On the Progenitors of Core-Collapse Supernovae

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Abstract Theory holds that a star born with an initial mass between about 8 and 140 times the mass of the Sun will end its life through the catastrophic gravitational collapse of its iron core to a neutron star or black hole. This core collapse process is thought to usually be accompanied by the ejection of the star's envelope as a supernova. This established theory is now being tested observationally, with over three dozen core-collapse supernovae having had the properties of their progenitor stars directly measured through the examination of high-resolution images taken prior to the explosion. Here I review what has been learned from these studies and briefly examine the potential impact on stellar evolution theory, the existence of "failed supernovae", and our understanding of the core-collapse explosion mechanism.

Keywords stellar evolution, core-collapse supernovae

1 Introduction

Which stars explode as core-collapse supernovae (CC SNe)? Standard theory suggests that isolated stars with initial masses $\lesssim 8\ M_\odot$ end non-explosively by forming white dwarfs. Those born with $\gtrsim 8\ M_\odot$ die by exploding. The vast majority of these massive stars — those born with masses between roughly $8\ M_\odot$ and $140\ M_\odot$ — are believed to die as CC SNe through the implosion of their iron cores and the subsequent ejection of their envelopes, leaving behind neutron stars or black holes. Although not yet observationally demonstrated, it is possible that *some* of these massive stars fail to turn implosion into explosion and collapse to a compact object with no associated "fireworks" (i.e., "failed SNe"; Kochanek et al. 2008). Beyond $\sim 140\ M_\odot$ (provided Nature actually mints, or minted, such stars; e.g., Figer 2005) death likely arrives earlier in life through the "pair-instability" process that triggers explosive fusion of the oxygen core and the complete disruption of the star, resulting in a "pair-instability supernova" (Rakavy & Shaviv 1967; Gal-Yam et al. 2009; Moriya et al. 2010).

Here we focus specifically on CC SNe, what we have learned about the properties of their progenitor stars through observation, and the implications of these findings on stellar evolution theory, the existence of failed SNe, and the CC explosion mechanism. By registering pre-SN and post-SN images, usually taken at high resolution using either space-based optical detectors — or more recently with ground-based infrared detectors equipped with laser guide star adaptive optics systems (LGS-AO) — over three dozen CC SNe have now had the properties of their progenitor stars either directly measured or constrained by establishing upper limits on their luminosities. These studies have enabled direct comparison with stellar evolution models that, in turn, permit estimates of the progenitor stars' physical characteristics to be made. As we shall see, initial results of these progenitor studies have matched theoretical expectations in some regards, but the field is young and strewn with hints that in some areas a rethinking of standard stellar evolution theory may be in order.

This paper is organized as follows. § 2 provides a brief review of CC SN classification and stellar evolution theory and sketches out generic expectations for the progenitors of each of the major CC SN types. § 3 confronts expectations with existing observations, and § 4 concludes with a brief summary and discussion.

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2 Expectations

2.1 CC SN Classification, Stellar Evolution, and Zeroth-Order Progenitor Expectations

It is typical to subdivide CC SNe into at least five major categories (see Filippenko 1997 for a thorough review): II-Plateau (II-P; hydrogen in spectrum and plateau in optical light curve), II-Linear (II-L; hydrogen in spectrum, no plateau in optical light curve), IIn (hydrogen in spectrum and spectral and photometric evidence for interaction between SN ejecta and a dense circumstellar medium [CSM]), IIb (hydrogen in spectrum initially, with transformation into a hydrogen-deficient spectrum at later times), and Ib/c (no evidence for hydrogen in spectrum at any time). This ordering is thought to be a roughly increasing one in terms of inferred degree of envelope stripping prior to explosion. That is, SNe II-P are the least stripped at the time of explosion and SNe Ib/c are the most stripped, with the others falling in between. Although considerable uncertainty persists regarding the exact proportions, SNe II-P probably account for $\sim 60\%$ of all CC SNe, SNe Ib/c for $\sim 30\%$, and the final $\sim 10\%$ comprised of the rarer IIn, II-L, and IIb types (e.g., Smartt 2009, and references therein).

The most basic expectation for the stellar progenitors of CC SNe is that they should have properties consistent with the evolutionary endpoints of stars born with more than $\sim 8\ M_{\odot}$, the theoretical lower limit for which core-collapse will occur. The expected characteristics of such stars are most easily viewed on the theoretical Hertzsprung-Russell Diagram (HRD), an example of which is shown in Figure 1. Quick examination yields simple predictions: Stars between about 8 $M_{\odot}$ and 25 $M_{\odot}$ should end their lives with properties consistent with red supergiants (RSG), while those above $\sim 25\ M_{\odot}$ should end as hot Wolf-Rayet (WR) stars, which have lost all, or nearly all, of their H and (sometimes) He envelopes.

Stars born with $\gtrsim 50\ M_{\odot}$ are believed to experience a "luminous blue variable" ("LBV") phase *en route* to their deaths as stripped-envelope WR stars, during which violent episodic bursts of mass-loss can occur (eta-carinae being the most famous nearby example). With luminosities $\gtrsim 10^6\ L_{\odot}$, LBVs are the most luminous single stars known. An important point is that it has *not* traditionally been believed that such stars will explode as SNe during the LBV stage, since this evolutionary phase is thought to occur while the star is still at the end of core H burning, or possibly the beginning of core He burning (Maeder & Conti 1994).

The bottom line from conventional theory therefore is that CC SNe should arise from the RSG and WR regions on the HRD. Naturally, many issues complicate this simple picture. First and foremost, the HRD shown in Figure 1 is for single stars. Mass transfer with a companion can drastically affect a star's final properties prior to core collapse, and some fraction of CC SN progenitors are surely arising from interacting binary systems (e.g., Filippenko 1991; Nomoto et al. 1995). Second, although for stars that become RSG it is widely held that the greater the initial mass the stronger the mass-loss should be, details are not well established. There may well be a region in the upper-mass regime of RSG where stars have lost a significant fraction (but not all) of their H envelopes prior to exploding. Some models suggest that such stars could undergo "blue loops" on the HRD, during which they experience temporary blueward excursions (e.g., Xu & Li 2004), and it is possible that some of these stars could even explode during these brief migrations. This would give their progenitors characteristics consistent with hotter supergiant stars, e.g., yellow supergiants (YSG) or, even, blue supergiants (BSG). In fact, the BSG progenitor of SN 1987A is sometimes explained in this

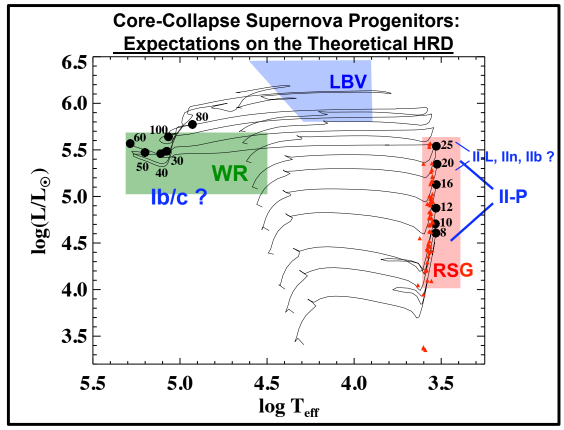

Fig. 1 Theoretical HRD with evolutionary tracks (*thin lines*) and stellar endpoints (*large, filled circles*) for solar metallicity stars, taken from the STARS stellar evolution models (Eldridge & Tout 2004). The models follow stellar evolution up to the initiation of core neon burning, which is likely to give an accurate indication of the pre-SN luminosity; note that the 8 $M_{\odot}$ model does not include the uncertain "second dredge-up" phase, which would make its evolutionary endpoint significantly redder and more luminous (Eldridge & Tout 2004). The *RSG* location is indicated along with the effective temperatures and luminosities derived for a selection of Milky Way RSGs (*small, filled triangles*) by Levesque et al. (2005). The *LBV* and *WR* regions (from Smith et al. 2004 and Smartt 2009, respectively) are also shown. Regions from which one might expect SNe II-P, II-L, IIn, IIb, and Ibc to arise from the simple considerations discussed in the text (§ 2.2) are also indicated.

manner, although binary scenarios remain very popular for it, as well (e.g., Morris & Podsiadlowski 2007). Finally, metallicity and treatment of stellar rotation affect the final stellar characteristics, most notably the dividing line separating stars that will end as RSGs and those that will end as WRs. Values for this cutoff range from $\sim$ 22 $M_{\odot}$ to $\sim$ 34 $M_{\odot}$, depending on the model's characteristics (e.g., Heger & Langer 2000; Meynet & Maeder 2000; Heger et al. 2003). Such caveats aside, the theoretical picture remains fairly clear on the basic fact that exploding, single stars can be expected to largely populate the RSG and WR regions of the HRD.

2.2 Predictions for Specific CC SN Types

Of all of the types of CC SNe, perhaps the most confidence can be placed on the predicted SN II-P progenitor. SNe II-P are characterized by an enduring period ($\sim$ 100 days) of nearly constant optical luminosity (i.e., a "plateau") and strong spectral evidence for hydrogen at all times. These properties have long been thought to result from having the shock-deposited and radioactive decay energy of the explosion injected into a massive and extended envelope, which then slowly releases the energy as the hydrogen recombines during the "photospheric" phase of the SN's evolution (Chevalier 1976). SNe II-P are also very weak radio sources, indicating little interaction with circumstellar material. These outstanding characteristics finger single RSG as the likely progenitors of SNe II-P.

Clear-cut predictions for the other CC SN types are more difficult to make, but some reasonable expectations can be proposed based on their observed characteristics. Of primary significance is that none exhibit a light curve that is "held up" like an SN II-P light curve is. This implies that these other CC SNe do not have similarly extended envelopes when they explode. They are also typically much stronger radio emitters at early times (suggesting interaction with CSM) and generally show less evidence for hydrogen in their spectra (or, in the case of SNe Ib/c, no evidence for hydrogen). These characteristics indicate more substantial pre-SN mass-loss (or, mass-stripping). Putting these clues together, the regions from which we might expect these events to arise are *perhaps* the upper mass regions of the RSG for SNe II-L/IIb/IIn, and WR for SNe Ib/c.

Before proceeding to the observations, we note that a simple calculation finds that if one simultaneously posits a standard Salpeter IMF (slope $\alpha = -2.35$), SNe II-P arising from 8 $M_{\odot}$ to 20 $M_{\odot}$ progenitors, SNe II-L/IIn/IIb resulting from 20 $M_{\odot} \rightarrow$ 25 $M_{\odot}$ progenitors, and SNe Ib/c coming from 25 $M_{\odot} \rightarrow$ 140 $M_{\odot}$ progenitors, relative frequencies of 72% (SNe II-P), 8% (SNe II-L, IIn, and IIb), and 20% (SNe Ib/c) result. Given the large uncertainties involved in any attempt to connect such values with observed SN rates (e.g., the strong sensitivity to the mass cutoffs and the lower mass for which CC is assumed to occur; the substantial uncertainty in the calculation of relative SN rates; the effects of binarity; the uncertainty in the IMF slope itself), it is somewhat reassuring that such a calculation does not produce values *wildly* discrepant with estimates of CC SN fractions. While such indirect statistical comparisons are potentially illuminating, they are no substitute for results obtained from the direct observations of stars that actually explode as CC SNe, the subject to which we now turn.

3 Results

3.1 Experimental Method

To avoid source confusion, searches for SN progenitors demand two primary elements: (1) A very nearby SN (generally, within $\sim$ 20 Mpc), and (2) a high resolution pre-SN image (usually taken with the *Hubble Space Telescope* [*HST*]). If both conditions are met, an additional high resolution image must be obtained with the SN still visible (but, not saturated in the image), to permit registration between the pre- and post-SN images to better than $\sim$ 30 milli-arcseconds. This second image can be obtained at either optical wavelengths using *HST* several months after explosion (so that the SN is faint enough to permit a deep image) or at near-infrared (NIR) wavelengths using LGS-AO, which can be obtained nearly immediately (since CC SNe are quite faint in the NIR, even at early times). If nothing is found at the SN location in the pre-SN image, an upper-luminosity limit for the progenitor may be derived from the image's detection limit.

If spatial coincidence exists between the SN and a point source in the pre-SN image, the most convincing way to demonstrate its connection to the SN is to confirm its absence in an image taken years later, after the SN has faded beyond detection.[1] To date, roughly one dozen CC SN progenitors have now been directly detected (i.e., shown to be spatially coincident with the SN) in pre-SN images, two dozen upper limits

[1]Dust obscuration remains a difficult possibility to definitively exclude – e.g., if substantial dust is formed in the SN atmosphere and the putative progenitor star lies behind the SN along the line-of-sight, the star could be obscured in post-SN images.

derived from non-detections, and four progenitors confirmed through their absence in images taken after the SN has faded. For an exhaustive listing and discussion of all studies completed through early 2009, see Smartt 2009; details of the techniques used to register images and derive the upper limits for non-detections may be found in Leonard et al. (2008) and Leonard (2010).

3.2 Type II-Plateau

Given their relative frequency, it is not surprising that SNe II-P are by far the most well-defined category of CC SNe in terms of direct observational progenitor detections and constraints, making up over half of all progenitor studies to date. At present, seven putative SN II-P progenitor detections have been made using pre-SN images, 12 upper luminosity limits have been derived from non-detections, and one progenitor has been definitively identified through its disappearance in post-SN images. In the three best cases (SN 2003gd, SN 2005cs, and SN 2008bk), for which multi-filter pre-SN images exist that enable the SED of the progenitor star to be characterized, the stars are all found to have been RSG at the lower end of the RSG mass distribution (i.e., $\lesssim 10\ M_\odot$). It is noteworthy that the progenitor characteristics of two of these objects, SN 2005cs (Eldridge et al. 2007) and SN 2008bk (Mattila et al. 2008), are sufficiently well constrained to be deemed inconsistent with those expected for massive AGB stars, which are cooler and significantly more luminous than RSG (see caption to Figure 1). AGB stars have been proposed as the direct progenitors of "electron-capture" SNe, which might result from stars at the lower end of the mass sequence ($8\ M_\odot \rightarrow 10\ M_\odot$?) triggering collapse of their ONe cores through electron capture by magnesium-24 and/or neon-20 (Woosley et al. 2002).

In the remainder of the progenitor studies of SNe II-P — with the exception of two very recent investigations which are, at present, inconclusive (more on these below) — the observed or constrained properties of the progenitors are also consistent with having been RSG at the time of explosion. This conforms with expectations (§ 2.2). However, as shown by Smartt (2009), a close look at the data reveals the interesting result that all but one of the 20 SNe II-P progenitors have initial masses constrained to be $\lesssim 18\ M_\odot$. In fact, the best fit to the data (assuming a Salpeter IMF of slope $\alpha = -2.35$, although the result is quite robust to changes in the IMF) yields a lower mass for SN II-P progenitors of $M_{\rm min} = 8.5^{+1}_{-1.5}\ M_\odot$ and a maximum mass of $M_{\rm max} = 16.5 \pm 1.5\ M_\odot$ (Smartt 2009). What is more, at this point no progenitor star for *any* CC SN has been found to have properties consistent with RSG of initial mass $\gtrsim 20\ M_\odot$ (§ 3.3 — 3.6). Given that such stars are clearly present in the Milky Way and Local Group galaxies (see Figure 1), and would have been easily detected in pre-SN images had they been CC SN progenitors, the question arises: What is the fate of the most massive RSG? A few possibilities to consider:

- *They do not explode as RSGs.* Perhaps many (most? all?) explode during blueward excursions on the HRD. There is some tentative empirical evidence to support this contention. Two very recent CC SNe are claimed to have had possible YSG progenitors arising from stars with initial with masses $\gtrsim 15\ M_\odot$: SN 2008cn (Elias-Rosa et al. 2009) and SN 2009kr (Fraser et al. 2010; Elias-Rosa et al. 2010). Definitive identification of both progenitors is complicated, however, by potential source confusion since the host galaxies are quite distant ($>$ 30 Mpc) and the spatial resolution of the pre-SN images does not permit distinguishing among single stars, binary systems, or compact clusters. Final progenitor characterization therefore awaits late-time imaging. It is worth noting that neither event appears to have been a "normal" Type II-P (e.g., in the ilk of SN 1999em; Leonard et al. 2002). SN 2008cn exhibits spectral peculiarities as well as scant published photometric coverage to secure definitive classification as an SN II-P (Elias-Rosa et al. 2009), whereas SN 2009kr has a photometric evolution similar to a Type II-L (Elias-Rosa et al. 2010) or, perhaps, a "peculiar II-P" (Fraser et al. 2010).
- *They explode as SNe II-L/IIn/IIb.* Investigations into this possibility are, at present, starved for data. As we shall see in §3.3 — 3.5, direct progenitor studies exist for only four SNe II-L/IIn/IIb (not including the potential YSG progenitor of SN 2009kr, the possible II-L discussed earlier), and in no case is a higher mass RSG implicated. While more examples are clearly needed, at this point there is no evidence that high-mass RSG are the direct progenitors of SNe II-L/IIn/IIb.
- *They do not explode.* Quiescent collapse to a BH for massive RSG remains an intriguing possibility. As pointed out by Kochanek et al. (2008), at this point the optical signatures of direct BH formation are virtually unconstrained by either theory or observation. Could this "RSG problem" (as dubbed by Smartt 2009) be the first indication of a mass cutoff between stars that successfully eject their envelopes after core collapse (i.e., those below $\sim 16.5\ M_\odot$) and stars that do not (i.e., those above $\sim 16.5\ M_\odot$)? We return to this possibility in § 4.

3.3 Type II-Linear

Because of their rarity, it is perhaps not surprising that other than the possible YSG progenitor of the possible Type II-L SN 2009kr discussed earlier (§3.2), only one additional object, SN 1980K, has had a pre-SN image examined for a possible progenitor star. In this case, the analysis rules out massive RSG greater than about 18 $M_\odot$ (Thompson 1982). Analysis of the stellar population of the Type II-L SN 1979C by van Dyk et al. (1999) determines a mass range of $15 - 21\ M_\odot$ for its progenitor. From these studies, firm conclusions about the progenitors of SNe II-L can not be made, although early indications are that at least some do not arise from extremely massive stars.

3.4 Type IIn

There is only one study of a Type IIn progenitor, and it involves the interesting case of SN 2005gl. Initial work by Gal-Yam et al. (2007) demonstrated the spatial coincidence between this SN IIn and a remarkably bright source with an estimated luminosity of over $10^6\ L_\odot$, suggesting an LBV progenitor from luminosity considerations alone (§ 2.1); spectral evidence from SN 2005gl itself is also consistent with this idea. Strong claims of an association were tempered, however, by the distance ($\gtrsim 60$ Mpc) of SN 2005gl's host galaxy, which translates the $\sim 0.1''$ resolution of the pre-SN *HST* image to ~ 30 pc, raising suspicion that the detected object could have been an unresolved stellar cluster or association of several massive stars, with only part of the light coming from the actual progenitor of SN 2005gl. To settle the case, additional *HST* observations were obtained two years later, which clearly demonstrated that the luminous source in the pre-SN image had disappeared (Gal-Yam & Leonard 2009). Such a direct association between an LBV and an SN counters conventional theory (§2.1). Further, an additional suggestive (but, not conclusive) piece of evidence for such a connection comes from the peculiar Type Ib SN 2006jc, for which pre-SN images captured an LBV-like outburst two years prior to the final explosion (Pastorello et al. 2007). Unlike SN 2005gl, however, SN 2006jc had clearly lost its entire hydrogen envelope prior to exploding, and so may have had a progenitor transitioning from an LBV to a WR. In both cases, though, the evidence points towards a more highly evolved core than traditional models suggest should exist, and may necessitate a rethinking of stellar evolution theory for Nature's most massive stars (e.g., Smith & Owocki 2006).

3.5 Type IIb

Pre-SN images exist for two SNe IIb. First, SN 1993J in M81, where extensive analyses of pre-SN and post-SN images (and spectra) lead to the conclusion that a $13 - 20\ M_\odot$ star exploded in a binary system (the only binary conclusively implicated thus far by progenitor studies), with a slightly less massive secondary surviving the explosion (Maund et al. 2004; Maund & Smartt 2009). Second, for SN 2008ax, Crockett et al. (2008) find a flat SED at optical wavelengths for the progenitor object that favors an early-type WR (WN class) progenitor with a fairly large ($25 - 30\ M_\odot$) initial mass. Although late-time images are needed to better constrain other possibilities, for now SN 2008ax remains the only tentative detection of a WR star progenitor for any CC SN.

3.6 Type Ib/c

There are ten SNe Ib/c with progenitor studies, but at this point no progenitor detections. This is somewhat surprising, since it is commonly thought that at least some of the progenitors of SNe Ib/c should be luminous, single WR stars. While none of the non-detections are sensitive enough to definitively rule out a WR progenitor, Smartt (2009) demonstrates that it is quite unlikely at this point that all SNe Ib/c come from them; lower mass stars in interacting systems are almost certainly contributing.

4 Conclusions and Discussion

Tantalizing clues but few definitive conclusions characterize the infant field of SN progenitor studies. A zeroth-order result confirms theory: Only massive stars appear to explode as CC SNe. As of now, there is no evidence that stars born with significantly less than 8 $M_\odot$ undergo core-collapse and explode. Another rather firm claim can be made that the direct progenitors of SNe II-P are RSGs most likely confined to the lower-mass end of the RSG population. Beyond these statements lie outstanding questions for which present data only hint at resolution. We conclude by considering one: Do *all* massive stars actually explode at the ends of their lives?

On this point theory provides little guidance, since robust CC explosions continue to elude modelers. It may well be that a variety of mechanisms is required to produce viable explosions across the range of progenitor masses (e.g., Kitaura et al. 2006; Murphy & Burrows 2008; Dessart et al. 2008). In this regard, we take note of the present tension between evidence that at least some extremely massive ($\gtrsim 25\ M_\odot$) stars do explode (e.g., the progenitor studies of SN 2005gl, SN 2008ax, and SN 2006jc), with the possibility that some lower mass stars (i.e., those between $\sim 18\ M_\odot$ and $\sim 25\ M_\odot$ — the RSG problem) may not. Could it be that some version of the standard neutrino mechanism (Colgate & White 1966) is viable for exploding lower-mass stars whereas a magneto-rotational, jet-induced explosion (Wheeler et al. 2002) is at work for those with very high masses, relegating stars that are "in between" to quiet collapse?

With virtually no effort having been expended on directly searching nearby galaxies for disappearing massive stars, observation is at present almost as mute as theory on the issue of quiescent stellar collapse. Indeed, with a few notable exceptions[2], the requisite data for an extensive search for "disappearing stars" do not yet exist, although Kochanek et al. (2008) makes a compelling case for the need for — and feasibility of — such a survey. An indirect empirical argument against a significant number of massive stars failing to explode is made by Maoz et al. (2010), who find from a distance-limited sample that 0.010 ± 0.002 CC SNe are produced per unit stellar mass formed, a result deemed consistent with expectations provided *all* stars with initial masses greater than 8 $M_\odot$ explode. As with statistical arguments made on CC SNe progenitors in general, though, there is no substitute for actually looking.

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[2]A limited but otherwise ideal data set for such a study is being produced by the author as part of an Archival Legacy *HST* study (HST-AR-10673; P.I. Leonard) of the repeated observations of nearby galaxies observed by *HST* for Cepheid studies.

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