Seeking Core-Collapse Supernova Progenitors in Pre-Explosion Images

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Abstract.

I summarize what we have learned about the nature of stars that ultimately explode as core-collapse supernovae from the examination of images taken prior to the explosion. By registering pre-supernova and post-supernova images, usually taken at high resolution using either space-based optical detectors, or ground-based infrared detectors equipped with laser guide star adaptive optics systems, nearly three dozen core-collapse supernovae have now had the properties of their progenitor stars either directly measured or (more commonly) constrained by establishing upper limits on their luminosities. These studies enable direct comparison with stellar evolution models that, in turn, permit estimates of the progenitor stars’ physical characteristics to be made. I review progenitor characteristics (or constraints) inferred from this work for each of the major core-collapse supernova types (II-Plateau, II-Linear, IIb, IIn, Ib/c), with a particular focus on the analytical techniques used and the processes through which conclusions have been drawn. Brief discussion of a few individual events is also provided, including SN 2005gl, a type IIn supernova that is shown to have had an extremely luminous – and thus very massive – progenitor that exploded shortly after a violent, luminous blue variable-like eruption phase, contrary to standard theoretical predictions.

1. Introduction

This review focuses specifically on what we have learned about the progenitors of core-collapse supernovae (CC SNe) by examining images of the supernova (SN) sites taken prior to the explosion. By registering pre-SN and post-SN images, usually taken at high resolution using either space-based optical detectors, or ground-based infrared detectors equipped with laser guide star adaptive optics systems (LGS-AO), about one dozen CC SN progenitors have now been directly detected (i.e., shown to be spatially coincident with the SN) in pre-SN images, with roughly two dozen upper limits derived from non-detections (Smartt 2009). This field has come a long way in the last decade, and promises to advance rapidly as more and more nearby galaxies – hosts of future CC SNe – have high-resolution images added to the archive.

This review is organized as follows. Following a brief summary of SN classification and stellar evolution theory (§ 2), one example from each of the following three categories of progenitor studies is provided (§ 3; ordered from most-to-least common): (1) No progenitor star detected in pre-SN image(s); (2) Likely progenitor star identified via spatial coincidence in pre-SN and post-SN images;
(3) Progenitor star detected in pre-SN image(s) and subsequently confirmed by demonstrating its absence in images taken after the SN has faded beyond detection. A summary of overall results to date for each SN type is then given (§ 4), followed by a brief discussion of outstanding questions and areas in which future progress is likely (§ 5). Note that discussion is limited to what the examination of images of SN sites taken prior to the explosion has taught us, and necessarily excludes (or relegates to very brief comment) such related investigations as SN environments (e.g., Van Dyk et al. 1999a,b; see also the article by Elias Rosa in this volume) and SN progenitor “forensics” (e.g., Modjaz et al. 2009; see also the article by Modjaz in this volume). For a comprehensive discussion of all such related areas, see the recent review by Smartt (2009).

2. Background: SN Classification and Stellar Evolution

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, but transforms into a hydrogen-deficient spectrum at later times), and Ib/c (no evidence for hydrogen in spectrum at any time), where the ordering is a roughly increasing one in terms of inferred degree of envelope stripping prior to explosion (i.e., II-P are the least stripped at the time of explosion, and Ib/c are the most stripped).

While most of this review focuses on the observational advances that have been made, theoretical input is critical to translate observed progenitor luminosity (or limits) into zero-age-main-sequence masses ($M_{\text{ZAMS}}$) and stellar evolutionary states. Among the most complete (and accessible\footnote{The models can be downloaded from the code’s Web site, at http://www.ast.cam.ac.uk/~stars}) stellar evolution models at present are the metallicity-dependent models produced with the Cambridge stellar evolution code, STARS, the descendant of the code developed originally by Eggleton (1971) and updated most recently by Eldridge & Tout (2004; see also Smartt et al. 2009, and references therein), since they follow stellar evolution up to the initiation of core neon burning, which is likely to give an accurate indication of the pre-SN luminosity. The Hertzsprung-Russell diagram (HRD) of the STARS evolutionary tracks are shown in Figure 1 for stars ranging in initial mass from 6 $M_\odot$ to 100 $M_\odot$. Comparison with other contemporary model grids (e.g., Heger & Langer 2000; Meynet & Maeder 2000) show that the endpoints for stars in the 8 → 15 $M_\odot$ range differ by at most 0.2 dex in luminosity among the codes\footnote{The models can be downloaded from the code’s Web site, at http://www.ast.cam.ac.uk/~stars}, which gives some assurance that systematic uncertainties are not great, at least at the low-mass end for red supergiant (RSG) stars. Two areas of uncertainty in need of better quantification (or, at least, agreement within the community) include the effects that stellar rotation and mass-loss might have on the observable characteristics of stars prior to core collapse.
3. Seeking SN Progenitors in Pre-Explosion Images: Case Studies

3.1. Case I: No Progenitor Detected in Pre-Explosion Images

Not surprisingly, when no progenitor star is actually detected at the SN location in pre-SN images, only an upper limit to the progenitor’s luminosity and, hence, mass, can be derived. To illustrate the analysis process in such a situation, I consider SN 2006my, an SN II-P that exploded in a galaxy $\sim 20$ Mpc away (nearly all SNe with progenitor studies are within $\sim 30$ Mpc, since source confusion becomes an increasing problem with distance). Details for this particular event are provided by Leonard et al. (2008); here I briefly outline the steps my colleagues and I took to derive an upper mass limit on its progenitor.

The Hubble Space Telescope (HST) imaged the site of SN 2006my using the Wide-Field and Planetary Camera 2 (WFPC2) in 1994 (pre-SN) and again in 2007 (shortly after explosion). We registered the two images and pinpointed the SN location to better than 30 milli-arcsec in the pre-SN frame (Figure 2a,b). Such fine registration allowed us to rule out a nearby point source (source ‘1’ in Figure 2a) as the progenitor star with greater than 96% confidence. (Note that this source had been previously identified by Li et al. (2007) as the likely progenitor based on registration with lower-resolution ground-based optical post-SN images.) We next set an $I$-band detection limit in the pre-SN frame by

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[Figure 1. The HRD of the STARS evolutionary tracks, from Smartt (2009). The location of RSG, Wolf-Rayet (W-R), and luminous blue variable (LBV) stars are indicated by shaded regions. Figure reprinted, with permission, from the Annual Review of Astronomy and Astrophysics, Volume 47 ©2009 by Annual Reviews www.annualreviews.org.]
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placing artificial stars of progressively fainter magnitude at the SN location and letting the photometry software (in this case, HSTphot, see [Dolphin 2000]) attempt to detect them. The point at which the software no longer detected a point source then serves as the limiting upper magnitude for the progenitor star.

Figure 2. Site of SN 2006my in pre-SN image (a) and post-SN image (b), both taken with HST. Circles in (a) and (b) represent the approximate 5σ uncertainty of the position of SN 2006my when the pre-SN image is registered with the HST image (smaller circles) and a ground-based image taken with LGS-AO (slightly larger circles). Source 1, labeled in pre-SN image (a), is a nearby source determined to not be coincident with SN 2006my at the 96% confidence level. Panel (c) presents the initial mass vs. final predicted luminosity prior to explosion for $Z = 0.01$ stars (filled circles) evolved with the STARS stellar evolution code [Eldridge & Tout 2004]. Dashed lines indicate the estimated systematic uncertainty in the stars’ final luminosities, as described in the text (see §2). The solid, horizontal line represents the 3σ upper luminosity limit for a RSG that could have remained undetected by the analysis of pre-SN images of the site of SN 2006my. Figure adapted from [Leonard et al. 2008], and reproduced by kind permission of University of Chicago Press.

To translate this single-filter detection limit into a luminosity, we assumed that the progenitor was a RSG (given other SN II-P progenitor detections this seems a reasonable assumption; see §3.2 and §4), and then determined the greatest bolometric magnitude it could have had while still remaining below our detection threshold. This is accomplished through:

$$M_{bol} = -\mu - A_V + I + (V - I)_{RSG} + BC_V,$$

where $\mu$ is the distance modulus of the host galaxy (NGC 4651), $A_V$ the extinction to SN 2006my, $I$ the $I$-band detection threshold, $(V - I)_{RSG}$ the color range of RSG stars (i.e., spectral types K3 $\rightarrow$ M4), and $BC_V$ the bolometric correction corresponding to each $(V - I)_{RSG}$. Upon adopting the most conservative values for each of the parameters (i.e., the ones that produce the least restrictive $M_{bol}$ for the progenitor’s upper luminosity limit), and allowing for a maximum
systematic uncertainty of 0.2 dex in the theoretical stellar model endpoints (see § 2), the limiting bolometric magnitude above which any RSG would have been detected in our pre-SN image, $M_{\text{bol}}$, is derived. We then compared this with the final luminosity of stars with $M_{\text{ZAMS}} > 8 \ M_\odot$ predicted by the STARS stellar evolution models (Figure 2c) to derive an upper bound on the progenitor mass of $M_{\text{ZAMS}} = 15 \ M_\odot$. From this analysis, then, we conclude that any RSG progenitor with an initial mass greater than 15 $M_\odot$ would have been detected using our analysis procedure.

Analyses similar to that described here for SN 2006my have been carried out on each of 22 non-detections in pre-SN images (Smartt 2009). As we shall see (§ 4), it is the sheer number of such progenitor non-detections that permits rather strong conclusions to be drawn about CC SN progenitors from this category of progenitor studies.

### 3.2. Case II: Putative Progenitor Detected in Pre-Explosion Images

Next, we consider the individually more revealing situation where an object coincident with the transformed SN location is actually detected in the pre-SN image(s), a situation that exists now for 11 CC SNe (Smartt 2009). As an outstanding example of the analytic power provided by having multi-filter pre-SN images available (especially in the near infrared for RSG progenitors), we consider the recent work of Mattila et al. (2008) on SN 2008bk, a very nearby ($\sim$ 4 Mpc) SN II-P. In this case, pre-SN ground-based images in $BV\ IJ\ HK$ were registered with post-SN LGS-AO $K$-band images to yield solid progenitor star detections in $IJHK$, and upper luminosity limits in $B$ and $V$. When compared with the known spectral energy distribution (SED) of RSG, a good match for the progenitor of SN 2008bk is found with a progenitor of spectral type M4I (Figure 3). From comparison with the STARS stellar evolutionary models an initial progenitor mass of $8.5 \pm 1.0 \ M_\odot$ is derived for this SN. Similar studies on seven other detected SN II-P progenitors have found stars consistent with RSG in all cases, providing nice agreement between theory and observation. As we shall see in § 4, however, the range of masses inferred for these RSG progenitors is somewhat unexpected.

### 3.3. Case III: Progenitor Detected and Confirmed

Finally, we consider the most satisfying situation where images taken before, during, and long after the SN explosion exist that clearly show the progenitor star, the SN, and the absence of the progenitor star, respectively. Such a sequence provides nearly conclusive proof of the progenitor star’s identity. Currently, such a time series exists for only two objects: SN 1987A (e.g., Graves et al. 2003) and SN 2005gl (Gal-Yam et al. 2007; Gal-Yam & Leonard 2009). Because the case of SN 1987A is well-known, I present SN 2005gl as the example of

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2 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 l-o-s, the star could be obscured in post-SN images.

3 “Only two objects” as of February 2009, when this review was written. SN 1993J and SN 2003gd should now (August 2009) properly be added to the list of proposed progenitor stars confirmed to have disappeared in post-SN images; see Maund & Smartt (2009).
Figure 3. Observed SED (open diamonds) of the detected progenitor for SN 2008bk compared with the reddened colors of an M4I supergiant (solid, broad line; $A_V = 1$ mag assumed) and an M0I supergiant (dotted line; $A_V = 3$ mag assumed). Since spectra of SN 2008bk reveal little evidence of significant reddening, the M4I supergiant progenitor is favored. The width of the M4I line indicates the range in observed colors of M4I stars, from Elias et al. (1985). Figure reproduced by kind permission of Blackwell Publishing Ltd.

As shown by Gal-Yam et al. (2007), early spectra of SN 2005gl exhibited the classic features of a Type IIb event, showing narrow but resolved lines of hydrogen superposed on an intermediate-width component on an otherwise featureless continuum. Analysis of the spectral features indicate ejecta interacting with a dense CSM, whose properties suggest that the progenitor star exploded shortly after an LBV-like mass-loss episode. Comparison of a pre-SN HST image with a post-SN image obtained from the ground using the LGS-AO at the Keck II telescope established a spatial coincidence between the SN and a very bright source possessing an estimated luminosity of over $10^6 L_\odot$ (Gal-Yam et al. 2007; see Figures 4a and 4b). The only single stars known to possess such an extraordinary luminosity are very massive ($\gtrsim 70 M_\odot$; see Figure 1), which conventional theory predicts should explode only after the LBV phase has ended (Maeder & Conti 1994).

Initially, strong claims for the unexpectedly luminous progenitor/SN 2005gl association had to be tempered by consideration of the distance of SN 2005gl's host galaxy. At over 60 Mpc away, the $\sim 0.1''$ resolution of the pre-SN HST image corresponds to $\sim 30$ pc, which raises suspicion that the object could be, e.g., an unresolved stellar cluster or association of several massive stars, with only part of the light coming from the actual progenitor of SN 2005gl (Gal-Yam et al. 2007). Additional observations, therefore, were clearly needed to settle the case, and two years later, an additional HST observation was made.
This observation demonstrates that the luminous source in the pre-SN image has, indeed, disappeared (Figure 4c), which implies that the progenitor of SN 2005gl was a single, extremely luminous, star that exploded while in the LBV phase (Gal-Yam & Leonard 2009). Such a luminosity is indicative of having had an initial mass of \( M_{\text{ZAMS}} \gtrsim 70 \, M_\odot \), which likely left behind a stellar mass black hole (e.g., Orosz et al. 2007). In addition to exploding during an unexpected evolutionary phase, the very fact that such a massive star is demonstrated to have exploded at all— as opposed to directly collapsing to a black hole with no SN explosion—is important, since the optical signature produced at the time of stellar collapse to a black hole is, at present, virtually unconstrained by either observation or theory (see, e.g., Kochanek et al. 2008, and references therein).

![SN 2005gl: Confirming an Extremely Massive Progenitor Star](image)

Figure 4. A demonstration that the progenitor star of SN 2005gl has vanished, using images taken before (a, progenitor star indicated with arrow), shortly after (b), and long after the SN explosion (c), from Gal-Yam & Leonard (2009). Figure reproduced by kind permission of Nature Publishing Group.

4. Summary of Results to Date

The three examples discussed in § 3 serve to illustrate how the science of seeking progenitors in pre-SN images is carried out, and what conclusions can typically be drawn. I now briefly summarize results to date arising from direct progenitor searches in pre-SN images; for a more comprehensive review, see Smartt (2009).

**Type II-Plateau:** SNe II-P are by far the most well-defined category of CC SNe in terms of direct observational progenitor constraints, having had eight putative progenitor detections made and 12 upper luminosity limits established. All of the available evidence suggests that RSG are the immediate progenitors of SNe II-P. By employing a uniform reduction and analysis procedure, Smartt (2009) has produced the cumulative frequency distribution shown in Figure 5 for SNe II-P, from which an intriguing result is immediately evident: All but one of the SNe II-P have initial masses constrained to be \( \lesssim 18 \, M_\odot \), with the most massive detected progenitor of an SN II-P having a mass of only 16.5 \( M_\odot \). This is surprising, since RSG up to 25 \( M_\odot \) are clearly observed in the Local Group (Smartt et al. 2009, and references therein), and would have easily been
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detected in the pre-SN images. This lack of massive RSG progenitors for SNe II-P lead Smartt et al. (2009) to speculate that these massive RSG progenitors may be forming black holes heralded by faint, or non-existent, SN explosions (see also Kochanek et al. 2008).

Figure 5. Initial masses of SNe II-P progenitor stars displayed as a cumulative frequency plot, from Smartt (2009). Right-hand axis gives the number of SNe II-P known to have progenitors less massive than the given SN. Solid line is a Salpeter initial mass function (IMF; $\alpha = -2.35$) with a minimum mass of 8.5 $M_\odot$ and a maximum mass of 16.5 $M_\odot$, and represents the most likely fit to the data. Dashed line is a Salpeter IMF but with a maximum mass of 30 $M_\odot$, and is a poor fit to the data. Figure reprinted, with permission, from the Annual Review of Astronomy and Astrophysics, Volume 47 ©2009 by Annual Reviews www.annualreviews.org.

Type II-Linear: A rare type of CC SN, it is perhaps not surprising that only one SN II-L (SN 1980K) has a pre-SN image, the analysis of which 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. (1999b) determines a mass range of 15 – 21 $M_\odot$ for its progenitor. At this point, 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.

Type IIn: SN 2005gl, described earlier in this review (§ 3.3) as having a very massive ($\geq 70$ $M_\odot$) progenitor that exploded while in the LBV phase, is the only example of an SN IIn for which a progenitor has been detected in pre-SN images. Whether such a massive progenitor is indicative of the class as a whole is not known.

Type IIb: Pre-SN images exist for two events. 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, with a slightly less massive secondary surviving the explosion (Maund et al. 2004, and
references therein). Very recently, the Type IIb SN 2008ax has provided a great opportunity to further investigate this rare class of CC SNe since pre-SN HST/WFPC2 images exist in BVI. A study by Crockett et al. (2008) finds a curiously flat SED for the progenitor star, which is impossible to reconcile with a single RSG, but may be consistent with an early-type W-R (WN class) progenitor, suggesting a progenitor star with a large (25 – 30 \( M_\odot \)) initial mass.

**Type Ib/c:** A well-studied class, with ten upper limits but no detections from analysis of pre-SN images. The lack of detections is surprising, since it is commonly thought that at least some of the progenitors of SNe Ib/c should be luminous, single W-R stars, in addition to others perhaps arising from lower mass stars in binary systems. While none of the non-detections definitively rule out a W-R progenitor, Smartt (2009) demonstrates that it is quite unlikely at this point that all SNe Ib/c come from them.

A summary of the current state of affairs of CC SN progenitor research via studies of pre-SN images is provided by Figure 6.

![Core-Collapse Supernova Progenitor Results](image)

**Figure 6.** A concise summary of CC SN progenitor knowledge gained solely from investigations of pre-SN images (in the case of SNe IIL, the post-SN image environment study by Van Dyk et al. (1999b) is also incorporated).

5. **Future Directions**

The science of seeking SN progenitors has made tremendous strides in just the last ten years. For the future, I look with particular interest at the extremes as areas ripe for breakthrough discoveries, since it is there that many of our most fundamental questions lie. On the low-mass end, how will the lack of massive RSG progenitors for SNe II-P be resolved? Are we seeing the first glimpse of the mass cutoff for direct collapse to black holes? If so, then how will this be reconciled with the very massive stars (i.e., the other mass extreme) that apparently do explode as SNe IIn or possibly IIb? And finally, how does binarity...
influence all of these conclusions? Clearly, we are just at the beginning stages of this exciting field of research, and great advances will no doubt be made in the coming decade.

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