Massive stars in their death throes

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The study of the stars that explode as supernovae used to be a forensic study, working backwards from the remnants of the star. This changed in 1987 when the first progenitor star was identified in pre-explosion images. Currently, there are eight detected progenitors with another 21 non-detections, for which only a limit on the pre-explosion luminosity can be placed. This new avenue of supernova research has led to many interesting conclusions, most importantly that the progenitors of the most common supernovae, type IIP, are red supergiants, as theory has long predicted. However, no progenitors have been detected thus far for the hydrogen-free type Ib/c supernovae, which, given the expected progenitors, is an unlikely result. Also, observations have begun to show evidence that luminous blue variables, which are among the most massive stars, may directly explode as supernovae. These results contradict the current stellar evolution theory. This suggests that we may need to update our understanding.

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1. Introduction

The term supernovae was first introduced by Baade & Zwicky (1934) when they separated such events from common novae. Novae occur frequently in our Galaxy and are the result of hydrogen accreting on to the surface of a white dwarf star that ignites after a thick enough layer is deposited. The super-novae are far more luminous and rare, only occurring once or twice a century in our own Galaxy. The last supernovae observed in our Galaxy were the Tycho and Kepler supernovae in 1572 and 1604, respectively.

Supernovae can be so luminous that they outshine all the other stars in a galaxy. After a sharp rise to maximum light over a few days, their luminosity decays and slowly fades over weeks and months. Some have a light-curve plateau and remain at a constant brightness for up to four months before fading. The energy required to power a typical supernova display is similar to the amount of energy our Sun will output over its 10 billion year lifetime. To produce that amount of energy over a few days, the progenitor star must be significantly altered in a supernova.

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The modern understanding of supernovae divides them into two main types: thermonuclear and core-collapse. Thermonuclear supernovae (also known as type Ia supernovae) are the detonation of carbon–oxygen white dwarfs. I do not discuss them in this review (see Hillebrandt & Niemeyer 2000). Core-collapse supernovae account for 72 per cent of all supernovae in a volume-limited sample (Smartt et al. submitted). They are the final events in the lives of stars more massive than approximately eight solar masses (8 \( M_\odot \)). The basic evolution of a star is relatively well understood. A star begins on the main sequence, burning hydrogen to helium. Here, it spends the largest fraction of its lifetime. Once a helium core is formed, hydrogen continues to burn in a shell around the core and the stellar radius swells to between 100 and 1000 times that of the Sun. At this stage, the star becomes a red giant or, for the most luminous, a red supergiant. Massive stars undergo further burning stages. Helium burns to form carbon and oxygen and then progressively heavier elements burn, preventing stellar collapse until an iron core is formed. Iron fusion is an endothermic reaction. With no further energy source to prevent the core from collapsing, a neutron star or a black hole is formed. Figure 1 shows the evolution of a star in schematic form.

Creating a neutron star releases a tremendous amount of energy in neutrinos. A fraction of these neutrinos interact with the stellar envelope, providing the energy to heat and eject it and thus give rise to the supernova. The ejected material is rich in heavy elements synthesized during the star’s life and in the supernova. Eventually, this material mixes with the interstellar medium and pollutes it. When future generations of stars form, they will be more metal rich than the previous generation. Most of the heavy elements in our bodies were formed in the evolution of a massive star and its explosive end.

The exact mechanism of how the energy is transferred to the envelope is uncertain. Most current simulations of supernova do not produce explosions after the core becomes a neutron star. Different additional mechanisms such as acoustic driving by the proto-neutron star or jets from a magneto-rotational instability as material accretes on to the proto-neutron star have been suggested (see Burrows et al. 2007; Dessart et al. 2008 and references therein).
There are two exceptions to the standard picture of iron core collapse. Stars approximately 7–8\(M_\odot\) are not massive enough to progress past carbon burning, and they therefore form oxygen–neon–magnesium cores supported by electron degeneracy pressure. If the core mass reaches the Chandrasekhar mass of 1.4\(M_\odot\), then it begins to collapse. Eventually, the central density is high enough that electrons are captured by magnesium and neon. This removes the electrons supporting the core and accelerates the collapse to a neutron star and an electron-capture supernova occurs (Eldridge et al. 2007; Poelarends et al. 2008). The other exception is the pair-production instability when photons in the core form electron–positron pairs, reducing the radiation pressure that was supporting the star and hence leading to its collapse. The resulting evolution is complex and the entire star can be disrupted in an explosion (Heger et al. 2003). However, such supernovae are rare, occurring only in the most metal-poor galaxies (Langer et al. 2007).

The appearance of a supernova strongly depends on the structure and the composition of the material ejected. This is determined by how much mass is lost from the surface of the star during its evolution. Stars of mass less than 25\(M_\odot\) have weak stellar winds and do not lose their hydrogen envelopes before an iron core is formed. Stars more massive than 25\(M_\odot\) have strong stellar winds and all hydrogen is lost from the surface before the star explodes. These stars are known as helium stars or Wolf–Rayet stars. Figure 2 shows the structure of such a star. The hydrogen envelope can also be removed if the star is in a binary. The stars in a binary interact if their radius is similar to the radius of the orbit and mass transfer can occur, with one star losing mass and the other gaining mass.

Core-collapse supernova progenitors naturally separate into two main groups: those that contain hydrogen when they explode and those that do not. Supernovae are also classified by the same aspect. If hydrogen is detected in the supernova spectrum, then it is classified as a type II supernova; otherwise it is a type I. These two main types can be further subdivided based on the photometric and spectroscopic behaviour of the supernova (Filippenko 1997).

There are two types of type I core-collapse supernovae: type Ib, with helium lines but no silicon lines in their spectra; and type Ic, with neither helium nor silicon lines in their spectra (silicon lines indicate a thermonuclear type Ia supernova).
For type II supernovae, if the luminosity is constant for a few months after the supernova appeared (a plateau in the light curve), then it is a type IIP. These are the most common type of supernovae, making up 59 per cent of core-collapse supernovae in a volume-limited survey (Smartt et al. submitted). The luminosity is constant because, as the ejecta expand in radius, the visible surface where the observed light is emitted from (the photosphere) moves inwards in mass and therefore remains stationary.

There are three other rarer subtypes of type II supernovae. If the light curve decays linearly, then the supernova is a type IIL. The progenitors of these supernovae are thought to have lost hydrogen from their envelopes so that there is not enough hydrogen to produce the luminosity plateau. If the supernova has narrow hydrogen lines, which indicate slow-moving ejecta, then it is a type IIn. This occurs when the supernova ejecta encounter a large amount of material surrounding the progenitor star and are decelerated from a typical ejection velocity of $10^5$ km s$^{-1}$ to 1000 km s$^{-1}$. The last subtype is the hybrid class, type IIb. These are type II events that metamorphose into Ib supernovae. The progenitors of these supernovae have only the barest trace of hydrogen left at the time of core collapse.

The deduction of which stars produce which supernova was a series of educated guesses. It was thought that red supergiants produced type IIP supernovae and that the other types were produced depending on the amount of mass lost before core collapse. The more mass that is lost from a star, the deeper the layers and the heavier the elements that are exposed at the surface. This leads to the stellar type of the progenitor changing from a red supergiant to a Wolf–Rayet star and the supernova type progresses from IIP → IIL → IIb → Ib → Ic. The amount of stripping depends on the initial mass of the star, with the most massive stars losing the largest fraction of their initial mass and exposing the deepest interiors at explosion.

The only way to confirm whether this theory is correct is to study the star that exploded in a supernova. This is difficult because the star is destroyed in the supernova. It is possible, however, that an image may have been taken before the explosion, but supernovae are rare. Also, only a few galaxies are close enough for individual stars to be resolved in ground-based images. However, the supernovae 1987A and 1993J took place in nearby galaxies and it was possible to find the progenitor star in pre-explosion images and determine their nature (see §2).

The situation dramatically improved with the launch of the Hubble Space Telescope (HST). Its resolving power and sensitivity were such that it became possible to resolve individual stars in galaxies out to 60 million light years rather than out to a few million light years. This increased the number of galaxies observed in detail, and for a few supernovae a year pre-explosion images of the progenitor should exist (rather than a few per century before HST). In 2003, two groups simultaneously found the first progenitor of a type IIP supernova (Van Dyk et al. 2003; Smartt et al. 2004). With the concept tested, many discoveries have followed. The success can be reflected in that, out of the 135 supernovae that occurred from 1999 to 2007 within the range of HST, 29 had HST pre-explosion images of the supernova site. The results have confirmed some theories and caused problems for others.
In this paper, I review the study of supernova progenitors, beginning with the first two discovered. This is followed by a discussion of the study of progenitors during the HST era, with highlights of the main results of the observations of type IIP progenitors. I also discuss the progenitors for type Ib/c supernovae and the growing evidence that type IIn supernova have progenitors that challenge the preconceptions of stellar theorists.

2. The supernovae 1987A and 1993J

The first two supernovae with observed progenitors were rare types. In both cases, the progenitor was the result of binary, rather than the better-understood single star, evolution (figure 3).

(a) Supernova 1987A

Supernova 1987A occurred in the Large Magellanic Cloud, a satellite galaxy of the Milky Way. This made it the closest event to be observed since the invention of the telescope and it was also visible to the naked eye. It was an unusual supernova, spectroscopically similar to a type IIP supernova but with a peculiar light curve. The progenitor was discovered from photometry and spectroscopy to be a blue supergiant with a small radius, 45 times the radius of the Sun...
(Walborn et al. 1987), whereas theory predicted that it should have been a red supergiant with a radius a few hundred times that of the Sun. We now understand that the supernova was unusual owing to the small radius of the progenitor, but why was the progenitor blue? There are several possible reasons, including low metallicity, rapid rotation or binary evolution (Podsiadlowski 1992).

The favoured hypothesis today is that the progenitor was the result of two stars merging in a binary. Initially, both stars were on the main sequence burning hydrogen to helium. The more massive, a $16M_\odot$ star, burnt all core hydrogen to helium first and expanded to become a red supergiant. Then, between this point and core collapse, the size of the primary star became greater than the radius of the orbit and the whole system entered a common-envelope phase of evolution. The secondary star, a $3M_\odot$ star, was swallowed by the more massive primary to form a single more massive blue supergiant.

While this model agreed with the progenitor observation, there was no other evidence supporting the theory of binary evolution. Then, in 1997, a triple-ring system that had surrounded the progenitor became visible after it was ionized by the supernova’s ultraviolet flash. Analysis showed that these rings were formed, during the common-envelope phase of evolution, from material that was lost during the merger. This was further evidence for the binary scenario and provided a method to determine that the merger occurred 20 000 years before the supernova (Morris & Podsiadlowski 2007).

(b) Supernova 1993J

Supernova 1993J started out as a type IIb supernova. The progenitor must have lost most, but not all, hydrogen from its envelope before core collapse. The event was nearby in the galaxy M81, 12 million light years away. Pre-explosion images of the object were consistent with a red supergiant but there was excess blue flux (Aldering et al. 1994). The immediate suggestion put forward was that the progenitor was in a binary system and had a blue companion star. In 2004, the supernova had faded enough for its position to be observed by HST. The blue companion star was found but the red supergiant had disappeared, confirming that the red supergiant star had exploded and a binary companion was present (Maund et al. 2004).

The binary companion is necessary because, without it, the exploding star would have retained much more hydrogen and have produced a type IIP supernova. Initially, the progenitor was $15M_\odot$ but it lost $10M_\odot$ of material. After this, it became a red supergiant and its radius became similar to the orbital separation. Unlike the extreme interaction of 1987A, material was transferred to the companion that increased in mass from $14M_\odot$ to $22M_\odot$, the remainder being lost from the system (Maund et al. 2004). In the future, this star will also explode but it is difficult to predict how the accretion will have affected the resulting future evolution.

3. Supernova 2003gd and other type IIPs

After HST was launched in 1990, its archive grew and so did the chance that a supernova would have a pre-explosion image. The first progenitor discovered by HST was the red supergiant progenitor of supernova 2003gd. The star was
remarkable in its normality (see figure 4; Van Dyk et al. 2003; Smartt et al. 2004). Subsequently, a firm progenitor detection was made for supernova 2005cs (Maund et al. 2005; Li et al. 2006). The two observations confirmed for the first time that the progenitors of the most common type of supernova were the expected red supergiants, as shown in figure 1. Both were found to have masses of $8\,M_\odot$, the predicted minimum mass for a supernova to occur (e.g. Heger et al. 2003; Eldridge & Tout 2004).

Other supernovae with available pre-explosion images have less conclusive detections and in many cases no progenitors have been detected. However, it is possible to place an upper limit on how luminous (and thus massive) the progenitor could have been and yet remain undetected.

For the IIP progenitors, enough observations are available (20 detections and non-detections) to make some statements about the progenitor population, specifically the mass range of stars that gives rise to these supernovae. A statistical analysis shows that the minimum mass for a star to explode in a supernova is approximately $7.5\,M_\odot$, while the maximum mass to give rise to a type IIP supernova is approximately $16.5\,M_\odot$ (Smartt et al. submitted). Therefore, we know that type IIP supernovae only come from a relatively small range of masses, despite being in 59 per cent of core-collapse supernovae.

There is a problem in that theory suggests that single stars with masses between 16.5 and $25\,M_\odot$ should retain their hydrogen envelopes. So, what do these stars explode as? One answer is that the hydrogen envelope is not massive enough to produce the plateau in the light curve resulting in a type IIb supernova. An alternative is that these stars have cores massive enough for a black hole to form at core collapse and have only a small explosion energy because a large fraction of ejecta material falls back on to the remnant. In principle, the resulting supernovae may be dim and difficult to observe. Until progenitors for the other type II supernovae are observed, we shall continue to speculate.

Figure 4. The progenitor discovery images for supernova 2003gd (SN2003gd) from Smartt et al. (2004). Reproduced with permission from AAAS. (a) The HST post-explosion image showing the location of the supernova in relation to nearby stars. (b) The HST pre-explosion image showing the location of the progenitor. (c) A ground-based Gemini telescope image showing the reason why the HST is required to make these observations. If this image had been used, then the star identified as the progenitor would have been a blend of stars A and C in (b).
4. Type Ib/c supernovae

A massive star can lose its hydrogen envelope in stellar winds or a binary interaction. The resulting Wolf–Rayet stars are the suspected progenitors of type Ib/c supernovae (figure 2). It is difficult to separate out the type Ib and type Ic progenitors, as both stellar models and observed Wolf–Rayet stars tend to contain helium. In general, the more helium-rich Wolf–Rayet stars produce type Ib supernovae, while the highly stripped helium-poor Wolf–Rayet stars produce type Ic supernovae.

There are currently nine type Ib/c supernovae with pre-explosion images, but their progenitors are undetected (Crockett et al. in preparation). If we assume that the observed Wolf–Rayet population (van der Hucht 2001) are the progenitors of these supernovae and use the detection limits from the progenitor observations to run a Monte-Carlo simulation, then we find that the probability of nine non-detections is less than 0.05. This suggests that Wolf–Rayet stars are not the only type of progenitor. The most sensitive pre-explosion observation to date is for supernova 2002ap. The observation rules out a normal Wolf–Rayet star and favours a binary system with a low-mass Wolf–Rayet star with lower mass, $M \approx 5M_\odot$, than a typical Wolf–Rayet star, $M \approx 10M_\odot$ (Crockett et al. 2007).

Low-mass Wolf–Rayet stars lose their hydrogen envelopes in binary interactions. These are stars with an initial mass less than $25M_\odot$, which cannot become Wolf–Rayet stars by themselves. However, such stars have never been observed in our Galaxy. They may be difficult to find because either they are less luminous than the normal Wolf–Rayet stars or the binary companion required to strip the hydrogen may hide the low-mass Wolf–Rayet star. Nothing can be firmly concluded until a progenitor is observed. Even if the explosion of a normal Wolf–Rayet star is observed, there are still the non-detections to explain. Hence, the low-mass Wolf–Rayet stars in the Galaxy must be found to back up this hypothesis. The only uncertainty is: Will we be able to recognize them when we observe them?

5. Type IIn supernovae have luminous blue variable progenitors?

A supernova is classified as a type IIn when there are narrow hydrogen lines in its spectrum. This indicates that the hydrogen is moving slower than the typical ejecta velocities. These lines occur when the ejecta are slowed through interaction with dense circumstellar material around the progenitor star, such as a dense stellar wind. The stars with the densest winds are luminous blue variable (LBV) stars. Rather than having a steady constant wind, these stars are highly variable and can eject more than a solar mass in a single mass-loss event, a process that leads to a very dense environment around the star. Traditionally, they have been considered transition objects between main-sequence stars and Wolf–Rayet stars with initial mass greater than $60M_\odot$.

Kotak & Vink (2006) were the first to suggest that LBVs are the progenitors of some supernovae. They were able to model modulations in the radio light curve of some supernovae by assuming the pre-supernova mass loss varied as for an LBV star undergoing S-Doradus type variations. Supernova 2005gl further increased interest in supernovae of this type and their progenitors. A source
consistent with an LBV was in pre-explosion imaging, but it is too distant to be sure it was a single star and not a cluster of stars (Gal-Yam et al. 2007). In addition, the supernovae 2006jc, 2006gy and 2005gj had indirect evidence that their progenitors had properties similar to LBV stars (Pastorello et al. 2007; Smith & McCray 2007; Trundle et al. 2008). This is an active area of research and the subject is in a state of flux. LBV stars have traditionally been interpreted as objects that have yet to begin or complete core helium burning. Suggesting that they can explode is uncomfortable for most theorists because the stars still have to burn helium and the other products before core collapse. While these burning stages occur, the envelope can be lost and the star becomes a Wolf–Rayet star.

A possible approach is to say that most LBVs are still transition objects. We therefore need to ask whether there are stars that look similar to LBV stars but are in fact close to core collapse. To answer this question, we would need to understand what drives the LBV behaviour. We do not fully understand this behaviour, although Stothers & Chin (1996) find that, in the most massive stars with hydrogen envelopes and helium cores, the stellar structure separates into two quite separate structures, an inner core and a separate unstable outer shell. It is this outer shell that is ejected from the star, leaving the inner core intact. These structures occur in the most massive stars after the end of the main sequence. However, a similar structure can be found in a narrow mass range, approximately $30M_{\odot}$, in more evolved stars near to core collapse. While typical LBV stars experience the evolution sequence of main sequence $\rightarrow$ LBV $\rightarrow$ Wolf–Rayet $\rightarrow$ supernova, these more centrally evolved LBVs experience the evolution of main sequence $\rightarrow$ red supergiant $\rightarrow$ LBV $\rightarrow$ supernova. During the red-supergiant phase, their cores evolve close to core collapse as their luminosities grow. They become LBV stars at the same time as their cores are close to collapse. These stars would differ from the traditional LBVs in their evolutionary status but would appear as LBV stars when observed and be indistinguishable. The luminous and variable red supergiant HV 11423 (Massey et al. 2007) could be a red supergiant evolving towards an LBV phase of evolution.

Finally, a recent type IIn supernova 2008S must be mentioned. While no progenitor has been observed for this object, a dusty cocoon surrounding the progenitor star was detected. The inferred luminosity indicates that the progenitor was a star with a mass $4–7M_{\odot}$ rather than an LBV star (Prieto et al. 2008). However, there is some debate as to whether the event was a supernova because several expected observational features have not been observed.

The true nature of LBV stars and the progenitors of type IIn supernovae make a complex problem, investigation of which is currently observationally led. More work by theoreticians is required in addition to further detailed observational study.

6. Discussion and conclusions

The direct study of pre-supernova imaging in the archives has led to some quite remarkable and usually understated successes in the determination that the progenitors of type IIP supernovae are red supergiants. Despite this, it is still a
subject in its infancy. The remaining supernova types are still lacking firm constraints. The importance of direct study is highlighted by the current confusion of type IIn progenitors.

By detecting the progenitors of supernovae, we can make fundamental tests of stellar evolution, which were not possible before we were able to observe their progenitors. Each time we see something new, it provokes us to reach a new understanding. Our understanding of the lives of stars and the nature of supernovae is evolving dramatically owing to this exciting avenue of science.

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