). For these there is no

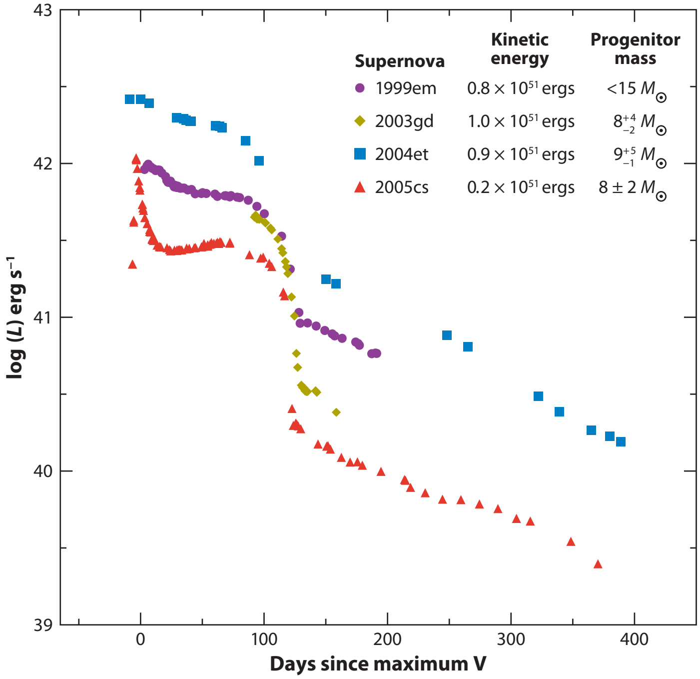


Figure 10

Bolometric lightcurves of II-P supernovae. 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); and SN2004et, Misra et al. (2007).

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 in the lightcurve models and ejecta masses proposed by Zampieri et al. (2003) and Nomoto et al. (2006), 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 to be 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 $-8 < M_{\rm bol} < -9$, which are easily detectable in the images of the quality discussed in Sections 2.3 and 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 analogs.

As it stands, the masses from direct detections and limits for progenitors suggest there is an order-of-magnitude scatter in the mass of ^{56}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 & Hillebrandt 2006), but these occur after second dredge-up when the progenitors would be SAGB stars and, hence, rather luminous, log $L/L_\odot \simeq 10^5$ (Eldridge & Tout 2004, Poelarends et al. 2008). Eldridge, Mattila & Smartt (2007) show that SN2005cs, for example, was unlikely to have been a SAGB star. The diversity in explosion properties of stars with apparently similar progenitor masses could reflect dependence on the density profile above the core, the rotation rate, chemical

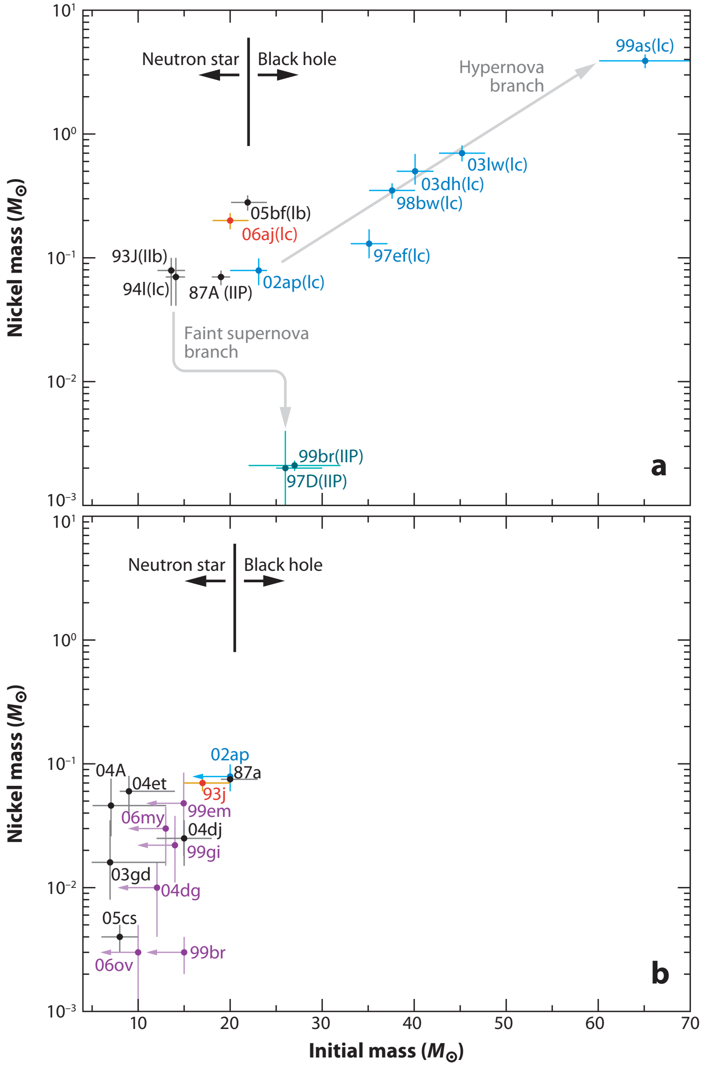


Figure 11

(*a*) ^{56}Ni mass versus main-sequence initial mass, reprinted from *Nuclear Physics A*, Copyright 2006 (Nomoto et al. 2006), with permission from Elsevier. The initial masses in this plot are estimated from the ejecta masses derived from lightcurve modeling. (*b*) The ^{56}Ni masses for nearby supernovae for which there are reliable restrictions on the progenitor masses from direct constraints (Smartt et al. 2009).

composition, or stellar magnetic field. As discussed by many modelers (e.g., Woosley & Weaver 1986; Nomoto 1987; Woosley, Heger & Weaver 2002; Eldridge & Tout 2004), the computation of evolution, and subsequent explosion, of 8–11 $M_\odot$ stars is complex owing 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, 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 RSGs. There appears to be little correlation of kinetic energy, ^{56}Ni mass, or plateau luminosity with progenitor mass. The progenitors of SNe 2005cs and 2003gd appear very similar but their ^{56}Ni mass and kinetic energies differ by a factor of around 5. SN2003gd has a similar kinetic energy to SN1999em but their tail phase luminosities are significantly different; the inferred ^{56}Ni mass is 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 compare as it was another explosion of a fairly low-mass RSG (Section 4.1.3).

The differences between the observed characteristics of II-P SNe in particular have previously been attributed to large differences in the progenitor mass and radii (Hamuy 2003, Nadyozhin 2003, Utrobin & 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. Neutron Star 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 ∼3–4.5 Myear. Assuming that the progenitor was coeval with the star-formation episode that created the cluster, this would imply a mass of greater than ∼50 $M_\odot$. SGRs are thought to be magnetars, which are slowly rotating ($P \sim 1$–10 s), highly magnetized ($B \sim 10^{14}$ G) NSs. 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 owing to difficulties in identifying a main-sequence turn-off. However, the two M5 supergiants have bolometric luminosities, which might suggest masses of between 8–12 $M_\odot$ 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 ± 1 Myears suggesting a progenitor mass for the X-ray pulsar of >40 $M_\odot$, 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 that includes two SN remnants and a cluster of massive stars with ages of 6–8 Myears. 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 imperitive.

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 7–11 $M_\odot$. The mass estimates and limits from Section 4 (see **Figure 6**) for the

II-P SNe provide a minimum mass estimate of $m_{\min} = 8.5^{+1}_{-1.5}\ M_\odot$, 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 $M_\odot$ at 95% confidence by Williams et al. (2009) and Rubin et al. (2008). It is not known if the most massive white dwarfs (1–1.2 $M_\odot$) 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 (7–9 $M_\odot$; **Figures 4** and **6**) would suggest a convergence toward 8 $\pm$ 1 $M_\odot$ 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 of 7.5–9.25 $M_\odot$ they become SAGB stars and form an O-Ne core (Nomoto 1984). The most massive (9–9.25 $M_\odot$) can reach the Chandrasekhar limit and explode as ECSNe (see Section 7.1) while above 9.25 $M_\odot$ normal Fe core collapse occurs. The stellar models predict high luminosities for the SAGB progenitors of log $L/L_\odot \sim 5.0$, 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 certainly 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 SAGB star (Eldridge, Mattila & Smartt 2007). It may be that these were weak ECSNe as the ^{56}Ni and explosion energies were similar to those of the explosion models of Kitaura, Janka & Hillebrandt (2006), but the stars did not undergo second 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 analogs 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 $L/L_\odot \lesssim 5.6$, which corresponds to an initial evolutionary mass of 30 $M_\odot$. It is likely that this is their final resting place before explosion as the minimum initial mass for a star to evolve into a H-deficient WR star is 25–30 $M_\odot$ at around solar metallicity. Massey, DeGioia-Eastwood & Waterhouse (2001) studied the WR population in 12 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) points 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 of 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 8**, 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 $m_{\rm min} = 8.5^{+1}_{-1.5}\ M_{\odot}$, and a maximum mass of $m_{\rm max} = 16.5 \pm 1.5\ M_{\odot}$. Comparing this to the Local Group massive stellar populations immediately raises the question of the lack of detected RSG progenitors with initial masses between 17–30 $M_{\odot}$. Smartt 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 $\alpha = -2$. It would need to be at least $\alpha = -3$ to reduce the lack of massive RSGs to a statistically insignificant number. Weidner & Kroupa (2006) argue that galaxy-integrated IMFs could be steeper than Salpeter owing to the maximum stellar mass being linked to its natal cluster mass.
- All massive stars above 17 $M_{\odot}$ 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 8.5–17 $M_{\odot}$. 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 that is optically thick at visible and NIR wavelengths (dusty RSGs are known in the LMC; van Loon et al. 2005). Hence, the detections and limits reviewed in Section 4 could be biased against these stars, although the explosion would need to fully destroy the dust envelope, 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 $M_{initial}$ ~17–30 $M_{\odot}$ 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 & 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.

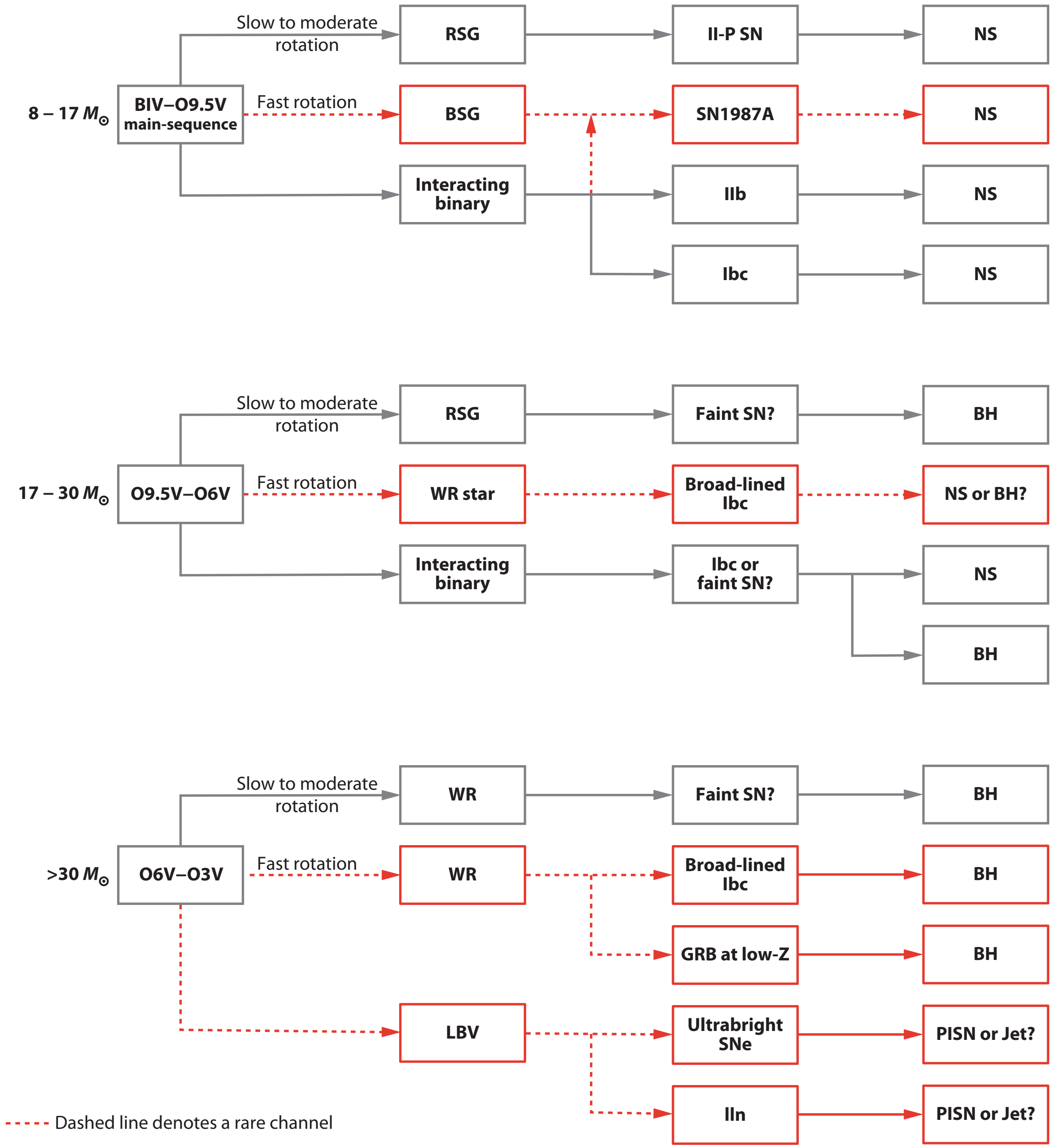


Figure 12

A summary diagram of possible evolutionary scenarios and end states of massive stars. These channels combine both the observational and theoretical work discussed in this review, and the diagram is meant to illustrate the probable diversity in evolution and explosion. It is likely that metallicity, binarity, and rotation play important roles in determining the end states. The acronyms are neutron star (NS), black hole (BH), and pair-instability supernova (PISN). The probable rare channels of evolution are shown in red. The faint supernovae are proposed and have not yet been detected.

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 0.5 $Z_\odot$, stars with initial masses above 25 $M_\odot$ may not be able to explode through the presumed core bounce and neutrino-driven mechanism. This might suggest that RSGs above 25 $M_\odot$ and massive WR stars from initial masses above 30 $M_\odot$ 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 of 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 SN 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 owing 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 that 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 & 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 give 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 to 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.

SUMMARY POINTS

1. The progenitors of II-P SNe have been confirmed as RSGs, 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 $\pm$ 1 $M_\odot$.

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 characterized, 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 SN, 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 that 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 H-rich SNe known also suggest high-mass LBV-type progenitors. The explosion mechanism that 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 that may have dust-embedded massive-star progenitors. Their nature is currently uncertain but it is possible they are ECSNe in S-AGB stars.

FUTURE ISSUES AND PROSPECTS

1. 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, multiwavelength (from the UV to mid-IR), wide-field imaging of nearby galaxies for future SN progenitor characterization. This can be a combination of space and ground-based images. The SNe themselves require rapid and intense follow-up to characterize their explosions.
2. 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.
3. The rare ultrabright 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.
4. 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 that 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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Volume and time-limited search for progenitors of II-P SNe, consistent analysis and statistical results for progenitor mass ranges.

First paper discussing the new class of ultrabright type II SNe.

Reviews the supernova–gamma-ray burst connection.

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